A STUDY OF CENTRIFUGAL ATOMIZATION OF MELTS

By

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Abstract

The literature on atomization of melts has been reviewed. Models have been developed and applied to analyze the phenomena associated with centrifugal atomization of melts using rotating disk method. Some suggestions and guidelines for the development and operation of a centrifugal atomizer have been given.

Previous experiments of melt atomization and present observations of water disintegration at the edge of a rotating disk have confirmed that the disintegration of melts or water occurs in one of three basic modes: direct droplet formation (DDF), ligament formation (LF) and film formation (FF). Wave theories have been used to analyze the disintegration of melts in the different regimes. The equations for the fastest growing wave number have been derived. Models for the calculation of powder particle sizes have been suggested and the calculated results have compared with available experimental data in the literature. Calculations have shown that disk diameter and disk rotating speed are two very important atomizing parameters. The type of melt and melt superheat also affect the powder particles size. In general, fine powder particles can be obtained by increasing disk rotating speed and using large diameter disk, provided that the melt does not solidify on the disk. In the DDF regime waves forming at the periphery of a disk are responsible for the break up of melts. The fastest growing wave number depends on the disk speed, disk diameter and properties of melt. In the FF regime sheet wave theory of Dombrowski and Johns was used to study the collapse of the melt sheet. The fastest growing wave number is a complex function of the speed and thickness of film and the properties of melt and atomizer atmosphere. The effects of disk diameter, disk rotating speed and melt flow rate on atomization are achieved through influencing the speed and thickness of film.

The studies on the flow of melts on rotating disks have shown that the film forming
on the disk was very thin, about tens of microns and the tangential velocity of melts was much higher than the radial velocity.

The analysis of heat transfer of melts on a rotating disk has shown that partial solidification of melts on the disk is possible. To obtain a good atomization condition it is necessary to control the partial freezing of melts on the disk. A large melt superheat and a high melt flow rate are required to prevent melts from freezing on the disk. The use of a small diameter disk can also avoid freezing of the melt on the disk. Combining the calculations of heat transfer on the disk with the prediction of wave theory for particle sizes, it is shown that a disk of small diameter rotating at high speed is desirable for the production of fine powders.

The cooling ability obtained by centrifugal atomization using the rotating disk method depends on the design of atomizer, the operating conditions and the type of material to be atomized. A large diameter disk on which solidification of melt is avoided and a high disk rotating speed result to the formation of fine powder particles which experience a high cooling rate. The nucleation undercooling of melt depends on particle size, disk speed, material to be atomized and the nucleation condition. A small particle size and a high disk speed lead to a large undercooling.

The times for the completion of solidification of powder particle of typical sizes produced by centrifugal atomization have been calculated and their effects on the atomizer vessel diameter have been discussed.
List of symbols

\( A \) heat transfer area or droplet surface
\( A_n, A_p, A_s, S_p \) coefficients in finite difference equations
\( a \) amplitude of wave
\( a_0 \) initial amplitude of wave
\( a_t \) the first differential of amplitude with respect to time
\( a_n \) the second differential of amplitude with respect to time
\( C_1 \) and \( C_2 \) constants in equations 4.14 and 4.15
\( C_d \) drag force coefficient
\( C_p \) specific heat of melt
\( C_{pg} \) specific heat of gas
\( C_{pl} \) specific heat of liquid droplet
\( C_{ps} \) specific heat of mushy droplet
\( C_{ps} \) specific heat of solid droplet
\( D \) disk diameter
\( D_0 \) constant of diffusivity
\( D_i \) diffusivity in melt
\( d_{50} \) mass median particle size
\( d_m \) molecular jump distance
\( d_l \) diameter of ligament
\( d_p \) mean droplet size
\( d_s \) mean powder particle size
\( E \) activation energy for diffusion
\( F \) force
\( f \) solidified fraction
\( g \) acceleration due to gravity
\( h \) thickness of film
\( h_0 \) film thickness at \( r_0 \) or at the edge of a disk
\( h^* \) film thickness at breakup
\( h_c \) convective heat transfer coefficient between droplet and gas
\( h_{lg} \) convective heat transfer coefficient from melt to surroundings during fall of
the melt

$h_{ms}$ heat transfer coefficient by impingement from melt to disk

$h_{mg}$ convective heat transfer coefficient from melt to surroundings during the spreading out stage of the melt on the disk

$h_p$ Planck constant

$h_{sw}$ convective heat transfer coefficient between the disk and cooling media

$I$ control variable

$J$ nucleation rate

$K$ wave number

$K_{opt}$ optimal wave number

$k$ thermal conductivity of melt

$k_b$ Boltzmann constant

$k_{gas}$ thermal conductivity of gas

$k_d$ thermal conductivity of disk material

$L_{s}$ flight distance at completion of solidification

$l_{o}$ distance from the nozzle to the plane of disk

$Ma$ Mach number, $Ma=u/U_g$

$m$ mass flow rate of melt or droplet mass

$m_0$ dimensionless parameter, $m_0=r_0\omega/u_o$

$N, M$ nodal number in r- and z- direction respectively

$Nu$ Nusselt number of melt, $Nu=h_{mg}r/l/k$

$Nu_{gas}$ Nusselt number of gas, $Nu_{gas}=h_{mg}r/k_{gas}$

$Nu_d$ Nusselt number of droplets, $Nu_d=h_{d}d/l/k_{gas}$

$n$ number of droplets appearing at the edge of a rotating disk

$n_l$ number of ligaments forming at the edge of a rotating disk

$Pr$ Prandtl number of melt, $Pr=\mu C_p/k$

$Pr_{gas}$ Prandtl number of gas, $Pr_{gas}=\mu_{gas} C_{pg}/k_{gas}$

$p$ pressure of melt

$Q$ flow rate of melt

$Q_h$ change in thermal enthalpy of melt

$Q_{conv}$ heat transfer by convection and radiation from melt to surroundings

$Q_{impinge}$ heat transfer by impingement
critical flow rate for the transition from DDF to LF

Q, c

critical flow rate for the transition from LF to FF

Q, c

heat transfer through the disk

q, w

gas constant or radius of disk

R

Re Reynolds number of melt, \( Re = \omega R^2 / \mu \)

Re, gas rotational Reynolds number of gas, \( Re_{gas} = \omega r^2 / \mu_{gas} \)

Re, jet Reynolds number of melt, \( Re_j = r_0 u_j / \mu \)

Re, droplet Reynolds number, \( Re_d = d_p \left| u_p - u_g \right| / \mu_{gas} \)

Re, rotational Reynolds number of melt, \( Re_{rot} = \omega r_1^2 / \mu_{gas} \)

r, \( \theta \), z coordinate system

r radial position of disturbance

r_0 radius of nozzle

r_1 critical radius

r, crit critical radius for splashing

temperature

T average temperature of melt across the film

T, b average temperature of melt across the film

T, g gas temperature

T, i temperature of melt approaching disk

T, m melting point

T, n nucleation temperature

T, p temperature of melt after impingement

T, d droplet temperature

T, p, w pouring temperature of melt

T, s disk temperature

\( \Delta T_{super} \) superheat of melt

T, w temperature of surroundings

t time

u solidification rate (growth velocity) or velocity of gas in Ma

u, \( v \), w velocity components of melt in r, \( \theta \)- and z-direction respectively

u_0 velocity of melt at r_1

u_0' velocity of melt at the exit of nozzle
\( u_g \) gas velocity
\( u_m \) mean radial velocity of melt at the edge of a disk
\( u_p \) droplet velocity
\( u_{p_0} \) initial velocity of droplet at edge of a disk
\( u_r \) radial velocity of film beyond the disk
\( u_s \) sound velocity in gas
\( v \) velocity of film leaving disk
\( v_m \) molecular volume
\( v_i \) disk peripheral velocity
\( We \) Weber number, \( We=\rho_0^* R^1/\sigma \)
\( x_r \) radial film extent
\( x_r^* \) radial film extent at the break up of film
\( y \) displacement of wave

**Greek symbols**

\( \beta \) growth rate of wave, equation (5.6)
\( \beta' \) relative growth rate of wave
\( \beta_{max} \) mean maximum growth rate of wave
\( \beta_{max} \) maximum growth rate of wave
\( \gamma \) interface energy between liquid and solid
\( \Delta G_e \) critical free energy barrier
\( \Delta G_{sm} \) activation energy for migration
\( \Delta H_f \) latent heat of fusion
\( \Delta T \) undercooling of droplet, \( \Delta T = T_m - T_p \)
\( \delta \) displacement of disturbance away from the mean position
\( \delta_s \) thickness of disk
\( \varepsilon_{sm} \) emissivity of melt
\( \varepsilon_u, \varepsilon_v, \varepsilon_w, \varepsilon_h, \varepsilon_T \) control precision in iteration calculation for \( u,v,w,h \) and \( T \), respectively
\( \eta, \xi \) new coordinate system
\( \Delta \eta, \Delta \xi \) grid spacing in \( \eta \) and \( \xi \) direction, respectively
$\theta$  wetting angle

$\lambda_{opt}$  optimal wave length for the ligament break up

$\mu$  viscosity of melt

$\mu_0$  constant in equation 4.1

$\mu_{gas}$  viscosity of gas

$\rho$  density of melt

$\rho_{gas}$  density of gas

$\rho_s$  density of powder particle

$\sigma$  surface tension of melt or Stefan-Boltzmann constant

$\tau$  time

$\tau^*$  break up time

$\nu$  kinematic viscosity of melt

$\nu_{gas}$  kinematic viscosity of gas

$\phi$  disturbance potential

$\phi$  general variable in finite difference equations 3.20 and 4.16

$\omega$  angular speed of disk

$\varphi$  variable in equations 5.10 and 5.13
# List of abbreviations

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM</td>
<td>Boundary Element Method</td>
</tr>
<tr>
<td>CA</td>
<td>Centrifugal Atomization</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CSC</td>
<td>Centrifugal Shot Casting</td>
</tr>
<tr>
<td>CIP</td>
<td>Cold Isostatic Pressing</td>
</tr>
<tr>
<td>DDF</td>
<td>Direct Droplet Formation</td>
</tr>
<tr>
<td>EBRED</td>
<td>Electron Beam Rotating Disk</td>
</tr>
<tr>
<td>FD</td>
<td>Film Disintegration</td>
</tr>
<tr>
<td>FGM</td>
<td>Functional Gradient Materials</td>
</tr>
<tr>
<td>FF</td>
<td>Film Formation</td>
</tr>
<tr>
<td>HIP</td>
<td>Hot Isostatic Pressing</td>
</tr>
<tr>
<td>LD</td>
<td>Ligament Disintegration</td>
</tr>
<tr>
<td>LDC</td>
<td>Liquid Dynamic Compaction</td>
</tr>
<tr>
<td>LF</td>
<td>Ligament Formation</td>
</tr>
<tr>
<td>MIM</td>
<td>Metal Injection Moulding</td>
</tr>
<tr>
<td>PM</td>
<td>Powder Metallurgy</td>
</tr>
<tr>
<td>PREP</td>
<td>Plasma Rotating Electrode Process</td>
</tr>
<tr>
<td>REP</td>
<td>Rotating Electrode Process</td>
</tr>
<tr>
<td>RS</td>
<td>Rapid Solidification</td>
</tr>
<tr>
<td>RSR</td>
<td>Rapid Solidification Rate</td>
</tr>
<tr>
<td>USWA</td>
<td>Untrasonic Standing Wave Atomization</td>
</tr>
</tbody>
</table>
Contents

Acknowledgements i
Abstract iii
List of symbols v
List of abbreviations x

Chapter 1. Introduction 1

PREVIOUS WORK

Chapter 2. Literature Review 5
2.1 Application of melt atomization 5
2.2 Atomization techniques 8
2.3 Variants of centrifugal atomization 15
   2.3.1 Rotating electrode process 15
   2.3.2 Rotating disk/cup 17
   2.3.3 Other centrifugal processes 19
2.4 Studies of centrifugal atomization 21
   2.4.1 Rotating electrode process 21
   2.4.2 Centrifugal shot casting process 25
   2.4.3 Rotating disk method 29
2.5 Melt break up in atomization 32
   2.5.1 Break up process 32
   2.5.2 Wave theories 34
2.6 Conclusions 39
Chapter 3. Flow of melt on a rotating disk

3.1 Introduction 41
3.2 Physical description 44
3.3 Mathematical formulation 45
3.4 Solution method 47
3.5 Results and discussion 50
  3.5.1 Comparison of the calculated and experimental results 51
  3.5.2 Simulation of flow profiles 51
    3.5.2.1 Film thickness and velocity profiles 52
    3.5.2.2 Effect of disk speed 52
    3.5.2.3 Effect of flow rate 52
    3.5.2.4 Effect of different metals 52
3.6 Conclusions 52

Chapter 4. Heat transfer for melts on a rotating disk

4.1 Introduction 64
4.2 Mathematical formulation 65
  4.2.1 Heat transfer in falling zone 66
  4.2.2 Heat transfer in impinging zone 67
  4.2.3 Heat transfer in spreading zone 68
4.3 Solution method 70
4.4 Results and discussion 70
  4.4.1 Effect of disk speed 71
  4.4.2 Effect of mass flow rate 71
  4.4.3 Effect of melt superheat 72
  4.4.4 Effect of heat transferred through the disk 72
4.5 Conclusions 72

Chapter 5. Calculation of powder particle size

5.1 Introduction 81
5.2 Review of wave theories

5.3 Transition conditions

5.4 Calculation of powder particle size in the DDF regime
   5.4.1 Introduction
   5.4.2 Formation and growth of wave at the edge of a rotating disk
   5.4.3 Calculation of powder particle size
   5.4.4 Solution method
   5.4.5 Results and discussion
      5.4.5.1 Comparison of calculated and observed wave number
      5.4.5.2 Comparison of calculated and experimental particle sizes
      5.4.5.3 Effect of atomizing parameters

5.5 Calculation of powder particle size in the LF regime
   5.5.1 Calculation principle
   5.5.2 Solution method
   5.5.3 Calculated results and discussion
      5.5.3.1 Comparison of calculated and experimental powder particle sizes
      5.5.3.2 Effects of atomizing parameters

5.6 Calculation of powder particle size in the FF regime
   5.6.1 Introduction
   5.6.2 Mathematical formulation
      5.6.2.1 Aerodynamic instability of a liquid sheet
      5.6.2.2 Growth rate and optimal wave number
      5.6.2.3 Film thickness during film extension
      5.6.2.4 Calculation of powder particle sizes
   5.6.3 Solution method
   5.6.4 Results and discussion
      5.6.4.1 Comparison of calculated and experimental film extents
      5.6.4.2 Comparison of calculated and experimental particle sizes
      5.6.4.3 Effect of atomizing parameters

5.7 Effect of breakup parameter \( \ln \left( \frac{a^*}{a_0} \right) \) on calculated results
Chapter 6. Droplet dynamics and solidification

6.1 Introduction

6.2 Mathematical formulation
   6.2.1 Droplet dynamics
   6.2.2 Thermal histories and solidification progress
      6.2.2.1 Droplet heat transfer
      6.2.2.2 Droplet thermal histories

6.3 Solution method

6.4 Results and discussion
   6.4.1 Basic solidification process
   6.4.2 Effect of disk speed
   6.4.3 Effect of droplet superheat
   6.4.4 Effect of material type
   6.4.5 Effect of particle size
   6.4.6 Effect of gas type
   6.4.7 Effect of heterogeneous nucleation

6.5 Conclusions

Chapter 7. Water atomization: Experiment and observations

7.1 Introduction

7.2 Calibration experiments
   7.2.1 Calibration of tilting speed of crucible
   7.2.2 Calibration of disk speed

7.3 Results and discussion
   7.3.1 Tilting crucible mode
   7.3.2 Experiments using water stream of well defined diameter

7.4 Conclusions

Chapter 8. Preliminary experiment of melt atomization

8.1 Introduction
Chapter 1
Introduction

The development of advanced materials often requires advanced techniques to obtain uniform microstructures and better properties at competitive cost. Atomization of melts with subsequent powder consolidation is now a well established method for producing materials with metastable microstructures, extended solid solubility of alloying elements and improved properties. There are various types of atomization techniques. Water atomization is widely used to produce iron based powders. It is estimated that half the world production of iron powders is produced by this method. The main limitation of water atomization is powder purity, particularly with reactive metals and alloys. Gas atomization utilizes gas jets to break up a thin stream of liquid into droplets. The velocity of the atomizing gas is an important process parameter in controlling particle size and cooling ability. A high velocity of gas, such as supersonic, might be needed to obtain fine powders. High velocity gas jets lead to fast cooling of the droplets but process efficiency is low because of the large amount of gas used. Atomization using inert gas is also very expensive. Furthermore, use of ceramic delivery tubes in gas atomization may provide a source of contamination of the atomized powders. In this case gas atomization is not suitable for the processing of some metals and alloys, particularly for aerospace applications.

The solidification processing of high temperature melts of reactive (e.g. Ti) or refractory metals (e.g. Mo, Nb) and their alloys requires clean processing. In near equilibrium solidification processing this is achieved using cold hearth clean melting with arc melting with non-consumable or consumable electrodes or electron beam melting or transferable plasma melting as heat sources and water cooled copper crucibles as the cold hearths followed by ingot casting. Near equilibrium solidification processing cannot produce uniform solidification microstructures. Centrifugal atomization provides a possible solution for non-equilibrium solidification
processing of reactive or refractory metals and their alloys.

Centrifugal atomization utilizes centrifugal forces to disintegrate a liquid. In centrifugal atomization, a thin film disintegrates into droplets at the edge of the rotating body due to centrifugal force and aerodynamic effect at the interface of gas and liquid. A rotating bar or disk or cup can be used to accomplish this task. Since the rotating speed is adjustable and easy to vary, the particle sizes produced by this type of atomization are controllable. In general, the particle size distributions are narrow. The process efficiency is high, about 50-60%, compared with 1% for gas atomization and 10% for water atomization (Yule and Dunkley, 1994).

Rapid solidification processing for clean powder production of Ni or Ti alloy powders has concentrated mainly on the rotating electrode process (REP). In the case of Ni alloy powder production, the free fall gas atomization method has also been used with special care regarding melting and filtering of the melts prior to atomization and in subsequent handling of the powders.

REP is a variant of the centrifugal atomization process and requires that the material to be atomized is available first in bar form, the bar becoming the consumable electrode which is rotated at about 3000 to 9000 rpm to produce powders of mass median diameter around 200 μm in the case of Ti alloys. Another variant of the centrifugal atomization process is the spinning cup process and the atomization of melts falling on rotating disks. The latter has been applied to ferrous and non-ferrous melts for which gas atomization has traditionally been the atomization process used for powder production. The use of the rotating disk is particularly attractive for materials which are not available in bar form and also for R & D work to develop new alloys. A further attraction of the rotating disk method comes from the possibility of combining centrifugal atomization of melts with spray casting on cylindrical substrates, thus enabling the near net shape processing of components by the so-called centrifugal spray casting process.
In recent years some powders of alloys, such as 2024 aluminum alloy (Angers et al, 1994), Al-Cr-Fe alloys (Ziani and Michot, 1996) and AZ91 magnesium alloy (Labrecque et al, 1997) have been produced by rotating disk processes. The morphology and microstructure of centrifugally atomized powders have been studied by scanning and transmission electron microscopy and powder particle sizes have been determined by sieve analysis. There is limited research on the effects of atomizing parameters on powder particle size (Cherre and Accay, 1990; Halada et al, 1990; Dogan and Saritas 1994 and Angers et al, 1994). Preliminary studies of the mechanisms operating in the disintegration of melts have been done using video-recording and high speed photography (Halada et al, 1990 and Labreque et al 1997). Studies of the spreading out of melts on rotating disks, of the possible solidification of these melts on the disk and of the disintegration modes of melts on and beyond the disk as well as the solidification of the atomized droplets in flight are also limited. Design and operation of atomizers is still semi-empirical.

The aim of the research described in this thesis is to study the fundamental aspects of centrifugal atomization using a rotating disk. The objectives of the research are:

( a ) to understand the phenomena associated with the spreading of liquids and melts on a rotating disk.

( b ) to study the mechanisms of powder production via the break up of the film at and beyond the edge of the rotating disk and

( c ) to study the droplet dynamics and solidification history of the powders produced by centrifugal atomization.

The strategy adopted to achieve the above aim and objectives of the research is as follows:

[1] Develop theoretical models (i) to describe the spreading of melts on a rotating disk and (ii) to calculate the velocity profiles in the film on the rotating disk as a function of processing parameters.

[2] Develop a heat transfer model to study the processing conditions under which
freezing of the melt on the disk is possible.

[3] Develop theoretical models (i) to study the mechanisms of melt break up at the edge of the rotating disk and (ii) to calculate the size of the powders produced.

[4] Develop theoretical models (i) to study the droplet dynamics in flight and (ii) to analyze the solidification of droplets in flight.

[5] Use high speed camera photography to study the interaction of a liquid with a rotating disk and to compare some of the predictions of the theoretical models with the experimental observations.


The structure of the thesis is as follows. Chapter 2 gives a brief review of previous research on the atomization of melts with emphasis on centrifugal atomization and melt break up phenomena and theories. In chapter 3 the flow of melts on a rotating disk is studied and heat transfer phenomena in melts on a rotating disk are modelled in chapter 4. The calculation of powder sizes for different atomizing conditions in centrifugal atomization is discussed in chapter 5 and droplet dynamics and solidification are modelled in chapter 6. Experimental observations of the interaction of water with a rotating disk are described in chapter 7. The atomization of aluminium is briefly addressed in chapter 8. Conclusions and suggestions for future work are presented in chapter 9.
Chapter 2
Literature Review

2.1 Application of melt atomization

Powders, especially fine powders, have a high ratio of surface area to volume and thus surface activity, and offer many opportunities for the development of advanced materials. Powder metallurgy (PM) can benefit from the use of fine powders. Nowadays research on nanometre size powders is an active area in the field of materials.

Powders can be produced by various techniques. Each technique has its own advantages and disadvantages and meets some specific requirements for powders. Atomization of melts has many advantages over traditional methods for the production of powders and is widely used for the production of metal powders. The main advantages of melt atomization are (Yule and Dunkley, 1994):

a) Flexibility in powder characteristics

Atomization can handle a very wide range of outputs (from 1 to 100,000 tonnes a year), and produce a wide range of particle sizes (from 1 μm to 10 mm). It is also possible to control the particle size, size distribution and the shape of the particles. For example, one can generally obtain (i) near-spherical particles, using inert gas atomization, which give better flow properties than milled particles and (ii) particles with irregular shapes, using water atomization, which is ideal for powder compaction processes.
b) Improved microstructures

In most melt atomization processes rapid solidification (RS) occurs. This eliminates macrosegregation and is beneficial in promoting a microstructural homogeneity throughout the particles. Such homogeneity is not found in the particles formed by comminution as they preserve the inhomogeneity in the ingot from which they are formed.

c) Suitability for the production of both elemental and alloy powders

One can not get alloy powders by electrolytic and chemical methods. In principle, atomization is suitable for the production of any metal and alloy powders provided that the metals and alloys can be melted.

d) High efficiency

![Diagram showing various metal processing techniques and powder particle sizes](image)

Figure 2.1 Range of approximate powder sizes in different applications of metal powders (Lawley, 1992)
High powder production rates give economy of scale. For example, iron powders can be produced by water atomization at feed rates up to about 400 kg/min. High process efficiency also comes from the application of atomization in the manufacture of near-net shape products, such as in spray forming where the elimination of intermediate processing steps greatly reduces the cost.

Powder size is an important parameter in powder applications. Different applications require different powder sizes. Figure 2.1 shows the range of approximate powder sizes in different applications of metal powders (Lawley, 1992).

Powder shape is another important parameter in powder application. Powder shape affects powder packing, flow, and compressibility. It is difficult to quantify particle shape, and qualitative descriptors are frequently used to convey a sense of the shape. Figure 2.2 gives a collection of particle shapes and shows the appropriate qualitative descriptors (Yule and Dunkley, 1994).

Figure 2.2 Nomenclature for particle shape (Yule and Dunkley, 1994)

Major use of metal powders is the manufacturing of mechanical components and various processing applications for powder metallurgy, such as sintering, cold
isostatic pressing (CIP), hot isostatic pressing (HIP) and metal injection moulding (MIM) and for the development of coatings and advanced materials, such as in thermal/plasma spraying and in the preparation of functional gradient materials.

Metal powders are also used for many other purposes, such as solid rocket fuel, metallic paints, PM filters, solder creams, strips for diamond synthesis, dental amalgams, jewellery-brazing pastes, dense media for mineral and scrap separation, explosives, food additives, and batteries. New applications are being developed regularly.

2.2 Atomization techniques

Melt atomization can be defined as a process by which a molten metal stream is sprayed into a cloud of droplets which subsequently solidify to form powder particles. Atomization of melts is a relatively new area for the production of metal powders. Basically, atomization can be classified into the following groups according to the mode of forces applied to break up melts into powders: (1) two-fluid atomization, (2) vacuum atomization, (3) centrifugal atomization and (4) other methods.

In two-fluid atomization a molten metal stream is disintegrated into droplets by the application of impinging forces from a second fluid. The second fluid can be either water or oil or various gases. Correspondingly, the techniques are known as water atomization, oil atomization and gas atomization.

Water atomization is now a well established technique and is widely used to produce iron, steel, copper and copper alloy powders for pressing and sintering. It is estimated that about half the world production of iron powder is produced by water atomization (Dunkley, 1990). This method is also used to produce nickel powders for thermal spray coatings and brazing and to make precious metal powders for dental amalgams and for brazing and sintering. Pressure of water is the main process control variable.
in water atomization. Higher water pressure results in higher water velocity and smaller powder particle sizes. For many years steel powders of mass median size of 30-40 μm were produced at the highest pressures of about 20 MPa. The Japanese National Research Institute for Metals in association with some Japanese iron and steel companies have claimed that steel powders as fine as 5 μm have been obtained using water pressures of up to 150 MPa (Seki et al., 1990).

All melt nozzles in common use in water atomization are free fall with the distance of free fall typically in the range of 100 to 500 mm. There are three different types of water jets: annular or cone jet, symmetrical discrete multiple nozzles, such as 'V' jets and asymmetric discrete multiple jets. Of the possible jet configurations, the most widely used are variants of either the annular jet or 'V' jets. Powders produced by water atomization are typically irregular in shape. The mass median particle size, typically about 100 μm, depends on operation conditions and material properties, and the size distribution is relatively broad with a standard deviation in the range of 1.7 to 2.4. Cooling rate is dependent on particle size and falls in the range of \(10^3\) to \(10^5\) K/s. In general, water atomization is cheaper than other methods since it is intrinsically a high volume, low cost process. The main limitation of water atomization is powder purity, particularly with reactive metals and alloys. As a general criterion, any metal or alloy that does not react violently with water can be water atomized.

Oil atomization is applied in order to avoid the problem of powder oxidation inherent in water atomization. This technique was developed by Sumitomo Metals (Tamura et al., 1986) for the commercial production of low oxygen high quality steel powders. The main problem for oil atomization is the carbon pick-up by high melting point metals following pyrolysis of the oil and a special process is needed to decarburize the powders. Commercial application of oil atomization has thus been limited to the production of steel powder with a relatively high carbon content. Other liquids (such as liquidified inert gas) have been tested (Baker et al., 1991). There has been slow progress towards the industrial application of the technique because of its high cost.
Oil atomized powders resemble water atomized powder particles. They are irregular in shape. Mass median particle sizes are typically about 70 μm and particle size distributions are comparable to those achieved in water atomized powders. The cooling rate is similar to water atomization.

Non-ferrous metal powders have been produced since the 1920's by air atomization. At the time of World War II the Mannesmann process was used in Germany to produce iron powders by air atomization (Watkinson, 1958). Over the last five decades, two-fluid gas atomization technology has matured and powders of aluminium, copper, iron, low-alloy steels, superalloys, tin and tool steels are now produced on a tonnage scale for a range of applications (Howells et al, 1988 and Dunkley, 1990). In the early stage this technology was primarily based on the use of a single spray nozzle and air (Gummeson, 1971 and Lawley, 1977).

Various designs of nozzles and different gases have since been tested in gas atomization (Klar and Shafer, 1972; Klar and Fesko, 1984; Anderson and Figliola, 1986 and Unal, 1989). Closed (or confined) nozzles are thought of having the advantage over open (or free fall) nozzles in minimizing the loss of kinetic energy and gas velocity which occurs as the gas jet moves away from the nozzle. Thus they provide higher gas velocity in the melt breakup zone and tend to be favoured to obtain very fine powders. Open (or free fall) nozzles have the advantage in that the impacting point of the gas and melt is far away from the nozzle exit. Thus, they do not tend to result in severe cooling of the melt-nozzle assembly, which leads to freezing of melt in the nozzle and imposes severe thermal loads on the melt-nozzle material, and major change of pressure at the melt-nozzle outlet, which may cause a suction or choke effect on melt flow rate.

Inert gas is used either to keep the oxygen content low or to atomize reactive metals such as superalloys and titanium alloys. The viability of using inert gas atomization for the production of beryllium (Marder and Hashiguchi, 1988) and titanium-based alloys (Yolton, 1989) has been demonstrated. To minimize contamination of
reactive molten alloys, argon is often preferred. Alternatively, helium provides an inert environment and also increases the cooling rate of the atomized droplets. Mixtures of gases can be selected to achieve desired powder characteristics at low cost. Powders produced by inert gas atomization are spherical in shape with smooth surfaces. Small satellite particles are frequently seen attached to larger particles. Mass median particle sizes strongly depend on the design of nozzles, process parameters and properties of atomized materials, and are typically in the range of 25 to 300 \( \mu \text{m} \) with a standard deviation of about 2. The cooling rate is about one order of magnitude lower than that in water atomization, typically about \( 10^3 \text{ K/s} \) to \( 10^4 \text{ K/s} \) but can increase towards \( 10^5 \text{ K/s} \) in high pressure inert gas atomization where finer powder particles can be produced. However, gas atomization nozzles of suitable design are still required for the production of fine powders (<20\( \mu \text{m} \)) (Ayres and Anderson, 1986 and Anderson, 1991).

Vacuum atomization or soluble gas atomization or melt explosion atomization use the following principle. When a molten metal supersaturated with gas under pressure is suddenly exposed to vacuum the gas expands and comes out of solution with attendant atomization of the molten melt. Processes based on this principle were developed mainly for the production of high purity nickel and cobalt base superalloy powders (Wentzell, 1974) as well as aluminium, copper and iron alloy powders (Lawley, 1992). Vacuum atomized powders are smooth and spherical with very few satellite particles. Mass median particle sizes range from 40 to 70 \( \mu \text{m} \) with a broad size distribution. Compared to gas atomization, the cooling rate in vacuum atomization is lower, typically about \( 10^3 \text{ K/s} \), since the primary mode of cooling in vacuum atomization is by radiation rather than by convection, which is the main mode of cooling in gas atomization.

Centrifugal atomization relies on the use of centrifugal forces to disintegrate the melt. There are different variants of this type of atomization method and there will be discussed below in section 2.3.
Ultrasonic vibratory atomization involves the atomization of a film of liquid by vibration of the surface on which it flows. When a liquid film is introduced on a vibrating surface, capillary waves may be excited and these lead to ligament and droplet formation. Metals have been atomized by this technique (Lierke and Griesshammer, 1967), but its industrial application does not appear to be established. The obvious candidates for this method are low-melting metals, as the problems of avoiding thermal damage to the ultrasonic transducer and of materials selection for the vibrating surface rapidly become severe as temperatures rise above a few hundred degrees. Because of the interrelationship between scale, frequency and droplet size, the method has a low productivity, typically of the order of 1-50 kg per hour, if one requires mass median particle size less than 50 µm. A more recently demonstrated variant of ultrasonic atomization, ultrasonic standing wave atomization (USWA), was described by Anderson et al (Anderson, Schreckenberg and Bauckhage 1995, Anderson, Hansmann and Bauckhage 1996). The atomization is achieved by acoustic forces acting upon a jet of molten metal, which is guided into the central pressure node of a standing wave field. The Sn, Cu and Mg powders produced by USWA method were spherical. The minimum mass median diameter of powders is less than 15 µm. Cooling rates were estimated to be at least $2 \times 10^5$ K/s.

When a stream of liquid exits from a small nozzle, a cylindrical jet forms. Rayleigh theory predicts that the stream would spontaneously break up into droplets. If a vibration were superimposed on the stream, then it is possible to effectively shake off a drop at a time, each being almost of identical size, giving outstanding uniformity. Bienvenu and Chaleat (1980) made a millimetre-sized calcium granule for injection into steel using a mono-sized droplet atomization technique. More recently Yim et al (1996) produced mono sized Sn-Pb alloy powders with mass median particle size of 700-800 µm for potential integrated circuit packing application. The mono-sized droplet atomization technique is fundamentally limited in that it makes one particle at a time, so output is low and falls approximately with the square of orifice diameter.
### Table 2.1 General Characteristics of Different Techniques for Melt Atomization (Based on Yule and Dunkley, 1994)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Median particle size (μm)</th>
<th>Particle size spread (μm)</th>
<th>Metal flow rate (kg min⁻¹)</th>
<th>Efficiency (KWhr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air/gas atomization (open)</td>
<td>&gt;50</td>
<td>Broad (&gt;1.8)</td>
<td>5-100</td>
<td>Low (&gt;100)</td>
</tr>
<tr>
<td>Air/gas atomization (closed)</td>
<td>10-200</td>
<td>Broad (&gt;1.8)</td>
<td>1-50</td>
<td>Low (&gt;100)</td>
</tr>
<tr>
<td>Water atomization (sym.)</td>
<td>&gt;10</td>
<td>Broad (&gt;1.8)</td>
<td>1-1000</td>
<td>Medium (10-100)</td>
</tr>
<tr>
<td>Water atomization (asym.)</td>
<td>Coarse (&gt;200)</td>
<td>Broad (&gt;1.8)</td>
<td>100-1000</td>
<td>Medium (10-100)</td>
</tr>
<tr>
<td>Oil atomization</td>
<td>&gt;10</td>
<td>Broad (&gt;1.8)</td>
<td>1-1000</td>
<td>Medium (10-100)</td>
</tr>
<tr>
<td>Vacuum atomization</td>
<td>40-70</td>
<td>Broad (&gt;1.8)</td>
<td>10-100</td>
<td>Medium (10-100)</td>
</tr>
<tr>
<td>REP/CSC* atomization</td>
<td>50-400</td>
<td>Medium (1.4 -1.8)</td>
<td>Low (&lt;10)</td>
<td>Low (&gt;100)</td>
</tr>
<tr>
<td>RSR/cup/disk</td>
<td>50-200</td>
<td>Medium (1.4 -1.68)</td>
<td>up to 100</td>
<td>High (&lt;10)</td>
</tr>
<tr>
<td>EBRD*</td>
<td>&gt;100</td>
<td>Narrow (&lt;1.4)</td>
<td>Low (&lt;10)</td>
<td>Low (&gt;100)</td>
</tr>
<tr>
<td>Two-step</td>
<td>10-100</td>
<td>Broad (&gt;1.8)</td>
<td>up to 100</td>
<td>Low (&gt;100)</td>
</tr>
<tr>
<td>Electromagnetic atomization</td>
<td>Coarse (&gt;200)</td>
<td>Narrow (&lt;1.4)</td>
<td>Low (&lt;10)</td>
<td>Medium (10-100)</td>
</tr>
</tbody>
</table>

* EBRD=Electron beam rotating disk, # given by standard deviation.
+ CSC=Centrifugal shot casting process
Table 2.2 Principle Atomization Techniques in Industrial Use for Different Metals (Based on Yule and Dunkley, 1994)

<table>
<thead>
<tr>
<th>Metal or Alloy</th>
<th>Air</th>
<th>Gas</th>
<th>Water</th>
<th>Oil</th>
<th>vacuum</th>
<th>REP</th>
<th>RSR</th>
<th>Two-step</th>
</tr>
</thead>
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<tr>
<td>Sn</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pb</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn-Pb</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Zn</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Al</td>
<td>✓</td>
<td>✓</td>
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<td></td>
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<td></td>
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<tr>
<td>Mg</td>
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<td>✓</td>
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<td></td>
</tr>
<tr>
<td>Cu</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu-Sn</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu-x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au-Pd</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-Ni</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Co-Ni-x</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni-Cr-Ti-Al</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe-Cr-Ni</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Fe-Si</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Fe-Mn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Si</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt-x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Electromagnetic forces have been suggested to disrupt liquid metal. Ninagawa et al (1991) reported a typical process of this type in which a current was passed from a melt through the nozzle to a electrode. The gap between the nozzle and the electrode was placed in a strong magnetic field. When melt stream passed through this gap, it broke up into droplets due to the action of electromagnetic forces. By pulsing the current every 27 ms it proved possible to splash tin into very uniform particles ranging from 600 to 850 µm using a 0.5 mm diameter nozzle at flow rates in the range of 3-7 kg per hour.

Different atomization techniques produce powders of different characteristics and have different ability to control powder size, size distribution, morphology and the needs for some special applications. Table 2.1 compares the general characteristics of different atomization techniques. Table 2.2 shows the principle atomization techniques in industrial use for different metals and alloys.

2.3 Variants of centrifugal atomization

The basic principle of centrifugal atomization is the use of centrifugal forces to break up melts into droplets which subsequently solidify into powder particles in flight with/without additional cooling from gas jets/water quenching surrounding the disk/cup. The main advantages for centrifugal atomization are its capability to control the particle size and size distribution and its suitability for the production of powders of reactive and refractory alloys. There are variants of this kind of atomization. Basically, they fall into three categories according to the shape of the atomizer and the melting mode used.

2.3.1 Rotating electrode process (REP and PREP)

In the rotating electrode process (REP), the metal or alloy to be atomized is first fabricated into a bar. The bar is then used to form one end of the electrode and is melted while it is rotated about its longitudinal axis. The molten metal is ejected by
centrifugal force in the form of droplets from the periphery of the bar. The process was developed by Nuclear Metals Inc. and patents were issued in 1963 for the short bar design (Kaufmann, 1963) and in 1974 for a design that accommodated a larger bar (Kaufmann, 1974). Initial development of REP was stimulated by the need for a clean spherical powder to act as the carrier for carbon black in the printing cycle of a photocopier. Later on, this technology was adapted to the production of ultra clean advanced titanium alloys for potential aerospace applications.

![Figure 2.3 Schematic diagram of rotating electrode process](image)

The process is shown in Figure 2.3. The consumable rotating bar is the anode of a direct current power circuit and the permanent (non-melted) stationary cathode is either a cooled tungsten tipped device or a transferred arc plasma torch. When the latter mode is used to melt the end of the rotating anode, the atomization process is known as the plasma rotating electrode process (PREP). Powder particles produced by REP or PREP are spherical with smooth high quality surfaces. The particle size range is typically from 50 to 400 µm with a mass median particle size around 200 µm. The cooling rates are lower than in water and gas atomization, typically about $10^2$ K/s to $10^3$ K/s.
2.3.2 Rotating disk/cup

Another variant of centrifugal atomization uses a spinning cup/disk for melt disintegration. In this process melting of materials to be atomized relies on external heat sources unlike in the REP process. After melting the molten metal or alloy is directed onto a rotating disk/cup. The centrifugal forces throw the melt outwards as a thin film. When the film comes to the edge of the disk/cup it breaks into droplets, which subsequently solidify into powder particle with/without additional cooling from gas jets. Alternatively, the droplets are captured in a quench liquid positioned very close to the disk/cup. Origin of the rotating disk method is from the process designated RSR (rapid solidification rate). The latter was developed by the Pratt and Whitney Aircraft Group for the production of rapidly solidified Ni base superalloy powders. The first RSR unit was operated in late 1975, producing IN 100 powder as a model and patents were issued in 1978 and 1982. In addition to superalloys, the process has been used to produce specialty aluminum alloy, beryllium alloy, molybdenum, titanium alloy and silicide powders (Lawley, 1992). Figure 2.4 shows the main features of the facility.

Powders produced by the RSR process are spherical, satellite-free and have smooth surfaces. Particles are normally below about 200 μm with a mass median particle size of about 90 μm. The standard deviations are low, in the range of 1.4 to 1.6. Cooling rates up to about $10^5$ K/s can be achieved in the finer powder particles.

![Figure 2.4 Schematic diagram of rotating disk atomization](image)
Spinning cup atomization methods had been under development at Battelle's Columbus Division laboratories since the early 1980's and a patent covering the process was issued in 1983 (Raman and Carbonara, 1983). There are some variants of this process which are still under development (Cooper and Ayers 1993, 1994).

In the original single stage mode, a liquid quenchant held against the inside wall of the spinning cup was used to break up the stream of molten metal. In a newer two-step version of the spinning cup process the primary liquid metal stream was first disintegrated into droplets by low pressure gas atomization or conventional centrifugal atomization (Cooper and Ayers, 1994). These droplets then impacted the vertical shroud of rotating liquid quenchant and further disintegrated. The main features of the spinning cup atomization process are illustrated in Figure 2.5 for the two-step mode. The liquid quenchants can be either water or oil or other commercial quenching media. The powder particles were collected on the inside wall of the rotating cup during atomization and were subsequently separated from the liquid quenchant. Metals and alloys atomized by this method include: tin and lead; aluminium-base alloys; copper-base alloys; iron-base alloys; superalloys and zinc alloys.

Figure 2.5 Schematic diagram of spinning cup atomization process
The powder particle sizes produced by the spinning cup process were spherical and their size was below 100 μm. The cooling rates were estimated to be in the range of $10^4$ to $10^5$ K/s (Cooper and Ayers, 1993).

### 2.3.3 Other centrifugal processes

By combining the REP process and the spinning cup/disk method, some other designs have emerged. Among them are the centrifugal shot casting process (CSC) and the electron beam rotating disk process (EBRD). The CSC process (Hodkin et al., 1973), shown in Figure 2.6 is conceptually similar to REP. The process was developed at the United Kingdom Atomic Energy Research Establishment, Harwell in the early 1970's and was initially used to atomized refractory powders (e.g. alumina and uranium monocarbide) for use in nuclear fuels. Following modification of the original design, it has been used to produce a wide range of metal powders including iron, nickel, cobalt and titanium alloys and refractory metals. The principle is that a spinning crucible of water cooled copper, which usually contains a skull of the material to be atomised, rotates under a static or slowly revolving electrode. The melting is accomplished by striking an electric arc between the consumable electrode and the crucible.

![Figure 2.6 Centrifugal shot casting process (Hodkin et al 1973)](image)
Chapter 2

Under the action of centrifugal force, the melt moves up the inner wall of the crucible to the tip where it breaks up and is ejected in the form of droplets. The process has similar limitations to REP, but can tolerate lower-grade electrodes as they are not spun at high speeds. It can also process non-metals, such as ceramics, by using auxiliary heating methods. Melting, atomization and droplet solidification could occur under a controlled atmosphere of argon or helium. Powders made by the centrifugal shot casting atomization process are spherical or flakes. For spherical particles, the size range is from 100 to 1500 µm. Control of the mass median particle size over the range 150 to 1000 µm is possible and narrow size distributions are achieved with a standard deviation of about 1.3 to 1.4. The cooling rates are relatively high, and in the range of $2 \times 10^5$ to $7 \times 10^4$ K/s (Lawley, 1992).

![Figure 2.7 Schematic diagram of electron beam rotating disk process](image)

The EBRD process (Pietsch et al., 1983) is very similar to the CSC process except for the mode of melting. In the EBRD process a consumable ingot bar of the metal to be atomized is melted by one or more focused electron beams. After melting the melt drips onto a high speed rotating container in the form of a disk or cup and is subjected to centrifugal force at the rim of the container causing the liquid to be disintegrated into droplets and to be thrown away from the edge of the container. Figure 2.7 shows the basic features. The powders produced by EBRD process are either spherical or flake. Particle size is less than 700 µm and can be low as 30 to
2.4 Studies of centrifugal atomization

The centrifugal atomization of melts is a complicated process. Many fundamental aspects have not fully been understood. As a technique for the production of powders, its performance must be evaluated from many aspects. Main concerns are powder particle characteristics (particle size, size distribution, morphology and microstructure), flexibility for operation and control, productivity (yield, output) and cost. Among various centrifugal atomization techniques to date only the REP process has evolved as a commercial method for the production of powders. The other approaches are still under development.

In general, every atomization unit consists of a melting system, a melt delivery/feed system, the atomizer, the atomization chamber and powder collection system. Research may address any of the above. Studies on centrifugal atomization have focused on: [1] atomizer design; [2] atomizer performance (powder size, size distribution and morphology); [3] effects of atomizing parameters on atomizer performance; [4] atomization mechanism and melt break up process; [5] characterisation of atomized powders; [6] development of new materials.

Powder particle size, size distribution, morphology, breakup mechanism and the way they are affected by atomizing parameters in centrifugal atomization are briefly reviewed below for different processes.

2.4.1 Rotating electrode process

Even though the rotating electrode process (REP) was developed in the early 1960s (see section 2.3.1), systematical studies started in 1980s at Laval University in Canada (Champagne and Angers, 1980 and 1984; Angers, 1992). Figure 2.8 shows the morphology of particles produced by this process. The particle size distributions
are almost always bimodal with the dominant mode on the large particle side.

![Image of powders produced by the plasma rotating electrode process.](image)

(a) Ti-6Al-4V  
(b) Rene 95

Figure 2.8 Powders produced by the plasma rotating electrode process.  
(a) Ti-6Al-4V, (b) Rene 95

Studies using high speed camera photography at Laval University showed that melt
disintegration took place at the edge of the rotating bar and that the melt broke up according to one of the three basic modes: Direct droplet formation (DDF), Ligament formation (LF) and Film formation (FF). Figure 2.9 illustrates the processes of droplet formation.

a) DDF

b) LF
The direct droplet formation mode occurred at relatively small rates of melt supply and low rotating speeds. In this mode, melt flows towards the edge of the electrode and accumulates in the form of a small torus which deforms into several protuberances from which particles, having a fairly uniform size, are directly ejected. When the anode melting rate increases, the dimensions of protuberances around the edge of the anode also increase. These larger protuberances stretch into ligaments which eventually break down into strings of many particles at some distance from the edge of the rotating anode. With further increase in melt feeding rate ligaments at the edge of the anode cannot disintegrate all the liquid and thus a liquid film forms at the edge of the anode. The film goes beyond the rotating anode and breaks up into a cloud of droplets.

The transition conditions were determined by analysing the particle size characteristics. Figure 2.10 shows the atomization map. The following empirical equation was obtained for the mean median particle size by regression analysis of their experimental results on atomization of Fe, Al, Cu and Zn:

\[
d_{50} = 4.27 \times 10^{6} \frac{1}{\omega^{0.55}} \frac{1}{D^{0.61}} (\frac{\sigma}{\rho})^{0.42} Q^{0.12}
\]  

(2.1)
where $d_{50}$ is the mass median particle size, $D$ is the diameter of the rotating electrode, $Q$ is the anode melting rate, $\omega$ is the angular velocity of the rotating electrode, and $\rho$ and $\sigma$ are the density and surface tension of the melt, respectively.

![Atomization map for the rotating electrode process](image)

Figure 2.10 Atomization map for the rotating electrode process. $\gamma$, $\eta_h$, $\rho_h$, are the surface tension, viscosity and density of the melt respectively, $\omega$ is the disk angular speed, $Q$ is the anode melting rate and $D$ is the diameter of the rotating electrode. FD=film disintegration (or FF), LD=ligament disintegration (or LF) and DOF should be DDF, direct drop formation (Champagne and Angers, 1984).

### 2.4.2 Centrifugal shot casting process

Studies using high-speed cine film by Hodkin et al (1973) have shown that the mechanisms of droplet formation in the CSC process were very similar to those in REP, see Figure 2.11.

The studies showed that when molten metal was fed to the centre of the crucible at relatively low flow rates, it spread towards the periphery of the crucible and formed a toroidal rim. As further molten metal flowed into the toroid, its inertia increased and overcame the surface tension forces. Varicose disturbances appeared...
intermittently on the outer edge and as they grew in size and extended from the rim, they drew themselves into spherical globules, which remained attached by a fine attenuated thread. When such a drop was finally detached, the retaining thread broke up into small or satellite drops. The molten metal adjacent to the rim of the crucible was drawn back into the toroid but was prevented from doing so completely by incoming molten metal and the disturbance persisted and caused the process to be repeated.

[i] (a) to (d) show the stages of direct droplet formation
[ii] Solidified ligaments around the lip of a crucible

Figure 2.11 Photos illustrating the breakup of a titanium melt in the CSC process

( Hodkin et al, 1973 )

At an increased feed rate the bulges of the toroidal rim that gave rise to direct drop formation at low feed rates were drawn out into long thin jets or ligaments. The ligaments themselves were unstable to disturbances and broke up into droplets at some distance from the crucible lip. As the feed rate increased, the diameter of ligaments increased up to a maximum value. This value remained constant for a given crucible rotating at a given speed. For a further increase in feed rate beyond the point that the diameter of ligaments could not increase, the ligament mode transited into film formation mode. Figure 2.12 show the morphology of the particles produced by the CSC process.
Chapter 2  

The particles produced by the CSC process can be spheroids, substandard spheroids (i.e., spheroids with a flattened surface), and flake. Hodkin et al. (1973) thought that the particle shape is closely related to the temperature at which spheroids, formed at the crucible, impacted with the walls of the collection chamber. It was assumed that at impact the resultant spheroids had cooled sufficiently into the solid state as to be mechanically strong enough to resist plastic deformation, whereas the substandard spheroids were still hot enough to undergo plastic deformation, as the flake was still liquid.

Figure 2.12  The morphology of the stainless-steel particles produced by the CSC process (Hodkin et al, 1973)
2.4.3 Rotating disk method

Although the principle of rotating disk atomization was proposed in the early 1970's, it was not until recent years that some research started on the effects of design and process parameters on powder production by the rotating disk method. Dogan and Saritas (1994) studied the effect of disk shape (flat, cup shaped and vaned) and size, metal type (Pb, Al and 8640 steel), melt superheat, disk speed (15,000 to 25,000 rpm for a given disk diameter) and melt flow rate on particle size, size distribution and morphology of particles. Figure 2.13 shows the designs of the disks used in their study.

The particles produced were very irregular, see Figure 2.14.

![Figure 2.13 Various designs of rotating disks by Dogan and Saritas (1994)](image)

Cherre and Accary (1990) studied the effects of disk speed, disk diameter and atomizing gas on particle formation. Their results showed that the particles were near spherical. Figure 2.15 shows the morphology of the particles produced using their
Figure 2.14 The morphology of the aluminium particles obtained by Dogan and Saritas (1994).

Halada et al. (1990) observed the formation of droplets at the edge of the rotating disk. They found that the formation of droplets was very similar to the REP and the CSC processes and developed a centrifugal atomization (CA) map, (see Figure 2.16).

Angers and co-workers (1994) atomized a 2024 aluminum alloy using rotating...
inverted disk centrifugal atomization and tried to apply to their experimental results.

Figure 2.15 The morphology of the Bi-Sn alloy particles obtained by Cherre and Accary (1990)

Figure 2.16 Diagram of the disintegration states for centrifugal atomization, proposed by Halada et al. (1990)
Chavter 2 Literature Review

equation (2.1), which was obtained for the REP process. Calculated results showed a good agreement with experimental data. Recently Ziani and Michot (1996) examined the morphology and microstructures of centrifugal atomized particles of Al-Cr-Fe alloys. The microstructures of the particles were uniform and the particle sizes were small, about 80 μm. Rao (1992) also studied the microstructural features and mechanical properties of aluminium alloys produced using rotating disk atomized powders.

2.5 Melt break up in atomization

2.5.1 Break up process

Disintegration processes in melt atomization are very complicated. Also different processes have different modes for the disintegration of melts. Based on observations and high speed photographs some possible routes of particle formation have been suggested. Figure 2.17 shows the actual atomization process in gas atomization (German, 1994). Figure 2.18 is a suggested droplet formation route in gas atomization (German, 1994).

Figure 2.17 Photos showing the actual atomization process in gas atomization
(from German, 1994)

Figure 2.19 shows the possible atomization processes thought to be occurred in water atomization (German, 1994). Figure 2.20 shows schematically the break up of liquid in centrifugal atomization. Research on REP, CSC and rotating disk atomization has
confirmed the break up processes (see also sections 2.4.1 and 2.4.2). The breakup of melts into droplets in gas and water atomization is still an open question. Some models have been proposed to calculate particle sizes in gas atomization but only limited success has been achieved (Lavernia and Wu, 1997).

Figure 2.18 Schematic diagram showing suggested droplet formation route in gas atomization (from German, 1994)

Figure 2.19 A schematic diagram showing four possible particle formation mechanisms in water atomization (German, 1994)
Chapter 2 Literature Review

Regimes of centrifugal atomization: (a) direct droplet, (b) ligament, (c) sheet.

Figure 2.20 Schematic diagram showing the formation of droplets in REP, CSC and rotating disk processes (Yule and Dunkey, 1994)

2.5.2 Wave theories

(a) Break up of a cylindrical jet

When a liquid flows through an orifice a cylindrical jet forms. Depending on the relative velocity between the liquid and surrounding gas the liquid will break up according to one of several basic modes. Figure 2.21 shows schematically the processes of liquid break up (Reitz, 1987). Reitz (1987) classified the break up of a cylindrical jet into four regimes. Figure 2.22 shows the regimes of a cylindrical jet break up.

Rayleigh (1878) analyzed the break up process at low liquid velocities. He related the instability of a cylindrical jet to the growth of disturbances formed at the interface of gas and jet. The disturbance, causing disintegration of a jet, is a zero-order dilatational wave. When the amplitude of the disturbance grows to one-half the
Chapter 2 Literature Review

diameter of the undisturbed liquid jet, the liquid breaks up into droplets.

Figure 2.21 Liquid column breakup at different velocities (water with 0.5 mm diameter orifice) (Reitz, 1987)

For the case of negligible viscous and aerodynamic forces, the growth rate of disturbances can be described by (Marshall, 1954)

\[
\beta = \sqrt{\frac{\alpha}{\rho R_0^3}} \left[ \frac{2\pi R_0 I_\lambda(2\pi R_0/\lambda)}{\lambda I_0(2\pi R_0/\lambda)} \right] \left(1 - \left(\frac{2\pi R_0}{\lambda}\right)^3\right) \quad (2.2)
\]
where $\beta$ is the wave growth rate; $R_0$ is the radius of the jet; $\lambda$ is the wavelength; $\sigma$, $\rho$ are the surface tension and density of liquid, respectively and $I_n$ are the $n$-th order modified Bessel functions of the first kind.

Rayleigh predicted that the particle size formed is 1.89 times the diameter of the jet. Weber (1931) extended Rayleigh's theory by introducing the effects of liquid viscosity and velocity relative to the surrounding medium. The particle size $d_p$ was given by Weber (1931) as

$$d_p = (1.5)^{1/3} \lambda_{opt}^{1/3} d_{i}^{2/3}$$

(2.3)

where $d_i$ is the diameter of the jet, and the optimal wave length $\lambda_{opt}$ is given by

$$\lambda_{opt} = \sqrt{2\pi d_{i}} \left(1 + \frac{3\mu}{\sqrt{\rho \sigma d_{i}}} \right)$$

(2.4)

where $\mu$ is the viscosity of the liquid.

Theoretical description on the break up of a cylindrical jet in other regimes is still under research.

(b) Dombrowski and Johns sheet wave theory

When liquid comes out from a fan-type nozzle under pressure, a hollow cone may form as a circular thin liquid sheet. With the liquid moving away from the nozzle the sheet becomes thinner and thinner and eventually breaks up into droplets. The manner in which the sheet disintegrates into droplets depends on the operating conditions. Dombrowski and Johns (1963) suggested that the principle cause of instability is due to the interaction of the sheet with the surrounding gas, whereby rapidly growing waves are imposed on the sheet. Disintegration occurs when the
wave amplitude reaches a critical value and fragments of sheet are torn off. The fragments rapidly contract into unstable ligaments under the action of surface tension and droplets are produced as the ligaments subsequently break down. Figure 2.23 shows the break up process of this kind of sheet.

![Figure 2.23 Break up process of a thin sheet into droplets (a—stable sheet, b—growth of waves in sheet, c—ligament and d—ligament breakdown)](image)

When a sheet moves through a gas, some wave caused by disturbances forms on the sheet. The disturbances may decrease or increase, mainly depending on the forces acting on the sheet. Four forces (gas pressure, surface tension, inertia and viscous forces) act on the sheet. By balancing the forces Dombrowski and Johns (1963) derived an equation for the displacement (see Appendix II).

\[
2\rho_{gas}k\nu^2y + 2\sigma \frac{\partial^2 y}{\partial x^2} - \rho (h \frac{\partial^2 y}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t}) + \mu h \frac{\partial^3 y}{\partial t \partial x^2} = 0 \quad (2.5)
\]

For a sinusoidal wave motion, the amplitude of the wave can be expressed as

\[
2\rho_{gas}k\nu^2a - 2\sigma k^2a - \rho (h \frac{\partial^2 a}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial a}{\partial t}) - \mu h k^2 \frac{\partial a}{\partial t} = 0 \quad (2.6)
\]

where \( y \) is the displacement of disturbance; \( \nu \) is the velocity of the liquid; \( x \) is the
distance in the direction of wave propagation, \( t \) is the time; \( a \) is the amplitude of the wave; \( k \) is the wave number; \( h \) is the thickness of the sheet; \( \mu, \rho, \sigma \) are the viscosity, density and surface tension of liquid respectively, and \( \rho_{gas} \) is the density of the gas.

(c) Bradley's surface wave theory

When gas blows over the surface of an infinite deep liquid, it induces surface waves on the interface of gas and liquid. For an initially stationary liquid layer of infinite depth occupying the space \( y<0 \) and a gas flowing with uniform velocity \( v \) in the \( x \)-direction over the liquid surface, shown in Figure 2.24, Bradley (1973) obtained the dispersion equations for the growth of a wave.

![Image](image_url)

Figure 2.24 Formation and growth of wave on the surface of an infinite depth (after Lawley, 1992)

for \( Ma<1 \)

\[
(\beta + 2v k^2) \lambda^2 - 4v^2 k^3 (k^2 + \beta / v)^{1/2} + \frac{\rho_{gas}(\beta + ivk)^2}{\rho (1-Ma^2)^{1/2}} + \frac{\sigma k^3}{\rho} + gk = 0
\]

38
and for $Ma > 1$

$$(\beta + 2v k^2)^2 - 4 v^2 k^3 (k^2 + \beta / \nu)^{1/2} - \frac{\rho_g a_b \beta \nu k^2}{\rho (Ma^2 - 1)^{1/2}} + \frac{\sigma k^3}{\rho} + g k = 0$$

where $Ma$ is the gas Mach number defined as the ratio of gas velocity to velocity of sound in the gas.

The above theories can in principle be used to analyze disintegration of melts. For a specific case further work is needed.

### 2.6 Conclusions

The following conclusions can be made for previous research on centrifugal atomization.

(A) Disintegration of melts in centrifugal atomization follows one of the three modes: direct droplet formation (DDF), ligament formation (LF) and film formation (FF). Each mode occurs under different operating conditions. In general, at low rotating speeds and low melt flow rates the melt breaks up in the form of direct droplet formation. With an increase in rotating speed and in melt flow rate disintegration moves into the ligament formation regime. When the melt flow rate increases beyond a critical value, ligaments formed at the edge of a disk/cup can not disintegrate, a thin film/sheet forms beyond the disk/cup edge up to a certain distance and then breaks up into droplets. The centrifugal atomization diagrams of Champange and Angers (1984) and Halada et al (1990) (see Figure 2.10 and Figure 2.16) can be used to provide guidelines for the design and operation of a centrifugal atomizer.

(B) The particle size and size distribution critically depend on the atomizer design, atomizer operation and the thermal and physical properties of the material to be
atomized. Various shapes of particles can be obtained, from spherical to flake. The evolution of particle shape is not very clear.

(C) The formation and calculation of particle sizes in different atomization regimes require further studies.

(D) The effects of disk design, atomizing chamber geometry and processing and material parameters on powder size, size distribution and powder shape need to be explored.
Chapter 3
Flow of Melts on a Rotating Disk

3.1 Introduction

When melt is directed to the centre of a rotating disk through a small nozzle or tube positioned above the disk, the melt spreads radially out along the surface of the disk due to centrifugal and inertia forces while viscous force tries to keep it on the disk. Thus a thin film is formed. Film thickness will affect heat transfer between the melt and the disk and the surrounding gas. Some solidification may also occur on the disk depending on the operating conditions and design parameters. This will further affect the break up of the melt at the edge of the disk and/or beyond the disk and the formation of particles. Thus knowledge of melt flow on a rotating disk during centrifugal atomization using the rotating disk method is required to understand the whole atomization process. Chapter 3 is the first part of the modelling work and is specific to the melt flow on a rotating disk. Heat transfer on a rotating disk, disintegration of melt at the edge of a disk or beyond a disk and subsequent solidification of droplets during flight will be discussed in chapters 4, 5 and 6, respectively.

The flow of melt on a rotating disk is a complicated process. Melt properties, disk design, falling height of melt, disk angular speed and flow rate of melt all have a role to play in controlling the film thickness and velocity profiles in the film.

Flow of viscous liquids on a stationary or rotating disk is widely encountered in many engineering practices. The semiconductor industry uses this process to produce very thin and uniform coatings of photoresist films. In optical and magnetic recording media, a thin layer of lubricant is used to prevent the slider from excessive wear during the startup and turnoff. TV manufacturers coat the TV screen with a thin film
of phosphor coating. A thin film produced by a high speed rotating disk provides a very important means for evaporation and drying of such viscous liquids as milk, soaps, detergents etc. Atomization and spray combustion of fuel oil is also relevant to this kind of flow. This process has found new application in the space-based vapour-absorption refrigeration system.

In the field of spin coatings, researchers have mainly focused on how to obtain a thin and even liquid film and on the depletion of the liquid film. Emslie et al. (1958) developed the first model of Newtonian flow on a smooth surface to obtain the distribution of the liquid as a function of time and studied the effect of the initial liquid film distribution on the smoothness of the final film. Later experimental results showed that the model of Emslie et al predicted a longer depletion time. Investigations by Middleman (1987) revealed that air shear has a significant effect on the depletion of the liquid film. When the film became very thin, say, around a few angstrom, the model of air shear gave a faster depletion. Hwang and Ma (1989) noted the importance of the surface roughness of the disk in retaining the liquid film on the rotating disk and constructed a stochastic model of surface asperities to evaluate the effect of surface roughness. Recent research has revealed the existence of a special intermolecular force, the disjoining pressure. Kim et al. (1991) took this effect into account in their work using a polynomial approximation for the disjoining pressure. Their studies showed that the disjoining pressure has a positive but not very large effect in keeping the film on a rotating disk.

In the process of liquid atomization, Hinze and Milborn (1950) first analysed the flow of the liquid on a spinning cup and determined theoretically and experimentally the number of ligaments and the transition conditions from the ligament formation to the sheet formation during atomization using the dimensional analytical method. Matsumoto et al. (1973) used a polynomial approximation and compared earlier theoretical solutions for the thickness of a viscous liquid film on a rotating disk with experimental results. They concluded that a polynomial approximation up to fourth or fifth degree was in good agreement with the experimental results.
Chapter 3

Flow of Melts on a Rotating Disk

When liquid is supplied to the center of a rotating disk by a feed nozzle located above the disk, a hydraulic jump may occur. Watson (1964) first examined a smooth jet of water falling vertically on a horizontal plane. When the jet reached the center of the plane, it spread out radially in a thin film and bounded by a circular hydraulic jump, outside of which the liquid film thickness was much greater. Watson studied the flow in the film by means of boundary-layer theory and also devised an experiment to check the theoretical results. The calculated radius of the hydraulic jump and the thickness of the liquid outside the jump were in good agreement with the experimental result.

Miyasaka (1974) applied potential theory and momentum integration methods in the boundary layer to analyse the flow of glicerine solution assuming that the velocity profiles and film thickness can be represented with a polynomial approximation. His work showed that in a wide range of jet Reynolds numbers $Re_0 \geq 1000$ and values of the parameter $m_o$, $0 < m_o < 0.8$, where $m_o$ indicates the effect of the falling velocity of a jet and the revolution of a disk, the experimental results agreed with the polynomial approximation. For $200 < Re_0 < 500$ several percent error was recognized soon after the boundary layer developed up to the free surface.

Espig and Hoyle (1965) measured the thickness of water film on a horizontal rotating disk and observed the flow with a stroboscope. They found the existence of rivulets, circumferential waves and helical waves and accordingly classified the flow into different groups. Charwat et al. (1972) examined experimentally the effects of the viscosity and surface tension of a liquid film. Their experimental results revealed that concentric, spiral, and irregular waves occurred on the surface of the film, and that the waves were strongly affected by the liquid viscosity and surface tension. Craik et al. (1981) studied experimentally the circular hydraulic jump formed on a horizontal plate struck by a vertical jet of liquid and measured the liquid film depths ahead of and behind the jump using a light-absorption technique. Needham and Merkin (1987) studied theoretically the development of non-linear waves on the surface of a horizontally rotating thin liquid using an asymptotic expansion technique.
and determined the criteria for the stability of the film. Thomas et al. (1991) studied experimentally the flow of deionized water and measured the thickness of liquid film along the surface of a stationary and rotating disk with a rotational speed up to 300 rpm and flow rate in the range $1.17 \times 10^{-4}$ to $2.5 \times 10^{-4}$ m$^3$/s. Their observations of flow patterns also revealed the existence of surface waves.

The work of Miyasaka (1974) is most close to the situation in centrifugal atomization using the rotating disk method. Therefore, Mayasaka's work was modified to describe the flow of a melt on a rotating disk.

### 3.2 Physical description

Miyasaka (1974) analysed the flow on a rotating disk when a viscous jet, which has a free surface, falls down into the centre of the rotating disk. According to Miyasaka, when the viscous jet falls down on the rotating disk, a three dimensional boundary layer develops in the region close to its surface, as shown in figure 3.1. The thickness of the boundary layer grows with an increase of r-distance and then it attains the free surface at distance $r = r_1$. At this point $r_1$, the flow rate in the radial direction within the boundary-layer is equal to that of the falling jet on the rotating disk. Miyasaka modelled the flow by considering (a) the potential jet region, where the flow is inviscid, (b) the jet boundary layer region, where the thickness of the boundary layer increases with distance from the centre of the disk (r-distance) and (c) the flow region on the disk beyond distance $r_1$. By comparing theoretical calculations with experimental results, Miyasaka concluded that the radial velocity of the liquid almost recovers to the initial jet velocity at $r_1 = 3r_o$, where $r_o$ is the initial radius of the falling jet.

In the original work of Miyasaka it was assumed that the velocity profiles and film
thickness can be represented with a polynomial approximation and the pressure in the jet boundary layer region was approximated using an empirical equation. It is difficult to determine how many terms of the polynomial should be selected to accurately represent the velocity profiles and film thickness. It is also difficult to obtain an empirical equation for the pressure in the region (b). In this thesis only flow in the region c was modeled. In order to avoid the use of polynomials for velocity profiles and film thickness, a numerical method was developed to compute the velocity profiles and the thickness of the melt film. The method used here is different from the conventional one in that in the conventional numerical computation the domain of computation is fixed. Due to the existence of free surface and the atomization of molten metal at the edge of the rotating disk, the thickness of the melt film changes with distance from the centre of the disk. Also inertia force may cause a hydraulic jump. The characteristic feature of the computation method used here is iteration between the velocity profiles and the thickness of the film (see section 3.4).

3.3 Mathematical formulation

In order to simplify the analysis, the following assumptions were made: (i) the molten metal is an isothermal Newtonian fluid; (ii) the flow is steady state and axially symmetric; (iii) gravitation has negligible effect on the flow. In a system of cylindrical coordinates, see Figure 3.1, with a disk rotating at an angular velocity \( \omega \) about the \( Z \) axis, application of the Navier-Stokes equations to the flow gives (Miyasaka 1974):

Continuity equation

\[
\frac{\partial}{\partial x} (ru) + \frac{\partial}{\partial z} (rw) = 0 \quad (3.1)
\]

Momentum equation in \( r \)-direction

45
Chapter 3  
Flow of Melts on a Rotating Disk

\[
\frac{\partial u}{\partial r} + \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial r} + \frac{1}{\rho} \left( \frac{\partial^2 u}{\partial z^2} + \frac{\partial}{\partial r} \left( \frac{u}{r} \right) \right) \tag{3.2}
\]

Momentum equation in \( \theta \)-direction

\[
\frac{\partial v}{\partial r} + \frac{\partial v}{\partial z} = \frac{\partial}{\partial r} \left( \frac{v}{r} \right) \tag{3.3}
\]

Here \( r, z \) and \( \theta \) are the coordinate system (see Figure 3.1); \( u, v \) and \( w \) are the velocity components in the \( r, \theta \)- and \( z \)-direction respectively; \( p \) is the pressure of melt and \( \nu \) is the kinematic viscosity of melt.

Boundary conditions are :

at \( z=0 \)

\( u=0 \) \tag{3.4a}\\
\( v=\omega r \) \tag{3.4b}\\
\( w=0 \) \tag{3.4c}

at \( z=h(r) \)

\( \frac{\partial u}{\partial z} = 0 \) \tag{3.5a}\\
\( \frac{\partial v}{\partial z} = 0 \) \tag{3.5b}\\
\( w=u \frac{\partial h}{\partial r} \) \tag{3.5c}
Chapter 3  
Flow of Melts on a Rotating Disk

at \( r = r_1 \)

Where it is assumed that \( r_1 = 3r_0 \)

\[
u_0 = \sqrt{u_0^2 + 2g h_0} \quad (3.6)
\]

\[
h_0 = \frac{4Q}{3\pi r_1 u_0} \quad (3.7)
\]

\[
u = u_0\left(\frac{2z}{h(x)} - \left[\frac{z}{h(x)}\right]^2\right) \quad (3.8a)
\]

\[v = 0 \quad (3.8b)
\]

The thickness of the film is given by mass conservation as follow:

\[
Q = 2\pi r \int_0^{h(x)} udz \quad (3.9)
\]

In the above equations \( g \) is the acceleration due to gravity, \( h(x) \) is the thickness of film at position along radius of disk, \( \omega \) is the disk rotating angular speed, \( Q \) is the flow rate of melt, \( l_0 \) is the height from the plane of disk to the nozzle, \( u_0 \) is the velocity of melt at the exit of the nozzle, \( u_q \) is the falling velocity of the melt, \( r_1 \) is the critical radius and \( h_0 \) is the initial film thickness at \( r_1 \).

3.4 Solution method

Because of the change of the liquid film thickness with radial position and operating conditions, it is difficult to compute the velocity profiles according to the conventional numerical method since the computational domain will change during the computation. Here the methods of iteration and coordinate transformation were used to deal with the change of computational domain during the computation. First, the coordinate transformation technique was used to change a curved domain into a
rectangular domain, then the governing equations and boundary conditions were discretized with the finite difference method, and finally the iteration method was used to calculate the velocity profiles and the film thickness along the surface of a disk until the difference between the two iterations was less than a given error.

We define

\[ \xi = \frac{x}{r_0} \] (3.10)

\[ \eta = \frac{z}{h(\xi)} \] (3.11)

Here \( \xi, \eta \) are the new coordinate system.

After the transformation of the system of coordinates, the governing equations and boundary conditions become:

Continuity equation

\[ \frac{\partial u}{r_0 \partial \xi} + \frac{u}{r_0 \xi} + \frac{\partial \omega}{h(\xi) \partial \eta} = 0 \] (3.12)

Momentum equation in \( r \)-direction

\[ u \frac{\partial u}{r_0 \partial \xi} + \nu \frac{\partial u}{h(\xi) \partial \eta} = -\frac{1}{r_0 \rho} \frac{\partial p}{\partial \xi} + \nu \left[ \frac{\partial^2 u}{h(\xi)^2 \partial \eta^2} + \frac{\partial}{r_0 \partial \xi \partial \xi} \right] \] (3.13)

Momentum equation in \( \theta \)-direction

\[ u \frac{\partial v}{r_0 \partial \xi} + \nu \frac{\partial v}{h(\xi) \partial \eta} + \frac{uv}{r_0 \xi} = \nu \left[ \frac{\partial^2 v}{h(\xi)^2 \partial \eta^2} + \frac{\partial}{r_0 \partial \xi \partial \xi} \right] \] (3.14)
Chapter 3

Flow of Melts on a Rotating Disk

Boundary conditions:

at $\eta = 0$

\[ u = 0 \quad (3.15a) \]

\[ v = \omega r_0 \xi \quad (3.15b) \]

\[ w = 0 \quad (3.15c) \]

at $\eta = 1$

\[ \frac{\partial u}{h(\xi) \partial \eta} = 0 \quad (3.16a) \]

\[ \frac{\partial v}{h(\xi) \partial \eta} = 0 \quad (3.16b) \]

\[ w = u \frac{\partial h(\xi)}{r_0 \partial \xi} \quad (3.16c) \]

at $r = r_1$

\[ h_0 = -\frac{4Q}{3\pi r_1 \eta_0} \quad (3.17) \]

\[ u = u_0 (2\eta - \eta^2) \quad (3.18a) \]

\[ v = 0 \quad (3.18b) \]

The film thickness is determined by

\[ Q = 2\pi r_0 \xi \int_0^1 u \eta \, d\eta \quad (3.19) \]

The computational method is outlined below and the computational grid is shown in

49
Figure 3.2. The finite difference method was used to convert the partial differential equations into a set of algebraic equations. The general form of the finite difference equations is as follows:

\[ A_p \phi_{i,j} = A_n \phi_{i,j+1} + A_s \phi_{i,j-1} + S_p \]  
\[ i=1,2,...,N; \quad j=1,2,...,M-1 \]  

(3.20)

where \( A_p, A_n, A_s \) are coefficients in the nodal equations and \( S_p \) is the source term. The film thickness was calculated using the Simpson numerical integration method after finding out the velocity profiles (Korn and Korn, 1968). The equations are given by:

\[ h(\xi) = \frac{3Q}{2\pi x_0 \xi \Delta \eta (u_{0,0} + u_{0,m} + \sum_{j=1}^{N-1} 4u_{0,j} + \sum_{j=1}^{N-2} 2u_{0,j})} \]  
\[ (3.21) \]

The program flow chart is shown in Figure 3.3

3.5 Results and discussion

The film thicknesses calculated using this model have been compared with experimental data from the literature. After validation the model was used to study the effects of process parameters. The physical properties of the melts used in the calculations are given in Table 3.1.

Table 3.1: Physical properties of the melts used in the calculations

<table>
<thead>
<tr>
<th>Property*</th>
<th>Ti</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>4.110</td>
<td>7.905</td>
</tr>
<tr>
<td>Viscosity (m Ns/m³)</td>
<td>5.2</td>
<td>4.9</td>
</tr>
</tbody>
</table>

* All data are at \( T=T_m \) and from Smithell and Brandes (1976).
3.5.1 Comparison of the calculated and experimental results

Figures 3.4 and 3.5 compare the calculated and experimental film thicknesses for water and glycerin solution respectively as a function of disk radius and show that the calculated results are in good agreement with the experimental ones and that the model can predict reasonably well the hydraulic jump and film thickness as a function of disk radius, especially after some distance from the centre of the disk.

3.5.2 Simulation of melt flow on a rotating disk

3.5.2.1 Film thickness and velocity profiles

Figure 3.6 shows the film thickness of titanium melt on a disk of diameter 0.058 m rotating with an angular speed of 20,000 rpm (60.71 m/s) and mass flow rate of 0.05 kg/s. There is no hydraulic jump and the film becomes very thin with increasing distance from the disk center. This is because the centrifugal force induced by a disk rotating at a high speed is much greater than the inertia force. It can also be seen that the film at the rim of the disk is calculated to be about 20 \( \mu \)m thick.

The velocity profiles of Ti thin films at different radial distances from the centre of a disk are shown in Figures 3.7 to 3.9. It can be seen that (i) Near the centre of the disk, the inertia force has a great effect. This leads to a different radial velocity profile across the film (Figure 3.7 curve 1) and a higher axial velocity (Figure 3.9 curve 1). With increasing radial distance the centrifugal force becomes more important and the radial, tangential and axial velocity profiles change slightly (Figures 3.7 to 3.9 curves 2 to 4). (ii) The liquid experiences a non-solid rotation with the disk. The tangential velocity at the interface of the melt and disk is equal to the rotating speed of the disk while across the film the velocity gradually decreases and reaches a low value at the free surface (Figure 3.8). This leads to a thicker film than that of the solid-rotating model of Emslie et al (1958). (iii) The axial velocity (Figure 3.9) is much smaller than the radial and tangential velocity. This is in
agreement with the boundary-layer theory.

3.5.2.2 The effect of disk speed

The change of the Ti melt film thickness with the disk rotating speed is shown in Figure 3.10. With increasing disk rotating speed the film becomes thinner. At low rotating speeds the film thickness decreases very fast near the centre of the disk, while at high rotating speeds the film thickness changes more slowly. The effect of disk speed on the film thickness at the edge of the disk is shown in Figure 3.11. An increase of the disk rotating speed results in an increase of centrifugal force and of the radial and tangential velocities at the edge of the disk (Figures 3.12 and 3.13).

3.5.2.3 The effect of melt flow rate

Figures 3.14 and 3.15 show that the film thickness and the radial velocity on the surface of a rotating disk increase with increasing flow rate while the tangential velocity changes very little (Figure 3.16).

3.5.2.4 The effect of different metals

The film thicknesses of titanium and nickel melts on a rotating disk of 0.2 m diameter are shown in Figure 3.17. The nickel film is thinner at the same condition. From Figure 3.19 it can be seen that the kind of metal has a weak effect on the tangential velocity of the film at the edge of a rotating disk where a heavier metal film has a lower radial velocity (Figure 3.18). This is attributed to the lower volumetric flow rate at the same mass flow rate for the heavier melt.

3.6 Conclusions

(1) A mathematical model has been developed to describe the flow of molten metal on a rotating disk. The calculations are in good agreement with the available
experimental results. The model has been used to study the effects of various operating and design parameters on the velocity profiles and film thicknesses of liquids on rotating disks.

(2) At low rotating speeds there is a hydraulic jump, while at high rotating speeds the centrifugal force prevents the hydraulic jump from occurring. At large melt flow rates the inertial effect occurs near the centre of the disk. With increasing radial distance from the centre of disk the inertial effect becomes weaker, while the centrifugal force plays a more important role in controlling the film thickness and velocity profiles.

(3) With increasing disk rotating speed the film becomes thinner and the radial and tangential velocities of the film increase.

(4) An increase of mass flow rate results in a thicker film and a higher radial velocity of the film.
Figure 3.1 Schematic diagram of flow and coordinate system

Figure 3.2 Computational grid used in the calculations
Input \( p, \mu, D, m, Q, \tau_0, I_0, N, M, \varepsilon_u, \varepsilon_v, \varepsilon_0 \)

Specify the boundary conditions of \( U, V, W \)

Assign the initial value of \( h(\tau) \)

Evaluate the initial values of \( U, V, W \)

Calculate the velocity profiles using equations (3.20)

\[
\begin{align*}
\text{Max} & \quad \left| \frac{u_{i,j} - u_{i,j}'}{u_{i,j}} \right| < \varepsilon_u, \\
& \quad \left| \frac{v_{i,j} - v_{i,j}'}{v_{i,j}} \right| < \varepsilon_v, \\
& \quad \left| \frac{w_{i,j} - w_{i,j}'}{w_{i,j}} \right| < \varepsilon_w
\end{align*}
\]

yes

Calculate the film thickness of \( h(\tau) \) using equations (3.21)

\[
\begin{align*}
\text{Max} & \quad \left| \frac{h_i - h_i'}{h_i} \right| < \varepsilon_h
\end{align*}
\]

no

yes

\( I > N \)

no

Print the results

yes

END

Figure 3.3 Programme flow chart
Figure 3.4 Comparison of the calculated and experimental film thickness of water on the surface of a rotating disk for $\omega=300$ rpm and $Q=1.17\times10^{-4}$ m$^3$/s
(Experimental results are shown as filled squares and are from Thomas et al, 1991)

Figure 3.5 Comparison of the calculated and experimental film thicknesses of glycerine solution on the surface of a rotating disk for $Q=31.4\times10^{-6}$ m$^3$/s and $\omega=44$ rpm (Experimental and calculated results of Miyasaka 1974 are shown as filled squares and triangles respectively and our calculated data are shown as diamonds)
Figure 3.6 Ti melt film thickness on the surface of a disk for \( \omega=20000 \text{ rpm} \), \( Q=0.05 \text{ kg/s} \) and \( D=0.058 \text{ m} \)

Figure 3.7 Radial velocity distribution of Ti melt across the film at different radii for \( \omega=20000 \text{ rpm} \), \( Q=0.05\text{kg/s} \) and \( D=0.058\text{m} \) (curves 1, 2, 3 and 4 for \( r \) equal to 0.0094, 0.01675, 0.02165 and 0.029m respectively)
Figure 3.8 Tangential velocity distribution of Ti melt across the film at different radii for $\omega=20000$ rpm, $Q=0.05$ kg/s and $D=0.058$ m (curves 1, 2, 3 and 4 for $r$ equal to 0.0094, 0.01675, 0.02165 and 0.029 m respectively).

Figure 3.9 Axial velocity distribution of Ti melt across the film at different radii for $\omega=20000$ rpm, $Q=0.05$ kg/s and $D=0.058$ m (curves 1, 2, 3 and 4 for $r$ equal to 0.0094, 0.01675, 0.02165 and 0.029 m respectively.)
Figure 3.10 The effect of disk rotating speed on the Ti film thickness on the surface of a disk for Q=0.01667 kg/s and D=0.2 m (curves 1, 2, 3 and 4 for ω=5000, 10000, 20000 and 25000 rpm respectively)

Figure 3.11 The relationship between the disk rotating speed and the film thickness at the edge of a disk for Ti melt for Q=0.01667 kg/s and D=0.2 m
Figure 3.12 The effect of disk rotating speed on the radial velocity profiles of Ti melt across the film at the edge of a disk for \( Q = 0.01667 \text{ kg/s} \) and \( D = 0.2 \text{ m} \) (curves 1, 2, 3 and 4 for \( \omega = 5000, 10000, 20000 \) and 25000 rpm respectively).

Figure 3.13 The effect of disk rotating speed on the tangential velocity profiles of Ti melt across the film at the edge of a disk for \( Q = 0.01667 \text{ kg/s} \) and \( D = 0.2 \text{ m} \) (curves 1, 2, 3 and 4 for \( \omega = 5000, 10000, 15000 \) and 20000 rpm respectively).
Figure 3.14 The effect of flow rate on the Ti film thickness at the edge of a rotating disk for \( \omega = 15000 \text{ rpm} \) and \( D = 0.2 \text{ m} \)

Figure 3.15 The effect of flow rate on the radial velocity profiles of Ti film at the edge of a rotating disk for \( \omega = 15000 \text{ rpm} \) and \( D = 0.2 \text{ m} \) (curves 1, 2, 3 and 4 for \( Q \) equal to 0.01, 0.01167, 0.025 and 0.05 kg/s respectively)
Figure 3.16 The effect of flow rate on the tangential velocity profiles of Ti film at the edge of a rotating disk for $\omega = 15000$ rpm and $D = 0.2$ m (curves 1, 2, 3 and 4 for $Q$ equal to 0.01, 0.01167, 0.025 and 0.05 kg/s respectively).

Figure 3.17 The effect of different metals on the film thickness at the edge of a rotating disk for $Q = 0.01667$ kg/s and $D = 0.2$ m.
Figure 3.18 The effect of different metals on the radial velocity profiles at the edge of a rotating disk for \(Q=0.01667\) kg/s, \(\omega=10000\) rpm and \(D=0.2\) m.

Figure 3.19 The effect of different metals on the tangential velocity profiles at the edge of a rotating disk for \(Q=0.01667\) kg/s, \(\omega=10000\) rpm, and \(D=0.2\) m. Data for Ti and Ni fall on the same curve.
Chapter 4
Heat Transfer for Melts on a Rotating Disk

4.1 Introduction

In the practice of centrifugal atomization of melts using the rotating disk method the melt is delivered to the centre of a rotating disk. When the melt hits the disk, it spreads out on the disk due to centrifugal and inertial forces (Chapter 3). During this process the melt transfers heat to the disk and the surrounding gas. As a result the melt temperature decreases. When the temperature falls below the melting point solidification takes place. This will affect the disintegration at the edge of the disk. Thus, it is necessary to prevent melt from partially solidifying on the disk to achieve good atomization conditions. In this chapter we study the heat transfer phenomena for melts on a rotating disk and the effects of process and design parameters.

Heat transfer during centrifugal atomization of melt by a rotating disk needs to consider: (1) the falling of the melt, (2) the impingement of the falling melt on the rotating disk and (3) the spreading out of the melt on the surface of the disk. The heat transfer phenomena involve (a) the transfer of heat from the falling melt to the surroundings by convection and radiation and to the disk by impingement and (b) the heat transfer from the melt film to the rotating disk by convection and conduction and to the surroundings by convection and radiation.

There are basically two types of impinging jets: submerged jets, where the surrounding environment is the same fluid as the jet, this fluid typically being air, and unsubmerged jets, where a jet of liquid impinges on a surface in a gaseous environment. Gardon and co-workers (Gardon and Cobonpue 1961, Gardon and Akfirat 1966) studied submerged jets using air. Metzger and his co-workers
Chapter 4  
Heat Transfer of Melts on a Rotating Disk

(Metzger, Cummings and Ruby 1974; Metzger and Grochowsky 1977; Metzger and Brodersen 1992) investigated the effect of jet number, jet position and cross-flow field for submerged jets and of Prandtl number for unsubmerged jets. Carper et al (1986) studied the effects of jet and disk parameters on the heat transfer between the falling jet and the surface of a disk using oil and correlated the heat transfer coefficient with the jet Reynolds number, rotational Reynolds number and Prandtl number. These studies provide a basis for the calculation of heat transfer during the impingement.

Heat transfer over a rotating body in an infinite or finite quiescent fluid has also been studied. In the 1950s experiments and theoretical work aimed to determine the heat transfer coefficient. Wagner (1948) and Millsaps and Pohlhausen (1952) studied theoretically the convective heat transfer coefficient for laminar flow and Kreith and Taylor (1956) for turbulent flow for cooling in air. Young (1956) obtained experimental data for laminar flow and Cobb and Saunders (1956) for both laminar and turbulent flows. However, due to the complexity of the flow driven by a rotating body, there is still need for better understanding of the phenomena involved. Recently Ong and Dwen (1991) gave a numerical solution of heat transfer and flow over a rotating disk in an infinite quiescent air. Comparison of the calculations with the experimental results showed that their numerical model can be effectively used to study the effects of various operating parameters. This work provides a basis for the analysis of heat transfer between the melt and surroundings.

4.2 Mathematical description

Basically, the heat transfer phenomena after the melt exits from a delivery nozzle or tube can be divided into three stages. These are: a) the falling of the melt, b) the impinging of the falling melt on the centre of the disk and c) the spreading out of the melt along the surface of the disk. In this part of the thesis heat transfer in the above three stages will be analysed and the effects of process and design parameters will be studied. Some guidelines will also be given for the design and operation of
Chapter 4  

Heat Transfer of Melts on a Rotating Disk

centrifugal atomization using a rotating disk. In the analysis the theory of heat transfer and impingement are first used to determine the temperature of the melt on the disk. Then the heat transfer is coupled with the flow model developed in chapter 3. The thermal boundary conditions on the free surface are specified based on experimental results for a rotating disk in quiescent environment (Kreith et al 1959 and Kobayasli 1994). Figure 4.1 shows the coordinate system used and the typical velocity and temperature distribution across the film.

The basic equations of flow are the same as in Chapter 3 with the exception that here the temperature dependence of the viscosity of the melt needs to be taken into account. The dependence of viscosity on temperature is described by

\[ \mu = \mu_0 \exp \left( \frac{-E}{RT} \right) \]  

(4.1)

where \( \mu_0 \) is a constant, \( E \) is activation energy, \( R \) is the gas constant and \( T \) is the temperature. Equation (4.1) was used when values of \( E \) and \( \mu_0 \) were available in the literature.

4.2.1 Heat transfer in the falling zone

Consider a melt falling vertically down and impinging on the centre of a rotating disk. During fall the heat transferred to the surroundings is by radiation and convection and can be calculated from equation (4.2)

\[ Q_{rc} = 2\pi r_0 l_0 e_m c_m \sigma \left[ \left( \frac{T_p + T_i}{2} \right)^4 - T_m^4 \right] + 2\pi r_0 l_0 h_L \left[ \left( \frac{T_p + T_i}{2} - T_m \right) \right] \]  

(4.2)

where \( r_0 \) is the radius of the falling melt stream, \( l_0 \) is the distance from the pouring point to the plane of the disk, \( c_m \) is the emissivity of the melt, \( \sigma \) is the Stefan-Boltzmann constant, \( T_p, T_i, T_m \) are temperatures of the melt in the crucible (pouring
Chapter 4  Heat Transfer of Melts on a Rotating Disk

temperature), on the surface of the disk and of the surrounding gas respectively and 
h_{gs} is the heat transfer coefficient between the falling melt and the surrounding gas 
and can be evaluated according to the work of Glicksman (1968). The first term on 
the right hand side of equation (4.2) gives the heat transferred by radiation and the 
second term is the heat transferred by convection.

The change in the enthalpy of the melt during fall is given by

\[ Q_{\text{m}} = mC_{p}(T_{p} - T_{i}) \]  \hspace{1cm} (4.3)

where \( m \) and \( C_{p} \) are the mass flow rate and specific heat of the melt respectively.

Heat balance gives

\[ Q_{h} = Q_{\text{rc}} \]  \hspace{1cm} (4.4)

Equations (4.2 to 4.4) were used to determine the temperature of the melt approaching the surface of the disk. Because of the non linearity of the equations, a numerical iteration method was used to solve them.

4.2.2 Heat transfer in the impinging zone

Heat transfer between the impinging jet and the rotating disk was studied by Carper 
et al (1986). The heat transferred can be determined from

\[ Q_{\text{impinge}} = Ah_{ma}(T_{i} - T_{s}) \]  \hspace{1cm} (4.5)

where \( A \) is the heat transfer area, \( T_{s} \) is the surface temperature of the disk and \( h_{ma} \) is 
the heat transfer coefficient between the rotating disk and falling melt and can be 
evaluated from (Carper et al 1986)
where $N_u$ is the Nusselt number of the melt; $Re_t$, $Re_0$ are the rotational and jet Reynolds numbers of the melt, respectively and $Pr$ is the Prandtl number of the melt. The dimensionless numbers are: $Nu = \frac{h_m r_i}{k}$, $Re_t = \frac{\omega r_i^2}{u}$, $Re_0 = \frac{r_0 u_0}{u}$ and $Pr = \frac{\mu c_p}{k}$, where $r_i$ is the critical radius (see Section 3.2), $\omega$ is the rotating speed of the disk, $u$ is the kinematic viscosity of the melt and $u_0$ is the velocity of the melt at $r_i$ (see Section 3.3).

The change in the enthalpy of the melt during the impinging stage is given by

$$Q_h = mc_p(T_i - T_o)$$

(4.7)

where $T_o$ is the temperature of the melt after impingement.

Heat balance gives:

$$Q_h = Q_{impinge}$$

(4.8)

Equations (4.5 to 4.8) were used to determine the temperature of the melt after impingement.

### 4.2.3 Heat transfer in the spreading out zone

The flow equations were derived in Chapter 3. Heat transfer in the film can be described by considering energy conservation:

$$u \frac{\partial T}{\partial r} + w \frac{\partial T}{\partial z} = \frac{1}{\rho c_p} \left[ \frac{1}{r} \left( k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \right]$$

(4.9)

The boundary conditions are:

at $r = r_i$,

$$T(r_i, z) = T_o$$

(4.10)
at $z=0$

$$-k \frac{\partial T}{\partial z} = q_w$$  \hspace{1cm} (4.11)

where $q_w$ is the heat transferred from the melt to the disk and can be determined from

$$q_w = \frac{T - T_w}{\frac{\delta_d}{k_d} + \frac{1}{h_w}}$$  \hspace{1cm} (4.12)

In equation (4.12) $\delta_d$ and $k_d$ are the thickness and thermal conductivity of the disk, and $h_w$ is the heat transfer coefficient between the disk and the surroundings which can be evaluated according to work of Mizukami et al (1995).

At $z=h(r)$

$$-k \frac{\partial T}{\partial z} = h_{mg}(T - T_m) + \varepsilon w^4(T_d - T_m)$$  \hspace{1cm} (4.13)

where $h_{mg}$ is the convective heat transfer coefficient between the melt and the surrounding gas, which can be calculated from the following equations.

For laminar flow (Kreith et al 1959):\n
$$N_u_{gas} = C_1 R_{e_{gas}}^{0.5}$$  \hspace{1cm} (4.14)

For turbulent flow (Kobayasi 1994):

$$N_u_{gas} = C_2 R_{e_{gas}}^{0.8}$$  \hspace{1cm} (4.15)

where $C_1$ and $C_2$ are constants dependent on the Prandtl number of the gas, $R_{e_{gas}}$ is the Reynolds number, $R_{e_{gas}} = \omega r/\nu_{gas}$ and $N_u_{gas}$ is the Nusselt number of the gas, $N_u_{gas} = h_{mg}/k_{gas}$. When $Pr_{gas}=0.74$, $C_1=0.33$ (Kreith et al 1959) and $C_2=0.015$
Chapter 4  
Heat Transfer of Melts on a Rotating Disk

(Kobayashi 1994).

4.3 Solution method

As discussed in chapter 3, because the melt film thickness changes with radial position and operating conditions, it is difficult to compute the velocity profiles and temperature distribution in the film using the conventional numerical method since the computational domain changes during computation. A new coordinate system was set up and the finite difference method was used to solve numerically the equations of flow and heat transfer. The general finite difference equations are

\[ A_p \phi_{i,j} = A_m \phi_{i,j+1} + A_s \phi_{i,j-1} + S_p \quad (4.16) \]

where \( A_p, A_m, A_s \) are coefficients in the nodal equations; and \( S_p \) is source term. Figure 4.2 shows the computational grid used in this study. The flow chart of computation is shown in Figure 4.3.

4.4 Results and Discussion

The data used in the calculations are given in Table 4.1.

Figure 4.4a shows the average temperature distribution for Ti melt film along the surface of a rotating disk. The temperature distribution across the film thickness is shown in Figure 4.4b. It can be seen that the temperature of the melt decreases with increasing distance from the centre of the disk (Figure 4.4a). This is due to the increase of the area available for heat transfer as we move towards the edge of the disk as well as the fact that the film thickness decreases (chapter 3). For a given radial position the temperature across the film varies very little (Figure 4.4b) since the film is about a few micrometers thick (see chapter 3) and the melt has high...
thermal conductivity.

**Table 4.1 Data for Ti and disk material (steel) used in the calculations**

(Smithell and Brandes 1976)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>For Ti:</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>$c_p$</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>$k$</td>
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</tr>
<tr>
<td></td>
<td>$\varepsilon_m$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>$T_m$</td>
<td>1958</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>$\rho$</td>
<td>4110</td>
</tr>
<tr>
<td>For disk:</td>
<td>$k_1$</td>
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</tr>
<tr>
<td></td>
<td>$\delta$</td>
<td>0.05</td>
</tr>
<tr>
<td>Gas</td>
<td>$T_{gas}$</td>
<td>298</td>
</tr>
</tbody>
</table>

**4.4.1 Effect of disk speed**

The effect of disk rotating speed on the average temperature of Ti melt film is shown in Figure 4.5. The temperature of the melt decreases with increasing radial distance and with increasing disk rotating speed, since a high rotating speed leads to a thinner film (chapter 3) and to high heat transfer from the melt to the surrounding by convection. This effect is stronger near the edge of the rotating disk where the film thickness is smallest.

**4.4.2 Effect of mass flow rate**

The mass flow rate has a strong effect on the average temperature of the melt on the disk (Figure 4.6). With decreasing mass flow rate the temperature drops very quickly. For the conditions used in the calculation shown in Figure 4.6, when the...
mass flow rate is below about 1kg/min, the melt is predicted to solidify partially on the disk. Figure 4.7 shows the relationship between the point of freezing (radial distance where onset of solidification takes place) and the mass flow rate. The onset of solidification moves towards the centre of the disk with decreasing mass flow rate. Thus, the melt mass flow rate should be closely controlled to avoid solidification of the melt on the rotating disk in centrifugal atomization.

4.4.3 Effect of melt superheat

The effect of melt superheat on the average temperature of Ti melt films on a rotating disk is shown in Figure 4.8. A low melt superheat leads to an early onset of solidification of the melt. Figure 4.9 shows the relationship between the point of freezing on the disk and melt superheat. Large superheats are required to prevent solidification of the melt on large diameter rotating disks.

4.4.4 Effect of heat transferred through the disk

The heat transferred through the disk has a strong effect on the average temperature of the melt on the disk (Figure 4.10) and the onset of solidification on the disk (Figure 4.11). Choice of disk material and disk condition (e.g., water cooled) are thus expected to have a strong effect in controlling the onset of solidification on the disk.

4.5 Conclusions

A mathematical model has been developed to describe the heat transfer phenomena for melts on rotating disks. The effects of disk rotating speed, melt superheat, melt mass flow rates and heat transferred through the disk on the average temperature of the melt and the onset of solidification on the disk have been studied. High melt mass flow rates and melt superheats are required to avoid solidification of the melt on the disk. Small diameter disks and control of the heat transferred through the disk can prevent the onset of solidification of the melt on the disk.
Figure 4.1 Schematic diagram of flow and heat transfer on a rotating disk and coordinates system

Figure 4.2 Computational grid
Input $\rho, \mu, C_p, k, k_{\text{gas}}, C_{p_{\text{gas}}}, D_0, a_0, Q, r_0, I_0, T_{\text{super}}, T_s, T_w, N, M, \varepsilon_s, \varepsilon_r, \varepsilon_{h}, \varepsilon_T$

Calculation of heat transfer in falling zone

Calculation of heat transfer in impinging zone

$[=I=N+1]$

Evaluation of the initial values of $U, V, W, T, h(r)$

Calculation of temperature distribution in melt film

$\text{Max} \frac{\Delta T}{\Delta I} \leq \varepsilon_T$

Yes

Calculate the velocity profiles using equations (3.20)

$\text{Max} \left| \frac{\Delta u}{\Delta I} \right| \leq \varepsilon_u, \left| \frac{\Delta v}{\Delta I} \right| \leq \varepsilon_v, \left| \frac{\Delta w}{\Delta I} \right| \leq \varepsilon_w$

Yes

Calculate the film thickness of $h(r)$ using equations (3.21)

$\text{Max} \left| \frac{\Delta h}{\Delta I} \right| \leq \varepsilon_h$

Yes

Energy conservation?

Yes

$\text{I} = \text{N}$

No

Output the results

END

Figure 4.3 Programme flow chart
Figure 4.4a Average temperature of Ti melt along the surface of a disk for $Q=1.5 \text{ kg/min, } \omega=15000 \text{ rpm, } D=0.1 \text{ m and } T_p=2158 \text{ K}$

Figure 4.4b Temperature profiles across a film of Ti melt at different radial distances for $Q=1.5 \text{ kg/min, } \omega=15000 \text{ rpm, } D=0.1 \text{ m and } T_p=2158 \text{ K}$. (Curves 1 to 5 for $r$ equal to 0.016, 0.0245, 0.033, 0.0415 and 0.05 m respectively)
Figure 4.5 The effect of disk rotating speed on the average temperature of Ti melt on the surface of a disk for $Q=1.5 \text{ kg/min}$, $D=0.1 \text{ m}$ and $\Delta T_{\text{super}}=200 \text{ K}$

Figure 4.6 The effect of flow rate on the average temperature of Ti film on the surface of a disk for $\Delta T_{\text{super}}=200 \text{ K}$, $\omega=15000 \text{ rpm}$ and $D=0.1 \text{ m}$ (curves 1 to 3 for $Q$ equal to 0.6, 0.9, 1.5 $\text{ kg/min}$ respectively)
Figure 4.7 Relationship between the point of freezing (in terms of radial distance) and the mass flow rate for Ti melt for $\Delta T_{\text{super}}=200$ K, $D=0.1$ m and $\omega=15000$ rpm.

Figure 4.8 The effect of melt superheat on the average temperature of Ti melt on the surface of a disk for $Q=1.5$ kg/min, $\omega=15000$ rpm and $D=0.1$ m (curves 1 to 3 for $\Delta T_{\text{super}}$ equal to 50, 100 and 200 K).
Figure 4.9 Relationship between the point of freezing and the superheat of Ti melt for $\omega=15000$ rpm, $D=0.1$ m and $Q=1.5$ kg/min

Figure 4.10 The effect of heat loss through the disk on the average temperature of Ti melt on the surface of a disk for $\omega=15000$ rpm, $D=0.1$ m, $Q=1.5$ kg/min and $\Delta T_{\text{super}}=200$K (curves 1 to 3 for $h_{\text{sw}}=5000$, 500 and 50 W/m² K respectively)
Figure 4.11 Relationship between the point of freezing and the heat loss through the disk for $\omega=15000$ rpm, $D=0.1$ m, $Q=1.5$ kg/min and $\Delta T_{\text{super}}=200$K for Ti melt
Chapter 5
Calculation of powder particle size

5.1 Introduction

In centrifugal atomization using a rotating disk the melt breaks up into droplets according to one of three basic modes (see also chapter 2). These are: (i) Direct droplet formation (DDF), (ii) Ligament formation (LF) and (iii) Film formation (FF). At low rotating speeds and low flow rates the melt breaks up at the edge of the disk in the DDF mode. With increasing flow rate and rotating speed disintegration of the melt gradually moves into the LF regime. In this regime ligaments form at the edge of the disk and go beyond the disk to a certain distance and then break up into a "train" of droplets. With a further increase of rotating speed and flow rate the number and diameter of ligaments increase. When the flow rate reaches a critical value the ligaments cannot disintegrate all the melt. Thus, a thin film of sheet forms and extends beyond the disk. At certain distance the sheet film breaks up into ligaments, the latter further disintegrate into droplets, due to interactions with the surrounding gas. In this chapter we study the calculation of powder particle size in the different regimes using wave theories. First the theories are briefly summarised and then are used to analyse the disintegration of melts. Models are developed to calculate powder particle size. The results are compared with data in the literature.

5.2 Review of wave theories

Observations and studies of liquid atomization have shown that the waves, which are formed on the surface of a liquid when the latter is ejected into a gas atmosphere, are
responsible for the disintegration of the liquid. Basically, there are two types of instabilities: capillary instability and aerodynamic instability. In the case of capillary instability, the surface tension of the liquid promotes its disintegration while in the case of aerodynamic instability, the pressure variation caused by waves is responsible for the liquid break up while surface tension opposes the instability and reduces the growth of the disturbances. Accordingly, the theoretical study of liquid disintegration falls in two categories: the break up of circular liquid jets and the disintegration of film/sheet. The disturbances inducing the waves may occur in various forms depending on the real situation.

In the study of capillary instabilities of a circular jet, Rayleigh (1878) was the first to relate the instability of jets to the growth of disturbances formed at the interface of gas and jet. Weber (1931) extended Rayleigh's theory by introducing the effects of liquid viscosity and liquid velocity relative to the surrounding medium. Later experimental results showed that Weber's theory overestimated the aerodynamic effects. Sterling and Sleicher (1975) tried to modify Weber's theory by taking into account the ambient fluid viscosity. Yuen (1968), Lafrance (1975) and Chaudhary and Redkopp (1980) carried out nonlinear analyses of the circular jet break up. Their models improved the predicted surface distortions due to the capillary instabilities in the absence of gas-phase pressure variations and suggested the existence of satellite drops. Mansour and Lundgren (1990) developed a full nonlinear simulation of the Rayleigh breakup process by using a boundary element method (BEM). Reitz (1987) classified the jet break up into four regimes: (1) Rayleigh regime, (2) first wind-induced zone, (3) second wind-induced zone and (4) atomization zone. Christopher et al (1995) analysed the atomization in the first wind-induced regime using BEM. Li (1995) proposed a three-dimensional linear model for the circular liquid jet.

Considering the case of aerodynamic instabilities, Squire (1953) first treated the problem of the growth of waves on a flat sheet of liquid and proposed the first instability model. Hagerty and Shea (1955) did similar work for inviscid liquid
sheets with uniform thickness in an inviscid gas medium. Their studies showed that the principal sources of sheet instability are the formation of aerodynamic waves on the interface of gas and liquid and that the dominant type of disturbance inducing waves, which eventually leads to the breakup of the sheet into droplets, is antisymmetrical. Dombrowski and Hooper (1962) and Fraser et al. (1962) successfully applied Squire's theory to calculate the droplet size produced by fanspray for liquids with low viscosity and gave a theoretical basis for predicting the effects of several factors on drop size. Dombrowski and Johns (1963) extended Squire's and Hagerty and Sheas' work by taking into account the effect of liquid viscosity. The change of sheet thickness as it travels through the gas medium was also considered in their model. The gas was assumed to be inviscid. Li and Tankin (1991) gave a more detailed derivation of the growth of waves on a two-dimensional viscous liquid sheet and examined the modes of instability for viscous sheet and the roles of surface tension and viscosity of liquid. Church (1991) developed the first spatial instability model for plane fluid sheet.

See et al. (1973) and See and Johnston (1978) applied the sheet wave theory of Dombrowski and Johns (1963) to the gas atomization of melts. They evaluated the gas velocity at the break up point of the melt by arbitrarily assuming a thickness of the sheet. Bradley (1973) analysed formation and growth of waves on the surface of an infinite deep liquid blown over by a high velocity gas flow and suggested a model to calculate the particle size following the classic Rayleigh instability. In this model, the model parameter $\varepsilon$, which reflects that surface tension nips off the crest of the fastest-growing wave into a ligament whose diameter is some fraction of the fastest-growing wavelength was unknown and was intuitively set to 0.25. Also the effect of the ratio of the melt to gas flow rate was not considered. Burger et al. (1989, 1992) summarised mechanisms of melt disintegration and various theories of waves in gas atomization. They tried to use the wave crest stripping model to relate powder particle size with atomizing parameters. More recently Antipas, Lekakou and Tsakiropoulos (1993) also explored the application of wave theory to gas atomization.
5.3 Transition conditions

As mentioned in section 5.1 the melt breaks up into droplets according to one of three basic modes, when it comes to the edge of a rotating disk. Hinze and Milborn (1950), Tanasawa et al (1978), Fraser et al (1963), Matsumoto et al (1973) and Dombrowski and Lloyd (1974) studied the transition conditions from DDF to LF and from LF to FF for normal liquids and gave empirical criteria for the transitions. Champagne and Angers (1984) and Halada et al (1990) successfully applied these criteria to the centrifugal atomization of metallic melts and developed a centrifugal atomization (CA) diagram for metallic melts by using high speed camera photography and analysing morphology of the powder particles (see also chapter 2).

The equations proposed to describe the transition conditions are (Halada et al, 1990):

From DDF to LF

\[ \frac{Q_1}{Q_c} = 0.096 \cdot Re^{0.95} \cdot We^{-1.15} \]  \hspace{1cm} (5.1)

From LF to FF

\[ \frac{Q_2}{Q_c} = 0.34 \cdot Re^{2/3} \cdot We^{-0.83} \]  \hspace{1cm} (5.2)

where \( Q_1^* \) and \( Q_2^* \) are the dimensionless critical flow rates for the transitions from DDF to LF and from LF to FF respectively, \( Q_1 = Q_1/2\pi R^2 (\nu\omega)^{1/2} \) and \( Q_2 = Q_2/2\pi R^2 (\nu\omega)^{1/2} \), \( Re \) and \( We \) are the Reynolds and Weber numbers of the melt, and \( Q_1 \) and \( Q_2 \) are the critical flow rates for the transition from DDF to LF and from LF to FF respectively.
5.4 Calculation of powder particle size in the direct droplet formation regime

5.4.1 Introduction

At low flow rates and low rotating speeds the melt breaks up into droplets at the edge of a disk in the DDF mode (see chapter 2). In this part of the thesis wave theory is used to analyse the disintegration of the melt at the edge of a rotating disk. A model is proposed to calculate the size of powder particles in the DDF regime. The analysis considers the role of process parameters and material properties. Equations are derived to describe the growth of waves and to calculate the optimal wave number and melt break up time. The dependence of powder particle size on disk diameter and rotating speed as well as type of melt is calculated and compared to available experimental results. It will be shown that wave theory can predict reasonably well the powder particle size in the DDF regime.

5.4.2 Formation and growth of waves at the edge of a rotating disk

At the edge of a rotating disk centrifugal, viscous, surface tension and inertia forces work on the film. Depending on the operating conditions, the film may become unstable and disintegrate into droplets according to one of the three basic modes. Wave theory has suggested that the formation and growth of waves induced by disturbances are responsible for the disintegration of the film. In the DDF mode waves form at the edge of a rotating disk. When the amplitude of a wave reaches the critical value melt breaks up into droplets. In chapter 3 it was shown that the radial velocity of the film is much smaller than its tangential velocity. Thus, only the growth of disturbances in the radial direction needs to be considered.

Let us consider a two-dimensional thin liquid film of density $\rho$, viscosity $\mu$ and surface tension $\sigma$ moving around a disk of radius $R$ and rotating at the angular speed $\omega$ through a stationary gas, see Figure 5.1. The displacement caused by a disturbance can be expressed as (Kayano and Kamiya, 1978)
Chapter 5  Calculation of Powder Particle Size

\[ y = (r-R) = a \cos K(\theta - \omega t) \]  \hspace{1cm} (5.3)

where \( y \) is the displacement of the disturbance, \( K \) is the wave number and \( a \) is the amplitude of the disturbance.

The disturbance potential \( \Phi \) is

\[ \Phi = a^t r \cos K(\theta - \omega t) \]  \hspace{1cm} (5.4)

where \( a^t \) is the first differential of the amplitude with respect to time.

Waves induced by a disturbance can grow or decay depending on the forces acting on the film. For a film at the edge of a rotating disk, four forces are working on the film, as discussed above. The centrifugal and inertial forces try to throw the film away from the disk while the surface tension and viscous forces try to keep the film on the disk. A force balance allows the growth of the amplitude of the wave to be derived (Kayano and Kamiya, 1978, see also Appendix I).

\[ a_{tt} + K(4K-3) \frac{\mu}{\rho} \frac{1}{R^2} a^t + 2 \left( K^3 \frac{\alpha}{\rho} \frac{1}{R^3} - K\omega^2 \right) a = 0 \]  \hspace{1cm} (5.5)

where \( a^t \) is the second differential of the amplitude with respect to time.

Following the conventional practice in the description of disturbance growth, it is assumed that the amplitude of the disturbance increases exponentially with time as

\[ a = a_0 \exp(\beta t) \]  \hspace{1cm} (5.6)

where \( \beta \) is the growth rate and \( a_0 \) is the initial amplitude of the disturbance. By substituting equation (5.6) into equation (5.5), the equation for \( \beta \) can be derived as

\[ \beta^2 + K(4K-3) \frac{\mu}{\rho} \frac{1}{R^2} \beta + 2 \left( K^3 \frac{\alpha}{\rho} \frac{1}{R^3} - K\omega^2 \right) = 0 \]  \hspace{1cm} (5.7)
Chapter 5  

Calculation of Powder Particle Size

The solution of equation (5.7), which fits the phenomenon of disintegration of a liquid film, is given by equation (5.8).

\[
\beta^1 = \frac{\dot{\beta}}{\omega} = \frac{1}{2Re} K(4K-3) \left(1 + \frac{8Re^2}{WeK(4K-3)^2} (We-K^2)^{-1}\right) \quad (5.8)
\]

where \( \beta^1 \) is the relative growth rate of the disturbance, \( Re \) is the Reynolds number of the melt, \( Re=\rho \omega R^3/\mu \) and \( We \) is the Weber number, \( We=\rho \omega^2 R^2/\sigma \).

Equation (5.8) shows that the relative growth rate of a disturbance is a function of the Weber, Reynolds and wave numbers. When the Weber and Reynolds numbers are kept constant, the growth rate will change with the wave number in the form of a complicated function. At a certain wave number, the growth rate will reach a maximum value (see Figure 5.2). This means that at that wave number, referred to as the optimal wave number \( K_{opt} \), the film disintegration will be most probable. The optimal wave number can be found by differentiating equation (5.8) with respect to wave number and letting it equal to zero.

\[
\frac{d\beta^1}{dK} = 0 \quad (5.9)
\]

The resultant equation is:

\[
(8K^2_{opt} - 3) (\sqrt{\phi} - 1) = \frac{8Re^2 K_{opt}}{We(4K_{opt} - 3) \sqrt{\phi}} + \frac{12Re^2 (4K_{opt} - 1)(We-K_{opt}^2)}{WeK_{opt} (4K_{opt} - 3)^2 \sqrt{\phi}} \quad (5.10)
\]

where

\[
\phi = 1 + \frac{8Re^2}{WeK_{opt} (4K_{opt} - 3)^2} (We-K_{opt}^2)
\]

Equation (5.10) can be used to obtain \( K_{opt} \).
5.4.3 Calculation of powder particle size

In chapter 3 it was shown that in the atomization of melts by rotating disks the film thickness at the edge of the disk is very thin and the radial velocity at the edge of the disk is also small for low mass flow rates. Once the wave is formed at the edge of a disk, the amplitude of the wave will increase with time. When the amplitude of the wave reaches a critical value, referred to as the critical amplitude (the corresponding time is referred to as the break up time), the melt breaks up into droplets which subsequently solidify into powder particles. Below we calculate the mean size of atomized powder particles assuming that the drops will break up from the melt at the edge of the disk, when the disturbance of the melt increases up to the break up time and the number of particles ejected from the edge of the disk is equal to the optimal wave number of the disturbance.

If \( n \) is the number of drops appearing at the edge of the disk, \( d_p \) is the mean diameter of the drops ejected from the disk, \( d^* \) is the mean powder particle size, \( 1/\tau^* \) is the leaving frequency of drops from the disk, \( \rho_s \) is the density of the melt at room temperature and \( Q \) is the flow rate of the melt, the conservation of mass gives

\[
\frac{\pi}{6} d_p^3 \frac{n}{\tau^*} = Q
\]  

(5.11)

Therefore the mean drop size is

\[
d_p = \left(6 Q \frac{\tau^*}{\pi n} \right)^{\frac{1}{3}}
\]  

(5.12)

where \( \tau^* \) is the break up time of drops, equal to the reciprocal of the leaving frequency of drops and can be calculated from the growth rate of the disturbance when the ratio of the amplitude of the disturbance to the initial amplitude reaches a critical value.
Chapter 5 Calculation of Powder Particle Size

\[ \tau^* = 2 \Re \frac{\ln \left( \frac{a}{a_0} \right)}{K_{opt} \left( 4 K_{opt} - 3 \right) (\sqrt[3]{\varphi} - 1) \omega} \]  

(5.13)

The studies of Dombrowski and Hooper (1962) and Fraser et al (1962) have shown that \( \ln(a/a_0) \) is approximately constant (about 12).

The mean powder particle size can then be calculated from

\[ d_s = d_p \left( \frac{\rho}{\rho_s} \right)^{\frac{1}{3}} \]  

(5.14)

where \( \rho_s \) is the density of the powder particle at room temperature.

5.4.4 Solution method

Because of the non-linearity of equation (5.10) the numerical iteration method (Korn and Korn, 1968) was used to calculate the optimal wave number. The break up time was calculated from equation (5.13). After finding out the \( K_{opt} \) and break up time the powder particle sizes were calculated from equations (5.12) and (5.14). The programme flow chart is shown in Figure 5.3. The material properties, design and operating parameters and calculation accuracy etc. are first entered to the computer. The programme checks the regime in which the melt will break up. Then particle sizes are calculated according to the above model.

5.4.5 Results and discussion

The optimal wave number and powder particle sizes have been calculated and compared with available experimental data in the literature. The effects of material properties, design and process parameters on the optimal wave number and powder particle sizes will be studied in the following sections.
Chapter 5 Calculation of Powder Particle Size

Values of the physical properties of the melts used in the calculations are given in Table 5.1.

Table 5.1 Values of physical properties of melts used in the calculations

<table>
<thead>
<tr>
<th>Property</th>
<th>SAE-1090 steel</th>
<th>2024 Al alloy</th>
<th>Ni</th>
<th>Fe</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density* (kg/m³)</td>
<td>7015</td>
<td>2450</td>
<td>7905</td>
<td>7015</td>
<td>4110</td>
</tr>
<tr>
<td>Surface tension* (N/m)</td>
<td>1.546</td>
<td>0.88</td>
<td>1.778</td>
<td>1.872</td>
<td>1.65</td>
</tr>
<tr>
<td>Viscosity* (m Ns/m²)</td>
<td>5.5</td>
<td>1.408</td>
<td>4.9</td>
<td>5.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Density at 298 K (kg/m³)</td>
<td>7870</td>
<td>2940.8</td>
<td>8900</td>
<td>7870</td>
<td>4510</td>
</tr>
</tbody>
</table>

* data for SAE-1090 steel are from Champagne and Angers (1984), data for 2024 Al alloy are from Angers et al (1994), data for Ti, Fe and Ni melts are from Smithells and Brandes (1976), + data at T=T_m

5.4.5.1 Comparison of calculated and observed wave numbers

Figure 5.4 shows the waves forming at the edge of rotating bars (Champagne and Angers, 1980 and 1984). Figure 5.5 compares the calculated and observed wave numbers for REP atomized SAE 1090 steel (Champagne and Angers, 1980 and 1984). The calculations follow the same trend as the experimental data but for a given disk speed they always underestimate the observed wave number by about 10%. This discrepancy is considered acceptable considering how complicated is the atomization process.
5.4.5.2 Comparison of calculated and experimental particle sizes

Champagne et al (1980, 1984) atomized Al and Cu alloy melts and SAE 1090 steel and Armco iron melts by REP and obtained an empirical expression for the mass median particle size $d_{50}$ based on the experimental results of 126 atomization runs. The expression for $d_{50}$ was fitted with experimental data with a 99.2% multiple determination coefficient and is given by

$$d_{50} = 4.27 \times 10^6 \frac{1}{\omega^{0.85}} \left( \frac{\rho}{\rho_0} \right)^{0.42} \frac{1}{D^{0.61}} \rho^{0.12}$$

(5.15)

Angers (1992) and Angers et al (1994) also applied the above empirical equation to other rotating disk atomization processes (such as inverted disk centrifugal atomization) and showed that equation (5.15) is applicable to these processes. In order to check our model, both experimental results as well as $d_{50}$ values calculated from equation (5.15) were used as a reference.

Figure 5.6 shows the calculated and experimental mean particle sizes of 2024 aluminium alloy atomized using inverted rotating disks of diameters of 50 mm and 75 mm. The calculations are in good agreement with $d_{50}$ from equation (5.15) for both disk diameters and differ from the experimental results of Angers et al (1994) at low and high rotating speeds for the 50 mm and 75 mm disk diameters respectively. For the large disk diameter Angers et al (1994) had reported that the melt had partially solidified on the disk before reaching the edge of the disk. This was thought to be responsible for the production of coarse powders at high rotating speeds ($\omega > 25,000$ rpm).

5.4.5.3 Effects of atomizing parameters

Figure 5.7 shows the effects of disk diameter on the relative growth rate, optimal wave number and powder particle size for SAE 1090 steel. It can be seen that the relative growth rate and optimal wave number increase with increasing disk diameter.
(Figure 5.7a and 5.7b) while the mean powder particle size decreases with increasing disk diameter (Figure 5.7c). Thus, the calculations suggest that large diameter disks can be used to produce fine powders provided that the melt does not solidify on the disk (see chapter 4).

The effects of increasing disk speed on the relative growth rate, optimal wave number and mean powder particle size for SAE 1090 steel are shown in Figure 5.8 and are the same as for the case of increasing disk diameter. This confirms that the disk speed is another parameter that controls the size of the powder particles.

Figure 5.9 shows the effect of type of melt on the optimal wave number and mean powder particle size. Finer powders can be produced by centrifugal atomization of Fe than of Ti melts. This difference, which is also greater at low rotating speeds, is attributed to the higher ratio of density to surface tension for Fe melt (see equation 5.15). This ratio is an important material parameter which controls the atomized powder particle size in centrifugal atomization using the rotating disk method.

5.5 Calculation of powder particle size in the ligament formation regime

At moderate flow rates ligaments form at the edge of a rotating disk and go beyond the disk. At some distance ligaments break up into a "train" of droplets. In this section the calculation of powder particle sizes in the LF regime is studied. Wave theory is used to determine the number of ligaments which form at the edge of a rotating disk. Mass conservation is used to derive the diameter of ligaments. After finding out the number and diameter of the ligaments the powder particle sizes are evaluated using Weber's theory.

5.5.1 Principle of calculation

At moderate flow rates the melt breaks up at the edge of a rotating disk in the ligament formation mode. It is thought that formation of uniform ligaments at the
edge of a rotating disk (see Figure 5.10) is the result of the formation of waves at the periphery of the disk. Each fastest growing wave gives a ligament at moderate flow rate. Thus equation (5.10) can be used to evaluated the number of ligaments forming at the edge of a rotating disk. Assuming that the number of ligaments is equal to the wave number which gives the maximum growth rate of disturbance, the particle size can be calculated using Weber's wave theory.

Let us consider the situation shown in Figure 5.11, and denote the diameter of ligaments as \(d_l\), the number of ligaments as \(n_l\) and the melt flow rate as \(Q\). The mass conservation gives

\[
\pi \frac{d_l^2}{4} n_l u_m = Q \tag{5.16}
\]

where \(u_m\) is the average radial velocity of the melt at the edge of the disk and is given by (Halada et al, 1990)

\[
u_m = \left( \frac{\rho \omega^2 Q^2}{12 \pi^2 \mu R} \right)^{1/3} \tag{5.17}
\]

The diameter of the ligaments can be determined from

\[
d_l = \sqrt[3]{\frac{4Q}{\pi n_l u_m}} \tag{5.18}
\]

Since the radial velocity of melts at the edge of a disk is small, Weber's theory gives

\[
d_p = (1.5)^{1/3} \lambda_{opt}^{1/3} d_l^{2/3} \tag{5.19}
\]

where \(\lambda_{opt}\) is the optimal wave length in the ligaments and is given by

\[
\lambda_{opt} = \sqrt{2\pi d_l} \sqrt[3]{\frac{1 + \frac{3\mu}{\sqrt{\rho d_1}}}{\rho d_1}} \tag{5.20}
\]
Chapter 5 Calculation of Powder Particle Size

The powder particle sizes can be calculated by

\[ d_s = d_p \left( \frac{\rho}{\rho_s} \right)^{1/3} \]  \hspace{1cm} (5.21)

5.5.2 Solution method

Powder particle sizes in the LF regime can be calculated according to the above model. A computer code has been written for the calculation. The programme flow chart is shown in Figure 5.12 (see also Figure 5.3).

5.5.3 Results and discussion

5.5.3.1 Comparison of calculated and experimental powder particle sizes

The properties of Bi-Sn and AZ91 alloys are given in Table 5.2. Table 5.3 compares the calculated and experimental powder particle sizes for Bi-Sn and AZ91 alloys at different operating conditions.

Table 5.2 The properties of Bi-Sn and AZ91 alloys

<table>
<thead>
<tr>
<th>Property</th>
<th>Bi-Sn alloy*</th>
<th>AZ91 alloy#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m³)</td>
<td>8560</td>
<td>1669.5</td>
</tr>
<tr>
<td>Surface Tension (N/m)</td>
<td>0.38</td>
<td>0.595</td>
</tr>
<tr>
<td>Viscosity (mNs/m²)</td>
<td>1.82</td>
<td>1.255</td>
</tr>
<tr>
<td>Density at 298 (Kg/m³)</td>
<td>8375</td>
<td>1835</td>
</tr>
</tbody>
</table>

* Data are from Angers (1992). # Values were calculated by interpolation based on the data from Smithnell and Brandes (1976).
**Table 5.3 Comparison of calculated and experimental particle sizes**

<table>
<thead>
<tr>
<th>Powder size</th>
<th>Si-Bn Alloy*</th>
<th>AZ91 alloy#</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega = 12500$ rpm and $Q = 3.5 \times 10^{-6}$ m$^3$/s</td>
<td>$65.4 \mu$m</td>
<td>$97.2 \mu$m</td>
</tr>
<tr>
<td>$\omega = 20000$ rpm and $Q = 3.5 \times 10^{-6}$ m$^3$/s</td>
<td>$63.8 \mu$m</td>
<td>$66.7 \mu$m</td>
</tr>
<tr>
<td>$\omega = 20600$ rpm and $Q = 3.5 \times 10^{-6}$ m$^3$/s</td>
<td>$96.6 \mu$m</td>
<td>$97.7 \mu$m</td>
</tr>
</tbody>
</table>

*Data from Cherre and Accary (1990). # Data from Labrecque et al (1997).

In Table 5.3 it can be seen that the calculated particle sizes for the two alloys decrease with increasing disk speed and with decreasing melt flow rate. There is also reasonable agreement with the experimental data with the calculated values exceeding the measured ones by 20 to 25%.

### 5.5.3.2 Effects of atomizing parameters

Figures 5.13 and 5.14 show that the powder particle sizes decrease with increasing disk diameter and disk speed for a given disk diameter. Thus, it is expected that fine powders in the LF regime can be produced using large diameter disks rotating at high speeds.

The effect of melt flow rate on powder particle size in the LF regime is shown in Figure 5.15. It can be seen that a large melt flow rate results to coarse powder particles. Therefore, it is necessary to control the melt flow rate in order to obtain desirable powder particle sizes in the LF regime.
Figure 5.17 shows that particle size slightly decreases with increasing melt superheat.

5.6 Calculation of powder particle size in the film formation regime

5.6.1 Introduction

At high melt flow rates and high rotating speeds ligaments forming at the edge of the disk cannot disintegrate all the melt. As a result, a thin film of sheet forms at the edge of the disk and goes beyond the disk until a certain distance and then breaks up into ligaments. The ligaments in turn disintegrate into droplets. In this part of the thesis the sheet wave theory of Dombrowski and Johns (1963) is used to analyse the disintegration of melt beyond a rotating disk. The equation for the fastest growing wave number is derived. A combined model is proposed to calculate film extent and powder particle size. The predicted powder particle sizes are compared with experimental results. Effects of material properties and process parameters are also studied.

5.6.2 Mathematical formulation

5.6.2.1 Aerodynamic instability of a liquid sheet

When melt is directed on to the centre of a rotating disk, it spreads out and forms a thin film on the disk (see chapter 3). At high flow rates and high rotating speeds the film can extend beyond the disk to a certain distance, which is known as the film extent and then disintegrates in droplets which subsequently solidify in flight (see Figure 5.17).

Waves induced by disturbances on the film are responsible for the disintegration of the film/sheet (see chapter 2).

Let us assume that a small periodic disturbance is imposed on the sheet. The
amplitude of the wave is defined by

\[ a = a_0 \exp (\beta \tau) \]  \hspace{1cm} (5.22)

where \( a_0 \) and \( a \) are respectively the initial amplitude and amplitude at time \( \tau \) of the disturbance and \( \beta \) is its growth rate. If \( \beta < 0 \), the disturbance will decay with time and the system would be stable. When \( \beta > 0 \), the disturbance will grow and at a certain time it will reach a critical amplitude and break up into fragments. In this case the system would be unstable.

Weber (1931) and Fraser et al. (1962) showed that the ratio \( a/Va_0 \) of the amplitude at break-up to that of the initial disturbance is approximately a constant (i.e. \( \ln (a/Va_0) = 12 \)). Based on this finding, one can calculate the break-up time \( \tau^* \) and the film radial extent \( x_r^* \), once the growth rate \( \beta \) and radial velocity \( u_r \) of the sheet beyond the disk are known.

The break-up time can be calculated from equation (5.23)

\[ \tau^* = \frac{1}{\beta} \ln (a/a_0) \]  \hspace{1cm} (5.23)

and the film radial extent at break up is given by equation (5.24)

\[ x_r^* = \int_0^{\tau^*} u_r d\tau \]  \hspace{1cm} (5.24)

5.6.2.2 Growth rate and optimal wave number

Consider a two-dimensional thin sheet of melt of density \( \rho \), viscosity \( \mu \) and surface tension \( \sigma \) moving with a velocity \( v \) through a stationary gas of density \( \rho_{\text{gas}} \), see Figure 5.17. The growth rate of the disturbance is given by equation (5.25) (Dombrowski and Johns, 1963, see also Appendix II)
Chapter 5 _______________________________________Calculation of Powder Particle Size

\[ 2 \rho_{\text{gas}} K v^2 - 2 \sigma K^2 - \rho h \beta^2 - \mu h K^2 \beta = 0 \quad (5.25) \]

which has the solution

\[ \beta = \frac{-\mu h K^2 + \sqrt{\mu^2 h^2 K^4 - 4 \rho h (2 \sigma K^2 - 2 \rho_{\text{gas}} K v^2)}}{2 \rho h} \quad (5.26) \]

where \( h \) is the thickness of the sheet/film and \( K \) is the wave number.

The growth rate is a function of film thickness, film velocity and wave number and depends on the physical properties of melt and gas. When the properties of melt and gas and the film thickness are kept constant, the growth rate depends only on the wave number. At a certain wave number the growth rate reaches a maximum. At the optimal wave number the corresponding maximum growth rate results in break up of the melt film.

The optimal wave number and maximum growth rate can be found by differentiating the growth rate with respect to wave number and equating it to zero.

\[ \frac{d\beta}{dK} = 0 \quad (5.27) \]

The resultant equation for the optimal wave number \( K_{\text{opt}} \) is

\[ -\mu K_{\text{opt}} + \frac{\mu^2 h K_{\text{opt}}^3 - \rho (4 \sigma K_{\text{opt}}^2 - 2 \rho_{\text{gas}} v^2)}{\sqrt{\mu^2 h^2 K_{\text{opt}}^4 - 4 \rho h (2 \sigma K_{\text{opt}}^2 - 2 \rho_{\text{gas}} K_{\text{opt}} v^2)}} = 0 \quad (5.28) \]

Equation (5.28) can be solved numerically. The maximum growth rate \( \beta_{\text{max}} \) can be calculated by substituting \( K_{\text{opt}} \) into equation (5.26).
Since the thickness of the film changes with the extent of the film during atomization using a rotating disk, the optimal wave number and maximum growth rate will be different at different positions in the film. In order to calculate the break-up time, we define the mean maximum growth rate $\beta_m$ as

$$\beta_m = \frac{1}{\tau^*} \int_0^{\tau^*} \beta_{\text{max}} \, d\tau$$  \hspace{1cm} (5.29)$$

where $\tau^*$ is the break-up time at the edge of the extended film.

### 5.6.2.3 Film thickness during film extension

Assuming that the radial velocity of the film after the melt leaves the edge of the disk is $u_r$, the film thickness can be found by applying mass conservation and is given by equation (5.30)

$$h = \frac{Q}{\pi(d+2x_e)u_r}$$  \hspace{1cm} (5.30)$$

where $Q$ is the melt flow rate, $d$ is the disk diameter, $x_e$ is the radial position of the extended film from the edge of a disk and $u_r$ is the radial velocity of the extended film and can be calculated according to Fraser, Dombrowski and Routley (1963) from equation (5.31)

$$u_r = \frac{1}{(d+2x_e)} \sqrt{\frac{v^2(d+2x_e)^2 - d^2(v^2-u_m^2)^2}{d^2 u_m^2 + x_e d + x_e^2}}$$  \hspace{1cm} (5.31)$$

Substitution of equation (5.31) into equation (5.30) gives the film thickness as

$$h = \frac{Q}{2\pi v \sqrt{\left(\frac{d^2 u_m^2}{4v^2} + x_e d + x_e^2\right)}}$$  \hspace{1cm} (5.32)$$
where \( v \) and \( u_m \) are the velocity of the film and its radial component at the edge of a disk respectively and can be determined either according to the method outlined in chapter 3 or from equations (5.33) and (5.34) (Hinze and Milborn, 1950 and Halada et al, 1990).

\[ v = \sqrt{(\omega R)^2 + u_m^2} \]  
\[ u_m = \left( \frac{\rho \omega^2 Q^2}{12 \pi^2 \mu R} \right)^{\frac{1}{3}} \]

where \( \omega \) is the disk angular speed and \( R \) is the disk radius.

The film thickness at the edge of the disk is then given by

\[ h_0 = \left( \frac{3 \Omega \mu}{2 \pi \rho \omega^2 R^2} \right)^{\frac{1}{3}} \]

Because of the dependance of film thickness on position in the extended film and the complexity of equation (5.28), the iteration method was used to calculated numerically the optimal wave number and the maximum growth rate at different positions in the film and the film extent at break-up time.

5.6.2.4 Calculation of powder particle size

Fraser et al (1962) and Dombrowski and Hooper (1962) proposed a method to calculate the drop size from a fan-shaped spray nozzle. In their model the wave on the sheet continues to grow until the wave reaches the critical amplitude and the crests are blown out, thus breaking the sheet into fragments of half wavelength. The fragments of half wavelength rapidly contract into ligaments, which in turn break up into drops (Figure 5.18). Using this model and Weber's theory on the disintegration of a cylindrical jet, the drop size can be calculated.
The diameter of the ligaments from the fragments of half wavelength is given by
(Dombrowski and Hooper, 1962 and Dombrowski and Johns, 1963)

\[ d_l = \sqrt{\frac{4h^*}{K_{opt}^*}} \]  

(5.36)

where \( h^* \) and \( K_{opt}^* \) are the film thickness and the optimal wave number at the tip of
the film respectively and can be calculated from equations (5.32) and (5.28) respectively.

The drop size from break up of a ligament can be calculated from Weber's theory (1931)

\[ d_p = (3/2)^{1/3} (\lambda_{opt})^{1/3} d_l^{2/3} \]  

(5.37)

where \( \lambda_{opt} \) is the optimal wavelength of a wave on the ligament and is given by

\[ \lambda_{opt} = \sqrt{2\pi d_s} \left[ 1 + 3 \frac{\mu}{\sqrt{(\rho \sigma d_s)}} \right]^{1/2} \]  

(5.38)

The mean powder particle size can then be calculated using mass conservation and
is given by

\[ d_s = d_p \left( \frac{\rho}{\rho_s} \right)^{1/3} \]  

(5.39)

5.6.3 Solution method

The above model was used to calculate the powder particle sizes in the FF regime.
Chapter 5 Calculation of Powder Particle Size

A computer program has been written for the calculations. Figure 5.19 shows programme flow chart (see also figure 5.3). After checking the break up mode a film extent is assumed and used for initial calculation. Then, the calculated film extent is compared with the assumed value. When the difference between the two values is less than the preset error the iteration calculation ends and powder particles are calculated for further processing.

5.6.4 Results and discussion

The calculated and experimental film extents for aqueous millet jelly solutions at different operation conditions and powder particle sizes for different metals and alloys have been compared. After these tests, the model is used to study the effects of atomizing parameters on powder particle sizes.

5.6.4.1 Comparison of calculated and experimental film extents

The properties of aqueous millet jelly solutions are given in Table 5.4. The calculated and experimental film extents are compared in Tables 5.5 and 5.6 and also shown in Figures 5.20.

Table 5.4 Physical properties of aqueous millet jelly solutions
(Kamiya and Kayano, 1972)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Density (Kg/m³)</th>
<th>Surface tension (N/m)</th>
<th>Viscosity (Ns/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution 1</td>
<td>890</td>
<td>0.0364</td>
<td>0.134</td>
</tr>
<tr>
<td>Solution 2</td>
<td>1310</td>
<td>0.087</td>
<td>0.197</td>
</tr>
</tbody>
</table>

It can be seen from Tables 5.5 and 5.6 and Figures 5.20 that the calculated film
extents are in reasonable agreement with the experimental results.

Table 5.5 Comparison of calculated and experimental film extents as a function of disk speed for aqueous millet jelly solution 1

<table>
<thead>
<tr>
<th>film extent</th>
<th>$\omega = 2610$ rpm</th>
<th>$\omega = 3500$ rpm</th>
<th>$\omega = 4500$ rpm</th>
<th>$\omega = 5400$ rpm</th>
<th>$\omega = 6470$ rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculated</td>
<td>1.61 cm</td>
<td>1.01 cm</td>
<td>0.67 cm</td>
<td>0.50 cm</td>
<td>0.37 cm</td>
</tr>
<tr>
<td>exp. *</td>
<td>1.92 cm</td>
<td>1.49 cm</td>
<td>0.92 cm</td>
<td>0.75 cm</td>
<td>0.56 cm</td>
</tr>
</tbody>
</table>

*The experimental data are from Kamiya and Kayano (1972) and the experimental conditions are: disk diameter 6 cm, liquid flow rate $9.4 \times 10^{-6}$ m$^3$/s

Table 5.6 Comparison of calculated and experimental film extents as a function of disk speed for aqueous millet jelly solution 2

<table>
<thead>
<tr>
<th>film extent</th>
<th>$\omega = 2630$ rpm</th>
<th>$\omega = 3590$ rpm</th>
<th>$\omega = 4740$ rpm</th>
<th>$\omega = 5780$ rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculated</td>
<td>2.77 cm</td>
<td>1.71 cm</td>
<td>1.09 cm</td>
<td>0.78 cm</td>
</tr>
<tr>
<td>experimental</td>
<td>2.22 cm</td>
<td>1.68 cm</td>
<td>1.00 cm</td>
<td>0.65 cm</td>
</tr>
</tbody>
</table>

*The experimental data are from Kamiya and Kayano (1972) and the experimental conditions are: disk diameter 8 cm and liquid flow rate $25.3 \times 10^{-6}$ m$^3$/s

5.6.4.2 Comparison of calculated and experimental powder particle sizes

Values of the physical properties of the Bi-Sn alloy and Pb melt used in the
calculations are given in Table 5.7. The properties of Ti, Fe and Ni melts were given in Table 5.1.

Table 5.7 Values of physical properties of melts used in the calculations

<table>
<thead>
<tr>
<th>Property</th>
<th>Density* (Kg/m³)</th>
<th>Surface Tension* (N/m)</th>
<th>Viscosity* (m Ns/m²)</th>
<th>Density at 298 K (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-Sn Alloy</td>
<td>8560</td>
<td>0.38</td>
<td>1.82</td>
<td>8375</td>
</tr>
<tr>
<td>Pb</td>
<td>10678</td>
<td>0.468</td>
<td>2.65</td>
<td>11360</td>
</tr>
</tbody>
</table>

*Data for Bi-Sn alloy are from Angers (1992) and data for Pb are from Smithell and Brandes (1976). * at melting temperature.

Figure 5.21 compares the calculated mean powder particle sizes with the experimental results for Bi-Sn eutectic alloy atomized using a rotating disk of diameter 30 mm as a function of disk speed (experimental data are from Cherre and Accary, 1990). The general trend of the calculated powder particle sizes matches the experimental data well and shows that the wave theory can predict reasonably well the powder particle size produced in the FF regime by centrifugal atomisation using rotating disks.

Figure 5.22 compares the calculated and experimental mean particle sizes of Pb powder particles atomized by a rotating disk of diameter 32 mm as a function of melt flow rate with the pouring temperature as a parameter. The data in Figure 5.22 shows that: (i) For a given flow rate the predicted powder sizes are not sensitive to the melt pouring temperature (and therefore to the melt superheat). The powder particle size slightly decreases with increasing pouring temperature. The results showing the weak effect of melt superheat are in agreement with Unal's experimental results for the gas
Chapter 5 Calculation of Powder Particle Size

atomization of Al (see Table 5.8). (ii) For a given melt pouring temperature the predicted powder sizes increase with melt flow rate. Dogan and Saritas' (1994) experimental data at 973 K confirm the predicted trend while the experimental data at 673 K show that particle sizes slightly decrease with increasing melt flow rate. The data at 823 K show the powder particle size first increasing and then decreasing with flow rate. The effect of melt flow rate on powder particle sizes will be considered again in section 5.6.4.3. (iii) The predicted powder particle sizes are lower (by 50% or more in some cases) than the experimental powder sizes. Dogan and Saritas (1994) discussed that the oxidation of Pb had affected the final powder sizes as their atomization experiments were performed in air. Another reason why our model predicts finer powders than Dogan and Saritas' experiments is that in the latter the melt system was far away from the disk. During falling the melt would have lost heat to the surroundings and after it hit the disk, its temperature must have been lower than the pouring temperature. Some solidification on the disk was also reported. The above could result to coarser powder particles.

Table 5.8 Effect of pouring temperature on mean particle size and size spread in gas atomization (Unal, 1989)*

<table>
<thead>
<tr>
<th>Pouring temperature (K)</th>
<th>melt flow rate (Kg/min)</th>
<th>mean particle size (µm)</th>
<th>size spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>1048</td>
<td>0.516</td>
<td>24.83±4.16</td>
<td>2.06±0.06</td>
</tr>
<tr>
<td>1098</td>
<td>0.470</td>
<td>22.41±3.06</td>
<td>2.02±0.04</td>
</tr>
<tr>
<td>1168</td>
<td>0.54</td>
<td>21.89±3.84</td>
<td>1.93±0.05</td>
</tr>
<tr>
<td>1198</td>
<td>0.527</td>
<td>22.16±3.09</td>
<td>1.95±0.04</td>
</tr>
</tbody>
</table>

*Experimental condition: N₂ gas pressure 1.56 MPa, N₂ gas flow rate 3.41 Kg/min and Al melt flow rate 0.5 Kg/min.
Figure 5.23 shows the relationship between the disk speed and optimal wave number at the edge of a Bi-Sn eutectic alloy sheet atomized by a rotating disk of diameter 0.03 m in 5%H₂-Ar atmosphere. The optimal wave number increases with disk speed.

### 5.6.4.3 Effects of atomizing parameters

Figure 5.24 shows the effects of disk peripheral velocity (the product of disk radius and rotating speed) on the film extent and powder particle size. The film extent and powder particle size increase with decreasing disk peripheral velocity. Fine powders can be produced by increasing the disk peripheral velocity. For a given disk peripheral speed the film extent for Ti is predicted to be shorter than for Ni or Fe, and finer powder could be produced for Ni rather than for Ti.

#### Table 5.9 The effect of melt mass flow rate on particle size in gas atomization (Unal, 1987)

<table>
<thead>
<tr>
<th>Pure Al melt</th>
<th>$Q_{gas}=3.41$ Kg/min</th>
<th>Pure Al melt</th>
<th>$Q_{gas}=4.68$ Kg/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{x2}=1.56$ MPa</td>
<td>$T_p=1148$ K</td>
<td>$P_{x2}=2.10$ MPa</td>
<td>$T_p=1148$ K</td>
</tr>
<tr>
<td>melt flow rate (Kg/min)</td>
<td>particle size $d_{50}$ (μm)</td>
<td>melt flow rate (Kg/min)</td>
<td>particle size $d_{50}$ (μm)</td>
</tr>
<tr>
<td>0.378</td>
<td>22.42</td>
<td>0.545</td>
<td>27.07</td>
</tr>
<tr>
<td>0.54</td>
<td>21.89</td>
<td>0.703</td>
<td>26.17</td>
</tr>
<tr>
<td>0.69</td>
<td>25.46</td>
<td>0.92</td>
<td>26.28</td>
</tr>
<tr>
<td>0.982</td>
<td>28.42</td>
<td>1.09</td>
<td>29.13</td>
</tr>
<tr>
<td>1.205</td>
<td>30.97</td>
<td>1.214</td>
<td>26.85</td>
</tr>
<tr>
<td>1.421</td>
<td>31.86</td>
<td>1.607</td>
<td>30.86</td>
</tr>
</tbody>
</table>
Chapter 5 — Calculation of Powder Particle Size

Figure 5.25 shows the effect of melt flow rate on particle size. With increasing melt flow rate, the trend for the powder particle size is to increase. This trend is in agreement with experimental data on gas atomized Al, shown in Table 5.9.

5.7 Effect of breakup parameter \( \ln \left( \frac{a^*/a_0}{a} \right) \) on calculated results

One important assumption in our calculations is that melts will break up when the ratio of the amplitude of waves to the initial amplitude reaches 12 (see the work by Weber (1931), by Dombrowski and Hooper (1962) and by Fraser et al (1962)).

Figures 5.26 and 5.27 show the dependence of the calculated powder particle sizes on the parameter \( \ln \left( \frac{a^*/a_0}{a} \right) \). It can be seen that in the DDF regime a larger particle size is predicted (Figure 5.26), since a larger value of the break-up parameter indicates a longer breakup time in DDF. In the FF regime a larger breakup parameter implies that the film will travel a longer distance before it breaks up. Far away from the disk the film will become thinner. This leads to smaller powder particles (Figure 5.27). The powder particle sizes is more sensitive to \( \ln \left( \frac{a^*/a_0}{a} \right) \) in the DDF regime rather than in the FF regime.

5.8 Conclusions

The disintegration of melts at the edge of rotating disks and beyond rotating disks has been analysed using wave theories. The equations for the fastest growing wave number have been derived and solved numerically. Models have been proposed to calculate the powder particle sizes in different regimes. The calculated optimal wave number, film extent and powder particle sizes have been compared with available experimental data. It has been shown that wave theories can predict powder particle sizes in centrifugal atomization using a rotating disk with reasonable accuracy. The calculated results show that fine powder particles can be produced by increasing the disk diameter and/or disk speed provided that the melt does not solidify on the disk. The powder particle sizes are also controlled by melt superheat and melt flow rate. Lower melt superheats lead to slightly larger powder particle sizes. Large melt flow
rates also give coarse powder particles.
Figure 5.1 Schematic diagram of wave induced by disturbances at the edge of a rotating disk

Figure 5.2 A typical relationship between the wave number and relative growth rate of disturbance for SAE 1090 steel for \( \omega = 15000 \) rpm and \( D = 0.1 \) m
START

INPUT D, \omega, \sigma, \rho, \rho_2, \mu, Q, \varepsilon_k

Calculate Re, We, Q_1, Q_2

DDF regime?

Yes

Wave analysis

Calculate optimal wave number K_{opt} using numerical method

Calculate breakup time \tau^*

Calculate mean drop size d_j

Calculate mean particle size d_i

PRINT results

END

Figure 5.3 Programme flow chart
Figure 5.4 Solidified ends of anodes showing the formation of wave at the edge of rotating disks in the DDF regime for SAE 1090 Steel. (photos are from Champagne and Angers 1980 and 1984)

Figure 5.5 Comparison of the calculated and observed wave numbers for SAE 1090 steel atomized by REP. (observed data are from Champagne and Angers 1980 and 1984)
Figure 5.6a Comparison of the calculated and measured mean particle sizes for 2024 Al alloy atomized using an inverted rotating disk of diameter 50 mm (△—wave theory, ■—calculated according to Champagne et al, equation (5.15), ♦—data from Angers et al, 1994)

Figure 5.6b Comparison of the calculated and measured mean particle sizes for 2024 Al alloy atomized using an inverted rotating disk of diameter 75 mm (△—wave theory, ■—calculated according to Champagne et al, equation (5.15), ♦—data from Angers et al, 1994)
Figure 5.7a The effect of disk diameter on the relative growth rate of disturbance for SAE 1090 steel for \( \omega = 15000 \text{ rpm} \)

Figure 5.7b The effect of disk diameter on the optimal wave number for SAE 1090 steel for \( Q = 2.35 \times 10^{-6} \text{ m}^3/\text{s} \) and \( \omega = 15000 \text{ rpm} \)
Figure 5.7c The effect of disk diameter on mean particle size for SAE 1090 steel for $Q=2.35 \times 10^{-4} \text{ m}^3/\text{s}$ and $\omega=15000 \text{ rpm}$

Figure 5.8a The effect of disk rotating speed on the relative growth rate of disturbance for SAE 1090 steel for $D=0.1 \text{ m}$
Figure 5.8b The effect of disk rotating speed on the optimal wave number for SAE 1090 steel for $D=0.1\text{m}$ and $Q=2.35 \times 10^{-6}\text{ m}^3/\text{s}$

Figure 5.8c The effect of disk rotating speed on the mean particle size for SAE 1090 steel for $D=0.1\text{m}$ and $Q=2.35 \times 10^{-6}\text{ m}^3/\text{s}$
Figure 5.9a Optimal wave numbers for Ti and Fe at different disk rotating speeds for $D=0.1$ m and $Q=2.35 \times 10^{-5}$ m$^3$/s

Figure 5.9b Mean particle size of Ti and Fe as a function of disk rotating speed for $D=0.1$ m and $Q=2.35 \times 10^{-5}$ m$^3$/s (data for Fe, $\times$--Champagne et al, equation (5.15), $\Delta$--wave theory; data for Ti, $\blacksquare$--Champagne et al, equation (5.15), $\blacklozenge$--wave theory)
Figure 5.10 The solidified layer on the surface of a rotating disk showing the formation of ligaments at the edge of the disk (experimental condition: disk diameter 5 cm, melt flow rate $5.1 \times 10^{-6}$ m$^3$/s and disk speed 60,000 rpm. After Labrecque et al, 1997)

Figure 5.11 Schematic diagram of ligaments forming at the edge of a rotating disk
Calculate ligament number $m_l$ using numerical method

Calculate average radial velocity $u_m$

Calculate diameter of ligaments $d_l$

Calculate mean drop size $d_p$

Calculate mean particle size $d_s$

PRINT results

END

Figure 5.12 Programme flow chart (also see Figure 5.3)
Figure 5.13 The effect of disk diameter on the mean particle size of Ni for $Q=1.5\times10^5$ m$^3$/s and $\omega=15000$ rpm

Figure 5.14 The effect of disk speed on the mean particle size of Ti, Fe and Ni melts for $D=0.1$ m and $Q=1.5\times10^5$ m$^3$/s (●—Ti melt, ▲—Fe melt and ◆—Ni melt)
Figure 5.15 The effect of melt flow rate on the mean particle size of Ni for D=0.1 m and ω=15000 rpm

Figure 5.16 The effect of melt superheat on mean particle size of Ni for D=0.1 m, ω=15000 rpm and Q=1.5×10^{-5} m^3/s
Figure 5.17 Schematic illustration showing the formation of film/sheet on and beyond a rotating disk.

Figure 5.18 The break-up of a liquid sheet into droplets by sinuous wave (after Dombrowski and Hooper, 1962)
START

INPUT D, ω, α, β, ρ, ρgas, μ, μgas, Q, S0, ε

Calculate Re, We, Q₁*, Q₂*

FF regime?

Yes

Calculate u₀, v, h₀ at the edge of a disk

Evaluate radial film extent x₁*

Calculate the u₀, h at different positions of the film

Calculate n_{opt} and β_{max} using numerical method

Calculate mean maximum growth rate β_{m}

Calculate break up time τ*

Calculate the film extent x_{e}*

| Δx_{e} | < ε

Yes

Calculate K_{opt}, h*, β_{max}*

Calculate d₀, λ_{opt}, d_p

Calculate mean particle size d_{a}

PRINT results

END

Figure 5.19 Programme flow chart
a) film extent of aqueous millet jelly solution 1 for $Q=9.4\times10^{-6}$ m$^3$/s and $D=0.06$ m.

b) film extent of aqueous millet jelly solution 2 for $Q=25.3\times10^{-6}$ m$^3$/s and $D=0.08$ m.

Figure 5.20 Comparison of the calculated and experimental film extents for aqueous solution of millet jelly at different conditions (experimental data are shown in ▲ and are from Kamiya and Kayano 1972)
Figure 5.21 Comparison of the calculated and experimental powder particle sizes of Bi-Sn eutectic alloy atomized by a rotating disk of diameter 0.03m (experimental data are shown in ▲ and are from Cherre and Accary, 1990)

Figure 5.22 Comparison of the calculated and experimental powder particle sizes of Pb atomized by a disk of diameter 0.032m rotating at speed of 24000 rpm (experimental data are shown in □; Tp=700°C, ■; Tp=550°C, ×; Tp=400°C, ● and are from Dogan and Saritas, 1994)
Figure 5.23 A typical relationship between the disk rotating speed and optimal wave number for break up of Bi-Sn alloy at $Q=3.5 \times 10^5 \text{ m}^3/\text{s}$ and $D=0.03 \text{ m}$

a) film extent
b) mean particle size

Figure 5.24 The effect of disk peripheral velocity on film extent and mean particle size for different melts for $Q=5\times10^{-5}$ m$^3$/s. a) film extent and b) mean particle size.

Figure 5.25 The effect of melt flow rate on the mean particle size for different melts at $v_r = 78.5$ m/s.
Figure 5.26 The effect of break-up parameter on the calculated particle size of Al melt for \( D=0.1 \text{m} \) and \( Q=1 \times 10^6 \text{m}^3/\text{s} \) in the DDF regime (●--\( \ln (a/a_0)=10 \), ▲--\( \ln (a/a_0)=12 \), ×--\( \ln (a/a_0)=14 \) and ■--calculated according to equation (5.15))

Figure 5.27 The effect of break-up parameter on the calculated particle size of Al melt in the FF regime for \( D=0.1 \text{m} \) and \( Q=5 \times 10^5 \text{m}^3/\text{s} \) (●--\( \ln (a/a_0)=10 \), ▲--\( \ln (a/a_0)=12 \) and ●--\( \ln (a/a_0)=14 \))
Chapter 6
Droplet dynamics and solidification

6.1 Introduction

As discussed in the previous chapter, when the melt comes to the edge of a rotating disk, it breaks up into droplets. These droplets are thrown away from the disk due to the action of centrifugal and inertial forces and fly in the surrounding gas. During flight the droplets lose their kinetic energy by friction with surrounding gas. At the same time they lose their heat to the surroundings by convection and radiation. The velocity and temperature of the droplets decrease with increasing flight time/distance. When the temperature of the droplets falls below the melting point (for pure metals) or the liquidus temperature (for alloys) solidification commences. Generally, in the atomization of melts the droplets are expected to undercool. Undercooling is desirable for the development of advanced materials since solidification under high solid/liquid front velocities can lead to extended solubilities in the alloy, refined microstructures and the formation of metastable phases. From the point of atomizer design, solidification time of droplets is important as it determines the diameter of the atomization chamber. Thus it is necessary to understand how the atomizing conditions affect the solidification history of the droplets. In this chapter the thermal history of droplets during flight is modelled. Some guidelines for the design of the atomization chamber are also provided.

The solidification of droplets during flight involves droplet dynamics, heat transfer, solidification and evolution of microstructures. Bewlay and Cantor (1990), Grant and Cantor (1991) and Antipas et al (1993) measured the decay of axial gas velocity in gas atomization, which was also calculated using simple jet models. Application of computational fluid dynamics (CFD) software provides a more
powerful tool to study gas flow in atomization chambers (Fritsching et al, 1991 and Mi et al, 1996). Lavernia et al (1988) analyzed heat transfer of droplets in atomization and liquid dynamic compaction (LDC) and showed that the temperature difference inside a droplet is small and can be neglected. Hirth (1978) showed how nucleation theory would be applied to determine undercooling conditions in rapidly solidified powders. Clyne (1984) addressed the general numerical treatment in rapid solidification processing. Levi and Mehrabian (1982, 1988) studied the solidification of undercooled droplets. Tsakiropoulos and co-workers (Saunders and Tsakiropoulos 1988, Pan et al 1989 and Shao and Tsakaropoulos 1994) initiated the study of phase selection in rapid solidification. Perepezko (1986) and Libera et al (1987) noted the importance of nucleation site and number in heterogeneous nucleation. For very fine droplets transient nucleation could also play a role in controlling the microstructures of the solidified powders. Shao and Tsakiropoulos (1994) developed a model to calculate the incubation time in transient nucleation. Recently, further models (Grant et al, 1993, 1995, Liu et al, 1995 and Li et al, 1996) have been applied to analyze the droplet dynamics and solidification in gas atomization. In all these work droplet size was either preset or calculated according to empirical equation/s. To my knowledge there is no literature which deals with the modelling of the solidification processes in centrifugal atomization to date. The coupling of calculations of particle size with droplet solidification models is seldom seen.

6.2 Mathematical formulation

6.2.1 Droplet dynamics

When droplets form at the edge of a rotating disk they fly off the disk due to the centrifugal and inertial forces. During flight droplets transfer their momentum and heat to the surrounding gas. The velocity and temperature of droplets decrease. Figure 6.1 illustrates schematically the formation and flight of a droplet at the edge of a rotating disk with the variation of the velocity and temperature with flight distance.
The movement of droplets during flight can be described by Newton's second law

\[ F = m \frac{du_p}{dt} \]  

(6.1)

where \( F \) is the force acting on a droplet, \( m \) is the mass of the droplet, \( u_p \) is the velocity of the droplet and \( t \) is the flight time. In centrifugal atomization using a horizontally rotating disk the centrifugal force is much higher than the gravity and buoyant forces. In order to simplify the calculations, only the flight in the plane defined by the disk surface will be considered.

The force acting on the droplet after it leaves the disk is the drag force. Assuming that the droplet is spherical and that there is no deformation and no interaction between the droplets, the drag force can be described by

\[ F = \frac{1}{2} C_d \rho_g \left| u_p - u_g \right| \left( u_p - u_g \right) \]  

(6.2)

where \( C_d \) is the drag force coefficient which can be evaluated according to Clift et al. (1978)

\[ C_d = 0.28 + \frac{6}{Re_d^{0.8}} + \frac{21}{Re_d} \]  

(6.3)

when

\[ 0.1 < Re_d < 4000 \]

In equations (6.2) and (6.3) \( A \) is the projected area of the droplet, \( A = \pi d_p^2 \), \( Re_d \) is the Reynolds number of the droplet, \( Re_d = \rho_g d_p \left| u_p - u_g \right| / \mu \), where \( \mu \), \( \rho \) and \( u \) are the viscosity, density and velocity of the gas respectively, \( d_p \) is the droplet size, which can be calculated from the models described in chapter 5. Since the movement
of droplets and the associated heat transfer phenomena in the LF and FF regimes are complicated, only droplets produced in the DDF regime have been studied in this chapter. All the calculations are based on single sized particles since at present we are not able to predict the particle size distribution.

Substitution of equation (6.2) into equation (6.1) gives

$$\frac{\pi \rho d_p^3}{6} \frac{du_p}{dt} = -\frac{1}{2} C_d \rho \pi d_p |u_p - u_\theta| (u_p - u_\theta)$$  \hspace{1cm} (6.4)

Rearrangement of equation (6.4) gives

$$\frac{du_p}{dt} = -\frac{3}{4} \left[ 0.28 u_p^2 + 6 \left( -\frac{\mu_g}{\rho g d_p} \right)^{0.5} \frac{u_p^{1.5} + 21 \frac{\mu_g}{\rho g d_p} u_p}{\rho d_p} \right]$$  \hspace{1cm} (6.5)

Initial condition is

$$u_p |_{t=0} = u_{po}$$  \hspace{1cm} (5.6)

where $u_{po}$ is the velocity of droplets at the edge of the disk and can be calculated according to the following equations (see chapter 5)

$$u_{po} = \sqrt{v_t^2 + u_m^2}$$  \hspace{1cm} (6.7)

where $v_t$ and $u_m$ are the tangential and mean radial velocity of droplets at the edge of a disk which can be calculated from (see chapter 5)

$$u_m = \left( \frac{\rho \omega^2 Q^2}{12 \pi R \mu} \right)^{\frac{1}{3}}$$  \hspace{1cm} (6.8)

$$v_t = \omega R$$  \hspace{1cm} (6.9)
The above equations describe the motion of the droplets in flight.

After calculating the velocity of the droplets, the flight distance of the droplets can be calculated from

\[ l_s = \int_0^t u_p \, dt \]  \hspace{1cm} (6.10)

where \( l_s \) is the flight distance from the edge of the disk and \( t \) is the flight time.

### 6.2.2 Thermal histories and solidification of the droplets

During flight the droplets lose their heat to the surroundings by convection and radiation. The droplets experience different thermal histories. In order to simplify the analysis only the solidification of a pure metal droplet will be modelled. Figure 6.2 shows schematically the thermal history of a centrifugally atomized pure metal droplet. Typically, a droplet will pass through four regions: (i) cooling in the liquid state; (ii) recalescence; (iii) heat transfer controlled solidification and (iv) cooling in the solid state. In general the droplet should have certain amount of superheat which is required to prevent premature freezing. The temperature of the droplet is higher than the melting point \( T_m \) just after it leaves the disk. Travelling through the gas, the droplet cools by losing its heat to the surroundings. The droplet temperature decreases until it reaches the nucleation temperature \( T_n \). In this region the droplet is still liquid. The heat loss to the surroundings is balanced by the decrease of the droplet's thermal enthalpy. Once nuclei have formed in the droplet the solidification process takes place very fast. The heat released by solidification is much higher than the heat extracted by the surroundings so that droplet temperature rises again. This phenomenon is called recalescence. In this region the droplet is in mushy state (mixture of liquid and solid). With solidification advancing the solidification front velocity decreases until a certain temperature is reached at which heat released by solidification is just balanced by the heat loss. The droplet temperature does not rise...
any further (the temperature is called the arrest temperature $T_a$) and solidification continues until the whole droplet becomes solid. In this region solidification is controlled by heat transfer from the droplet to the surroundings and is called the heat transfer controlled solidification region. After the droplet has solidified, it experiences cooling in the solid state.

6.2.2.1 Droplet heat transfer

In the whole solidification process, the heat transfer from the droplet to the surroundings is accomplished by convection and radiation. The heat loss can be calculated from

$$Q_{rc} = h_c A (T_p - T_g) + \varepsilon \sigma a A (T_p^4 - T_g^4)$$

(6.11)

where $A$ is the surface of the droplet, $A = \pi d_p^2$, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon_a$ is the emissivity of the droplet, $T_p$ is the temperature of the droplet, $T_g$ is the temperature of the surrounding gas and $h_c$ is the heat transfer coefficient between the droplet and the gas. The latter can be calculated from Ranz and Marshall (1952)

$$N_{ud} = 2 + 0.6 \text{Re}_{ud}^{0.5} \text{Pr}^{0.33}_{gas}$$

(6.12)

where $N_{ud}$ is the droplet Nusselt number, $N_{ud} = h_c d_p / \kappa_g$, $\text{Pr}_{gas}$ is the gas Prandtl number, $\text{Pr}_{gas} = \mu C_p / k_g$ and $C_p$, $k_g$ and $\mu$ are the specific heat, thermal conductivity and viscosity, respectively.

Table 6.1 The physical properties of $N_2$ gas at 300 K (Eckert and Drake, 1972)

<table>
<thead>
<tr>
<th>Property</th>
<th>$N_2$ gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.1421 Kg/m$^3$</td>
</tr>
<tr>
<td>Viscosity</td>
<td>$1.784 \times 10^{-3}$ Ns/m$^2$</td>
</tr>
<tr>
<td>Specific heat</td>
<td>1041 J/Kg K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.0262 W/mK</td>
</tr>
</tbody>
</table>
and viscosity of the gas respectively. In this study it is assumed that N₂ gas is filled in the atomization chamber. The effect of other gases on droplet dynamics and solidification will be studied in section 6.4.6. The physical properties of N₂ gas are given in Table 6.1.

6.2.2.2 Droplet thermal histories

[1] Cooling in the liquid state

When the droplet is fully liquid, it loses its heat to the surroundings by convection and radiation. At the same time the enthalpy of the droplet decreases. The cooling is described by

\[ Q_h = Q_{ic} \]  

(6.13)

where \( Q_h \) is the change of droplet enthalpy, which is given by

\[ Q_h = \frac{\pi}{6} d_p^3 \rho \cdot C_{pl} \Delta T \]  

(6.14)

where \( C_{pl} \) is the specific heat of the liquid droplet and \( \Delta T \) is the temperature difference. Substitution of equation (6.11) and equation (6.14) into equation (6.13) gives

\[ \frac{dT_p}{dt} = -6 \left[ h_p (T_p - T_g) + \sigma \varepsilon (T_p^4 - T_g^4) \right] \frac{1}{\rho C_{pl} d_p^2} \]  

(6.15)

The above equation describes the droplet temperature change in region (i).

[2] Nucleation temperature and recalescence
The droplet undercools below the melting temperature \( T_m \). Because of the size of the powder particles produced in centrifugal atomization (see chapter 5), transient nucleation phenomena can be ignored. A number of expressions have been proposed for the steady state nucleation rate as a function of melt undercooling (Turnbull, 1950, Levi and Mehrabian, 1982 and Clyne, 1984). Basically, there are two types of steady state nucleation: homogeneous and heterogeneous nucleation. Heterogeneous nucleation is a very complicated process. At present it is difficult to describe mathematically the effect of nucleation site and number. In modelling solidification of the droplets produced by atomization using rotating disk method only the effect of the wetting angle is taken into account. In order to model both homogeneous and heterogeneous nucleation, Clyne's expression for the frequency of heterogeneous nucleation has been adopted:

\[
\mathcal{J} = \frac{k_b T}{V_m^2 \pi h_p} \exp \left( \frac{-\Delta G_{am}}{k_b T} \right) \exp \left( \frac{-\Delta G_c}{k_b T} \right)
\]

where \( k_b \) and \( h_p \) are the Boltzmann's and Planck's constants respectively, \( V_m \) is the molecular volume, \( \Delta G_{am} \) is the activation energy for molecular migration in the melt and \( \Delta G_c \) is the critical free energy barrier for the formation of the nuclei, which is given by

\[
\Delta G_c = \frac{16 \pi \gamma^2 \eta T^2}{3 \Delta H_f \Delta T^2} \frac{1}{4} (1 - \cos \theta)^3 (2 + \cos \theta)
\]

where \( \gamma \) is the solid/liquid interface energy, \( T_m \) is the melting temperature, \( \theta \) is the solid/liquid/nucleant contact angle or wetting angle, \( \Delta H_f \) is the latent heat of fusion and \( \Delta T \) is the undercooling of the droplet, \( \Delta T = T_m - T \). The first exponential term in equation (6.16) expresses the ease with which atoms may diffuse through the melt to the nucleus, and may be approximated to a value of \( 10^2 \) for liquid metals (Grant, Cantor and Katgerman, 1993). The \( f(\theta) = 1/4 \) in equation (6.17)
Chapter 6  
Droplet Dynamics and Solidification

represents the catalytic efficiency for heterogeneous nucleation.

A single nucleation event is assumed to signify the start of solidification at the nucleation temperature $T_n$. In a continuous cooling process, the nucleation temperature can be defined as (Hirth, 1978)

$$ v \int_0^{T_n} J(t) \, dt = v \int_0^{T_n} \frac{J(T)}{T^'} \, dT' = 1 \quad (6.18) $$

where $v$ is the volume of the droplet, $v = \pi/6 \, d_r^3$, $t_n$ is the flight time when the droplet temperature reaches the nucleation temperature, $T'$ is the cooling rate, $T' = dT/dt$ and $J(t)$ and $J(T)$ are the nucleation rates as a function of flight time and droplet temperature respectively. This expression is integrated numerically by summing instantaneous values of $J$ over successive time increments. At the same time the droplet temperature is calculated. When the integration is equal to unity the temperature is equated to the nucleation temperature $T_n$. Numerical interpolation method was used to calculate $T_n$ (see Figure 6.3).

Once a nucleus forms in the droplet, solidification occurs very fast and the heat released during solidification exceeds the heat extracted by the surrounding gas. The droplet experiences a fast raise of temperature. The solidification rate (or solidification front velocity) in continuous growth can be related to the undercooling by (Clyne, 1984)

$$ u = \frac{D_l}{d_m} \left[ 1 - \exp \left( \frac{-\Delta H^* v_m \Delta T}{k_B T_m^*} \right) \right] \quad (6.19) $$

where $d_m$ is the effective molecular diameter and taken as a molecular jump distance and $D_l$ is the melt diffusivity. Access to the variation of melt diffusivity with undercooling is difficult. The following expression was used (Clyne, 1984)
\[ D_j = D_0 \exp \left( -\frac{\Delta G_{sm}}{k_b T} \right) \]  

(6.20)

where \( D_0 \) is the diffusive constant.

When undercooling is small the growth velocity can be approximated by

\[ u = \frac{D_j \Delta H_f \nu_m \Delta T}{d_m k_b T_m^2} = k \Delta T \]  

(6.21)

For the solidification of a droplet the growth velocity can be related to solidification fraction by

\[ \frac{df}{dt} = 6 \frac{u}{d_p} \]  

(6.22)

where \( f \) is the solidification fraction, \( u \) is the solidification front velocity. In this thesis equations (6.19) and (6.20) are used to calculate the solidification front velocity.

In the recalescence region the droplet is a mixture of liquid and solid phases. The temperature of the droplet can be described by

\[ \frac{dT_p}{dt} = \frac{\Delta H_f}{C_{pl_s} d_p} \frac{df}{dt} \left[ \frac{d_f}{dt} \left( T_p - T_g \right) + \alpha \varepsilon \left( T_p^4 - T_g^4 \right) \right] \]  

(6.23)

where \( C_{pl_s} \) is the specific heat of the mushy droplet, given by

\[ C_{pl_s} = C_{pl} (1 - f) + C_{ps} f \]  

(6.24)


With recalescence accompanying and solidification front advancing the undercooling
becomes smaller and smaller. At some temperature the heat released by solidification is just balanced by the heat extracted by the surrounding gas and the droplet temperature does not rise any further. The solidification then enters the heat transfer controlled region and remains in this region until the whole droplet becomes solid.

[4] Solid state cooling

After solidification is completed the droplet temperature decreases again since the droplet has to reduce its thermal enthalpy to compensate for the heat loss. The temperature of the droplet in this region can be described by

\[ \frac{dT_p}{dt} = -\frac{6 [h_c(T_p - T_g) + \sigma e_m(T_p^4 - T^4)]}{\rho c_{ps} \alpha} \]  \hspace{1cm} (6.25)

where \( c_{ps} \) is the specific heat of the solid droplet.

Equations (6.11) to (6.25) describe the change of the temperature of a droplet during flight.

6.3 Solution method

Equations (6.1) to (6.25) describe the movement, thermal histories and solidification process of a droplet from a rotating disk. Since they are coupled and are non-linear, the Runge-Kutta method (Korn and Korn, 1968) was used to solve them. Figure 6.3 shows the programme flow chart. First all the data which are required for the modelling work are input to a computer, then the particle size programme is called to calculate the particle size. After obtaining the particle size, the velocity and temperature of the droplet are calculated from equations (6.5) and (6.6) and equations (6.15) to (6.25) respectively and are printed out for further processing. The input data include: 1) thermophysical properties of the material to
be atomized and of the gas, such as specific heat, density and viscosity, etc; 2) disk
design and operating parameters, for example disk diameter, disk speed, melt flow
rate and superheat, etc; and 3) process control parameter, such as time step,
calculation error precision and print interval, etc. All the calculations were completed
on a PC computer.

6.4 Results and discussion

The solidification of nickel and aluminium pure metals has been modelled. The
thermophysical properties of Ni and Al melts are given in Table 6.2. The properties
of N₂ gas are shown in Table 6.1 and the basic design and operating parameters are
given in Table 6.3. The dynamics and solidification of a single droplet are first
modelled, then the effects of material, design and operating conditions are studied.
Comparisons of the effects of homogeneous and heterogeneous nucleation on
solidification are also made.

6.4.1 Basic solidification process

The calculations have shown that for the conditions given in Table 6.3 melts break
up in the direct droplet formation regime. The mean particle size of the resultant
nickel droplets is about 100 microns. Some other parameters are summarized in Table
6.4.

Figures 6.4 shows the velocity, temperature, cooling rate and solidification fraction
of a nickel droplet during flight. It can be seen that with increasing flight time the
droplet velocity decreases because of the interaction of the droplet with the gas
(Figure 6.4a). The droplet experiences a large undercooling \( \Delta T/T_m \) (Figure 6.4b),
which is about 0.2 (see Table 6.4). After nucleation the droplet temperature fast
recalesces to near the melting point and remains there until the whole droplet is
solidified. Then the droplet cools further in the solid state. Compared with
equilibrium solidification (Figure 6.4b) the undercooled solidification lasts longer.


Table 6.2 Thermophysical properties of pure nickel and aluminium
(Smithnell and Brades, 1976 and Clyne, 1984)

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Nickel</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>Kg/m³</td>
<td>$\rho = 7905 - 1.16 \times (T - T_m)$</td>
<td>$\rho = 2385 - 0.28 \times (T - T_m)$</td>
</tr>
<tr>
<td>surface tension</td>
<td>N/m</td>
<td>$\sigma = 1.778 - 3.8 \times 10^4 \times (T - T_m)$</td>
<td>$\sigma = 0.914 - 3.5 \times 10^4 \times (T - T_m)$</td>
</tr>
<tr>
<td>viscosity</td>
<td>Ns/m²</td>
<td>$\mu = 1.663 \times \exp\left(\frac{50200}{RT}\right)$</td>
<td>$\mu = 0.1492 \times \exp\left(\frac{16500}{RT}\right)$</td>
</tr>
<tr>
<td>$T_m$</td>
<td>K</td>
<td>1728</td>
<td>933</td>
</tr>
<tr>
<td>$V_m$</td>
<td>m³/molecule</td>
<td>$1.15 \times 10^{-29}$</td>
<td>$1.8 \times 10^{-29}$</td>
</tr>
<tr>
<td>$\Delta G_m$</td>
<td>J/molecule</td>
<td>$9.15 \times 10^{-29}$</td>
<td>$4.15 \times 10^{-29}$</td>
</tr>
<tr>
<td>$\Delta H_f$</td>
<td>J/m³</td>
<td>$2.6 \times 10^9$</td>
<td>$9.75 \times 10^8$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>J/m²</td>
<td>0.255</td>
<td>0.12</td>
</tr>
<tr>
<td>$d_m$</td>
<td>m</td>
<td>$2.3 \times 10^{-10}$</td>
<td>$2.6 \times 10^{-10}$</td>
</tr>
<tr>
<td>$D_0$</td>
<td>m²/s</td>
<td>$1.8 \times 10^{-7}$</td>
<td>$2.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>$C_p_l$</td>
<td>J/m³K</td>
<td>$5.4 \times 10^6$</td>
<td>$2.85 \times 10^6$</td>
</tr>
<tr>
<td>$C_p_m$</td>
<td>J/m³K</td>
<td>$5.3 \times 10^5$</td>
<td>$2.8 \times 10^5$</td>
</tr>
</tbody>
</table>

Thus the undercooled droplet could have travelled a longer distance before it was fully solidified (see Table 6.4). This in turn would require a larger diameter of the atomization chamber in order to prevent the splatting of the droplet due to the impact on the vessel wall. The cooling rate is not constant during the flight period. In the undercooled region the cooling rate decreases slightly with decreasing droplet temperature or flight time owing to the effect of radiation heat transfer and the temperature dependence of the convection heat transfer coefficient. The cooling rate in this region is about $10^4$K/s for the conditions shown in Table 6.3. In the recalescence region the droplet temperature rises up very quickly, and the cooling rate has a negative value (Figure 6.4c).
Table 6.3 Basic design and operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>disk diameter</td>
<td>0.1</td>
<td>m</td>
</tr>
<tr>
<td>disk speed</td>
<td>15000</td>
<td>rpm</td>
</tr>
<tr>
<td>droplet superheat</td>
<td>50</td>
<td>K</td>
</tr>
<tr>
<td>melt flow rate</td>
<td>2.35×10⁻⁶</td>
<td>m³/s</td>
</tr>
</tbody>
</table>

Table 6.4 Some important atomizing and solidification parameters for Ni

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>particle size d_p</td>
<td>107.9</td>
<td>μm</td>
</tr>
<tr>
<td>T_a</td>
<td>1110</td>
<td>°C</td>
</tr>
<tr>
<td>arrest temperature T_a</td>
<td>1453.75</td>
<td>°C</td>
</tr>
<tr>
<td>undercooling ΔT/T_m</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>flight distance L_s at T_m</td>
<td>0.0766</td>
<td>m</td>
</tr>
<tr>
<td>flight distance L_s at T_n</td>
<td>0.632</td>
<td>m</td>
</tr>
<tr>
<td>flight distance L_s at f=1</td>
<td>0.739</td>
<td>m</td>
</tr>
<tr>
<td>without undercooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>flight distance L_s at f=1</td>
<td>0.804</td>
<td>m</td>
</tr>
<tr>
<td>with undercooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cooling rate dT/dt at T_m</td>
<td>4.9×10⁴</td>
<td>K/s</td>
</tr>
</tbody>
</table>
At the end of the recalscence period the droplet temperature has recalesced near to the melting point and remains at a nearly constant temperature. The cooling rate equals almost zero. When solidification completes, the droplet temperature drops again. The cooling rate in solid state cooling is smaller than that in the undercooled region since in the solid cooling region the droplet has a lower velocity and lower temperature and consequently the heat extracted by radiation and convection is lower. Cooling rate is a very important parameter for melt atomization. In order to compare the effects of different design and operating conditions, in the later part of this thesis we select the cooling rate when the droplet temperature reaches the melting point as a reference.

6.4.2 Effect of disk speed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\omega=15000 \text{ rpm} )</th>
<th>(\omega=20000 \text{ rpm} )</th>
<th>(\omega=25000 \text{ rpm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_p)</td>
<td>78.5 m/s</td>
<td>104.7 m/s</td>
<td>130.9 m/s</td>
</tr>
<tr>
<td>(d_p)</td>
<td>107.9 (\mu) m</td>
<td>85 (\mu) m</td>
<td>70.6 (\mu) m</td>
</tr>
<tr>
<td>(T_n)</td>
<td>1110 °C</td>
<td>1105.1 °C</td>
<td>1101.3 °C</td>
</tr>
<tr>
<td>(T_s)</td>
<td>1453.8 °C</td>
<td>1453.8 °C</td>
<td>1453.8 °C</td>
</tr>
<tr>
<td>(\Delta T/T_w)</td>
<td>0.20</td>
<td>0.202</td>
<td>0.204</td>
</tr>
<tr>
<td>(L_s) at (T_n)</td>
<td>0.632 m</td>
<td>0.519 m</td>
<td>0.445 m</td>
</tr>
<tr>
<td>(L_s) at (f=1)</td>
<td>0.804 m</td>
<td>0.654 m</td>
<td>0.557 m</td>
</tr>
<tr>
<td>cooling rate (dT/dt) at (T_n)</td>
<td>(4.9\times10^4) K/s</td>
<td>(8.01\times10^4) K/s</td>
<td>(11.76\times10^4) K/s</td>
</tr>
</tbody>
</table>
Droplet Dynamics and Solidification

Chapter 6

The effect of disk speed on the particle size, nucleation temperature, arrest temperature, undercooling, flight distances at Tm and at f=1 and cooling rate at Tm are compared in Table 6.5 and Figure 6.5. With increasing disk speed the droplet size decreases (see Figure 6.5a and Table 6.5) and the velocity of the droplets leaving a disk increases (Table 6.5). Higher rotating speed of the disk leads to a faster decay of the droplet velocity with flight distance since higher flight velocity causes a bigger drag forces (Figure 6.5b). Larger droplet velocity and smaller droplet size at higher rotating speed of the disk (Table 6.5) result together in an early start and completion of solidification (Figure 6.5c) and contribute higher cooling rate (Figure 6.5d). Smaller particle size and higher cooling rate lead to a slightly larger undercooling (Figure 6.5e). The undercooled solidification lasts longer and undercooled particle travels a longer distance compared with equilibrium solidification (Figure 6.5f).

6.4.3 Effect of droplet superheat

Figure 6.6 shows the effect of droplet superheat on the droplet velocity, thermal history, solidification fraction, cooling rate, nucleation temperature and flight distance at the completion of solidification. Some important process parameters are also listed in Table 6.6. Since melt superheat does not significantly affect the particle size (see chapter 5) and the velocity of droplets leaving the disk (Table 6.6), the droplet velocity in flight, cooling rate and nucleation temperature do not change significantly with the increase of droplet superheat (Figures 6.6a, 6.6c and 6.6d). With increasing droplet superheat the cooling rates at the melting temperature decrease slightly (Table 6.6), since a higher droplet superheat requires a longer time to cool the droplet down to the melting temperature. As a result when the droplet reaches melting temperature the velocity of the droplet is smaller. This in turn leads to slightly lower cooling rates and a slightly higher nucleation temperature (see Table 6.6), while a higher droplet superheat results in delayed start of solidification and therefore in longer solidification completion time (Figure 6.6b). Thus, a larger diameter atomization chamber is required for pouring at higher melt superheats.
Table 6.6 Effect of droplet superheat on some important solidification parameters (data for Ni)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Delta T_{\text{super}}$=50 K</th>
<th>$\Delta T_{\text{super}}$=100 K</th>
<th>$\Delta T_{\text{super}}$=200 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{p0}$</td>
<td>78.5 m/s</td>
<td>78.5 m/s</td>
<td>78.5 m/s</td>
</tr>
<tr>
<td>$T_n$</td>
<td>1109.8 °C</td>
<td>1110.1 °C</td>
<td>1110.2 °C</td>
</tr>
<tr>
<td>undercooling</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\Delta T/ T_m$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flight distance $L_a$</td>
<td>0.632 m</td>
<td>0.685 m</td>
<td>0.779 m</td>
</tr>
<tr>
<td>at $T_n$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flight distance $L_a$</td>
<td>0.804 m</td>
<td>0.852 m</td>
<td>0.937 m</td>
</tr>
<tr>
<td>at $T_m$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cooling rate $dT/dt$ at $T_m$</td>
<td>$4.9\times10^4$ K/s</td>
<td>$4.85\times10^4$ K/s</td>
<td>$4.79\times10^4$ K/s</td>
</tr>
</tbody>
</table>

6.4.4 Effect of material type

Figure 6.7 compares the solidification of Ni and Al metals atomized by centrifugal atomization. Different metals have different thermophysical properties. Thus at the same operating conditions their particle sizes will be different (Table 6.7). The droplet of Ni metal is smaller than the Al droplet. Larger droplets have a larger projected area and thus a bigger drag force. As a result Al droplet velocity decays faster than that of Ni droplet (see Figure 6.7a). Cooling of the droplets in flight depends on the heat transfer between the droplets and surrounding gas as well as on the thermophysical properties of the atomized metals and gas in the atomization chamber. In centrifugal atomization of melts transfer of heat by both convection and radiation has a role to play in controlling cooling rates. At high temperatures heat
transfer by radiation has a significant effect. Therefore, metals with higher melting point and larger thermal emissivity are expected to have a higher cooling rate and an earlier start of solidification as shown in Figure 6.7b.

Table 6.7 Effect of material type on some atomizing and solidification parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ni</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>particle size $d_p$</td>
<td>107.9 μm</td>
<td>122.8 μm</td>
</tr>
<tr>
<td>$v_{po}$</td>
<td>78.5 m/s</td>
<td>78.5 m/s</td>
</tr>
<tr>
<td>$T_n$</td>
<td>1109.8 °C</td>
<td>438.0 °C</td>
</tr>
<tr>
<td>undercooling $\Delta T/T_n$</td>
<td>0.2</td>
<td>0.24</td>
</tr>
<tr>
<td>cooling rate $dT/dt$ at $T_n$</td>
<td>$4.9\times10^4$ K/s</td>
<td>$3.2\times10^4$ K/s</td>
</tr>
<tr>
<td>flight time at start of solidification</td>
<td>$9.7\times10^{-3}$ s</td>
<td>$12.1\times10^{-3}$ s</td>
</tr>
<tr>
<td>flight time at the finish of solidification</td>
<td>$13.0\times10^{-3}$ s</td>
<td>$18.1\times10^{-3}$ s</td>
</tr>
</tbody>
</table>

The position where the solidification is just finished is mainly affected by the heat of fusion, heat extraction rate by the surroundings and the droplet heat capacity and depends on the particle size, particle velocity and the type of surrounding gas. In centrifugal atomization using a rotating disk the particle size is mainly controlled by disk diameter and disk speed. The effects of disk speed have been discussed in section 6.4.2. In the following sections we will study the effects of particle size and type of surrounding gas.
Chapter 6  Droplet Dynamics and Solidification

6.4.5 Effect of particle size

In centrifugal atomization using a rotating disk, the particle size is strongly affected by disk diameter and disk speed. In order to study the effect of particle size on solidification we assumed that all particles of different sizes leave the edge of the disk at the same speed and temperature. Table 6.8 summarizes some important solidification parameters for three typical particle sizes in rotating disk atomization. The effects of particle size on the solidification process are also shown in Figure 6.8.

Table 6.8 Effect of particle size on some important solidification parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( d_p = 50 , \mu m )</th>
<th>( d_p = 107.9 , \mu m )</th>
<th>( d_p = 250 , \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_n )</td>
<td>1095.2 °C</td>
<td>1109.8 °C</td>
<td>1121.8 °C</td>
</tr>
<tr>
<td>undercooling ( \Delta T/T_n )</td>
<td>0.207</td>
<td>0.2</td>
<td>0.19</td>
</tr>
<tr>
<td>cooling rate ( dT/dt ) at ( T_n )</td>
<td>( 1.73 \times 10^4 ) K/s</td>
<td>( 4.9 \times 10^4 ) K/s</td>
<td>( 1.42 \times 10^4 ) K/s</td>
</tr>
<tr>
<td>flight time at the start of solidification</td>
<td>( 2.78 \times 10^{-3} ) s</td>
<td>( 9.7 \times 10^{-3} ) s</td>
<td>( 3.28 \times 10^{-2} ) s</td>
</tr>
<tr>
<td>flight distance at ( T_n )</td>
<td>0.19 m</td>
<td>0.63 m</td>
<td>2.06 m</td>
</tr>
<tr>
<td>flight time at ( f=1 )</td>
<td>( 3.59 \times 10^{-3} ) s</td>
<td>( 1.3 \times 10^{-2} ) s</td>
<td>( 4.58 \times 10^{-2} ) s</td>
</tr>
<tr>
<td>flight distance at ( f=1 )</td>
<td>0.23 m</td>
<td>0.80 m</td>
<td>2.67 m</td>
</tr>
</tbody>
</table>
Table 6.9 Effect of particle size produced by different atomization methods on cooling rates

<table>
<thead>
<tr>
<th>particle size (µm)</th>
<th>Rotating disk pure Al</th>
<th>REP process # Al-4.5%Cu alloy</th>
<th>Gas atomization* Al-4.5%Cu alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.9</td>
<td></td>
<td></td>
<td>1.1×10^6 K/s</td>
</tr>
<tr>
<td>50.1</td>
<td></td>
<td></td>
<td>3.57×10^5 K/s</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td>1.31×10^5 K/s</td>
</tr>
<tr>
<td>94.5</td>
<td></td>
<td></td>
<td>8.12×10^4 K/s</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td>8.9×10^5 K/s</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td>2.6×10^5 K/s</td>
</tr>
<tr>
<td>128.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>780</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# Data from Dube et al, 1991. They did two runs: one atomization was conducted using anodes of diameter 1.25 cm at a rotating speed of 6000 rpm and produced particle size of about 780 µm and the other was done at 10,000 rpm and the mean particle size was about 480 µm. * data from Stone and Tsakiropoulos, 1992. They calculated the cooling rate from: \( \frac{dT}{dt} = 6 \left( T_{\text{melt}} - T_{\text{gas}} \right) h_i / c_{\text{melt}} d \) for \( T_{\text{melt}} - T_{\text{gas}} = 860 \, \text{K} \) and \( u = 100 \, \text{m/s} \) for N₂ gas.

Smaller particle sizes have a smaller momentum to resist friction of the gas and thus lead to a faster decay of droplet flight velocity (Figure 6.8a). Smaller particles have smaller heat content and a higher cooling rate (Figure 6.8d) and experience an earlier start and completion of solidification (Figure 6.8b). With increasing particle size the nucleation temperature increases (Figure 6.8e) since large particles experience a small cooling rate (Figure 6.8b). This means that the particle size is the
important parameter in controlling the nucleation temperature and therefore the solidification microstructure.

Table 6.9 compares the effects of particle size produced by the gas atomization and REP processes on the cooling rate. Small particles experience a large cooling rate and therefore are expected to exhibit an uniform microstructure. The larger particles produced by the rotating disk atomization method require a larger atomization chamber for the solidification to be completed in flight (Figure 6.8f).

6.4.6 Effect of gas type

Different gases have a different cooling ability. Table 6.11 and figure 6.9 compare the effects of He and N₂ gases on some important solidification parameters of the typical nickel droplet of 107.9 μm produced under the basic operating conditions given in Table 6.3. The properties of He gas at 300 K are shown in Table 6.10.

Table 6.10 The properties of He gas at 300 K (Eckert and Drake, 1972)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.1672 Kg/m³</td>
</tr>
<tr>
<td>Viscosity</td>
<td>1.985x10⁻⁵ Ns/m²</td>
</tr>
<tr>
<td>Specific heat</td>
<td>5200 J/KgK</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.1457 W/mK</td>
</tr>
</tbody>
</table>

The viscosity and thermal conductivity of He gas at 300 K were calculated from the following equations

\[
\mu_g = 3.93532 + 5.91286 \times 10^{-5} T_g - 2.0266 \times 10^{-11} T_g^2 \quad (6.26)
\]
which were obtained by regression analysis of data given by Eckert and Drake (1972) using a computer software GRAPHER (Microsoft, 1980).

Table 6.11 Effects of different gas on some important solidification parameters (data for Ni)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He gas</th>
<th>N₂ gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>nucleation temperature</td>
<td>1108.3 °C</td>
<td>1109.8 °C</td>
</tr>
<tr>
<td>cooling rate at Tₙ</td>
<td>9.97×10⁴ K/s</td>
<td>4.9×10⁴ K/s</td>
</tr>
<tr>
<td>flight distance at the start of solidification</td>
<td>0.357 m</td>
<td>0.632 m</td>
</tr>
<tr>
<td>flight distance at the end of solidification</td>
<td>0.461 m</td>
<td>0.804 m</td>
</tr>
</tbody>
</table>

He gas has a much higher thermal conductivity and specific heat than N₂ gas. Therefore, the use of He gas leads to a much stronger cooling effect than N₂ gas. It also leads to an earlier start and completion of solidification and allows the use of a much smaller atomization chamber. Since He brings about a higher cooling rate it allows a slightly lower nucleation temperature to be reached. He has a much lower density. This leads to a slow decay of droplet velocity (Figure 6.9a).

6.4.7 Effect of heterogeneous nucleation

As discussed in section 6.2.2.2, we study the effect of catalytic efficiency in heterogeneous nucleation via the function f(θ) where θ is the wetting angle. When wetting angle θ=180°, f(θ)=1 and we have the conditions as for homogeneous
nucleation. Figure 6.10 shows the effects of wetting angle on solidification history. Some important solidification parameters are also listed in Table 6.12. It can be seen that with decreasing wetting angle the nucleation undercooling gradually decreases. When the wetting angle is equal to zero, equilibrium solidification takes place. Thus obtaining a nucleation condition which is as near as possible to homogenous nucleation is a key in rapid solidification processing. Figure 6.10c shows that the nucleation temperature decreases with increasing wetting angle, i.e. with decreasing nucleant efficiency. The cooling rate is not affected by wetting angle (Figure 6.10a).

Table 6.12 Effect of wetting angle on some important parameters
(data for Ni)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>θ=180°</th>
<th>θ=90°</th>
<th>θ=45°</th>
<th>θ=30°</th>
<th>θ=15°</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_n</td>
<td>1109.8</td>
<td>1220.0</td>
<td>1379.1</td>
<td>1418.8</td>
<td>1444.3</td>
</tr>
<tr>
<td>ΔT/T_m</td>
<td>0.2</td>
<td>0.13</td>
<td>0.04</td>
<td>0.02</td>
<td>0.005</td>
</tr>
<tr>
<td>dT/dt at T_w</td>
<td>4.9x10^4 K/s</td>
<td>4.9x10^4 K/s</td>
<td>4.9x10^4 K/s</td>
<td>4.9x10^4 K/s</td>
<td>4.9x10^4 K/s</td>
</tr>
<tr>
<td>L_s (T=T_n)</td>
<td>0.63 m</td>
<td>0.45 m</td>
<td>0.19 m</td>
<td>0.13 m</td>
<td>0.09 m</td>
</tr>
<tr>
<td>L_s (f=1)</td>
<td>0.80 m</td>
<td>0.77 m</td>
<td>0.74 m</td>
<td>0.74 m</td>
<td>0.74 m</td>
</tr>
</tbody>
</table>

6.5 Conclusions

Droplet dynamics and solidification of droplets produced in the DDF regime of centrifugal atomization with a rotating disk have been modelled. In centrifugal atomization with a rotating disk the droplets experience undercoolings. The cooling rates experienced by the powder particles depend on the atomization conditions. The choice of atomizer chamber diameter is significantly affected by the operating and design parameters. In our study a chamber of 2 m diameter is required to prevent droplets hitting the wall before they are fully solidified. Droplet superheat has a weak
effect on nucleation temperature and cooling rates but a higher droplet superheat (therefore a higher melt superheat) delays the start of the solidification and requires a larger diameter of atomizing chamber.
Figure 6.1 Schematic illustration showing the formation and flight of a droplet from the edge of a rotating disk.

Figure 6.2 Schematic illustration showing cooling and solidification behavior of a pure metal droplet in flight. (i--undercooled zone, ii--recalescence zone, iii--heat transfer controlled solidification zone and iv--solid state cooling zone)
INPUT \( D, Q, \omega, n, \sigma, \rho, \gamma, \beta, T_m, T_n, v_m, D_m, C_p, \Delta H_m, \Delta G_m, \rho_p, C_p \rho, \lambda, T_g, s_m \)

CALL particle sizes

Calculate droplet initial velocity

\[ \text{time} = \text{time} + \Delta t \]

Calculate droplet \( T_p, u_p \)

No \( \rightarrow T_p > T_m \)

Yes

Calculate cooling rate, flight time & flight distance at \( T_m \)

Calculate nucleation rate \( J \)

\[ \text{SUM} \ VJ \geq 1 \]

No \( \rightarrow \) Calculate nucleation temperature \( T_n \)

Yes

Adjust time step

Calculate solidification velocity \( u \)

Calculate solidification fraction \( f \)

Calculate droplet \( T_p \) and \( u_p \)

No \( \rightarrow f \geq 1 \)

Yes

Calculate solidification time, flight distance, \( T_p \) and \( u_p \) at \( f=1 \)

Calculate droplet \( T_p \) and \( u_p \) in solid state cooling zone

PRINT results

END
a) droplet velocity

b) thermal history of droplet
Figure 6.4 Thermal history and solidification progress during flight of Ni droplet from a disk of diameter 0.1 m rotating at 15000 rpm with superheat 50K.
c) droplet temperature

d) effect of disk speed on the cooling rate
Figure 6.5 Effects of disk speed on the mean particle size, droplet velocity, thermal history, cooling rate, nucleation temperature and solidification end position of Ni droplet from a disk of diameter 0.1m with melt superheat 50K.
a) droplet velocity

b) droplet temperature
Figure 6.6 Effect of droplet superheat on the droplet velocity, thermal history, cooling rate and nucleation temperature of a nickel droplet formed using a disk of diameter 0.1 m rotating at 15000 rpm
Figure 6.7 Effect of different metals on the droplet velocity and thermal history for a disk of diameter 0.1 m rotating at 15000 rpm with droplet superheat 50 K.
a) droplet velocity

b) droplet thermal history
b) thermal history

c) solidification fraction
d) cooling rate

e) nucleation temperature
f) flight distance at the end of solidification

Figure 6.8 Effect of particle size on the droplet velocity, thermal history, solidification fraction, cooling rate, nucleation temperature and flight distance at the end of solidification for the conditions given in Table 6.3

a) droplet velocity
b) droplet temperature

c) solidification fraction

Figure 6.9 Effect of gas in atomization vessel on the droplet velocity and solidification process of a nickel droplet at the conditions given in Table 6.3
a) droplet temperature

b) solidification fraction
c) nucleation temperature

d) flight distance at the end of solidification

Figure 6.10 Effect of wetting angle on the solidification progress of a nickel droplet at the conditions given in Table 6.3
Chapter 7
Water atomization: Experiment and observations

7.1 Introduction
The Surrey centrifugal atomizer consists of a stainless steel atomization chamber of 2 m diameter, a flat disk (the diameter of the disk used for the experiments described in this study is 0.2 m), which is electrically driven and whose angular speed can be varied from 0 rpm up to 25,000 rpm, a water-cooled copper crucible of 3.5 litres volume, which is used for clean melting and which can be tilted for the delivery of melt on the disk. Charges in the crucible are melted using two transferable plasma torches. The atomizer can be evacuated and there is provision for observation via a number of observation ports. The atomizer can be seen in Figure 7.1. Figure 7.2 shows the disk and crucible assemblies. The vacuum system is shown in Figure 7.3 and currently consists only of a rotary pump. Figure 7.4 shows one of the control panels used for the operation of the torches and the movement of the crucible. Powders are collected from the bottom of the atomizer.

In order to study the atomization of a liquid by the rotating disk method, water was selected as the first atomisation medium. An Imacon 790 high speed camera, 100000 frames a second, was used to record the phenomena during the pouring, impacting, spreading and break up stages at and/or beyond the edge of the disk.

7.2 Calibration experiments

7.2.1 Calibration of tilting speed of crucible

As mentioned above, the atomizer has provision for the melting of a charge in a water-cooled copper crucible, which is situated near the top part of the atomization
Figure 7.1 The Surrey Centrifugal Atomizer
Figure 7.2 The disk and crucible
Figure 7.3 The Vacuum system
Figure 7.4 One of the control panels
vessel and can be tilted at different speeds via a gear box assembled in the atomization vessel and controlled from the atomizer control panel (setting 0 to 100). The provision for tilting the crucible is essential for pouring the melts on the disk. The latter could also be replaced by a permanent mould for ingot casting. The time taken to empty the crucible was measured and the average flow rate was calculated. It was noticed that the flow rate is not constant during tilting of the crucible. It is low at the beginning, then increases and decreases again towards the end of tilting. Typical values of the flow rate during the tilting are given in Table 7.1 and in Figure 7.5.

Table 7.1 The tilting speed of crucible and average flow rate data

<table>
<thead>
<tr>
<th>Tilting speed setting (no unit)</th>
<th>Average flow rate (m³/s×10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>50</td>
<td>43</td>
</tr>
<tr>
<td>80</td>
<td>71</td>
</tr>
</tbody>
</table>

Figure 7.5 Relationship between the average flow rate of water and the tilting speed setting of crucible
7.2.2 Calibration of disk speed

In the atomizer there is also provision for pouring melt on to a rotating disk whose speed can be changed from the atomizer control panel. A given setting is required to achieve a particular disk rpm which was measured using a stroboscope (Table 7.2 and Figure 7.6). The diameter of the disk used in these experiments was 0.2 m.

Table 7.2 Relationship between the disk speed setting and the disk speed

<table>
<thead>
<tr>
<th>Disk speed setting (no unit)</th>
<th>Disk angular speed (rpm)</th>
<th>Disk peripheral velocity*(m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>5000</td>
<td>52</td>
</tr>
<tr>
<td>175</td>
<td>10000</td>
<td>105</td>
</tr>
<tr>
<td>250</td>
<td>15000</td>
<td>157</td>
</tr>
<tr>
<td>340</td>
<td>20000</td>
<td>210</td>
</tr>
<tr>
<td>420</td>
<td>25000</td>
<td>262</td>
</tr>
</tbody>
</table>

*disk peripheral velocity, \( V_r \), was calculated according to equation: \( V_r = 2\pi R/\omega \), where \( R \) is the radius of the disk and \( \omega \) is the disk rotating speed.

Figure 7.6 Relationship between the disk speed and disk speed setting
7.3 Results and discussion

7.3.1 Tilting crucible mode

These experiments were conducted with the distance between the crucible and disk kept constant (0.2 m). Top and side view photographs were taken.

Figure 7.7 Uneven distribution of water on a rotating disk for tilting speed setting 50 and disk speed 5000 rpm (top view)

Observations showed that the impact point of the water on the disk changed with time during tilting for a given tilting speed. At the beginning the water fell and hit the disk near the centre, then the impact point moved towards the edge of the disk and finally returned to a point near the centre of the disk. An increase of tilting speed led to the point of impact moving further towards the edge of the disk. The point of impact was not affected by the disk speed for a given tilting speed.

Observations also showed that the distribution of water on the disk was uneven since the impact point was not always kept in the centre of the rotating disk. After hitting the disk, the water was forced to go in the direction of disk rotation. Consequently,
more water was distributed downstream the disk (Figure 7.7). Therefore, there was more water to be disintegrated downstream than upstream the disk. An increase of tilting speed led to more uneven distribution of water on the disk (Figure 7.8), while a higher disk rotating speed was beneficial for faster spreading out of the water and for the reduction of the uneven distribution of the water on the disk (Figure 7.9).

Figure 7.8 Effect of crucible tilting speed on distribution of water on the disk (top view)

a) tilting speed setting 30 and disk speed 5000 rpm

b) tilting speed setting 80 and disk speed 5000 rpm
It can be seen from Figure 7.10 that water extended beyond the edge of the disk and broke up into a mist around the disk. The water mists consisted of fine droplets, which leave a dark grey background in the photos.

(a) tilting speed setting 50 and disk speed 15000 rpm

(b) tilting speed setting 50 and disk speed 20000 rpm

Figure 7.9 Effect of disk speed on distribution of water on the disk (top view)
The break up of water during the tilting stage using the water cooled crucible is a complicated process owing to the variation of flow rate and impact point with time. The calculations for the condition given in Figure 7.7 indicate that water disintegrates in the film formation regime and that the resultant droplet size was about 60 μm.
Chapter 7 Water Atomization: Experiment and Observations

For tilting crucible mode the contact of the water with the disk was characterised by a splashing and subsequent uneven spreading of the water on the disk (Figure 7.11). When the point of impact was not near the centre of the disk this phenomena was more severe.

Figure 7.11 The splashing of water hitting a rotating disk (side view)

a) tilting speed setting 30 and disk speed 20000 rpm

b) tilting speed setting 50 and disk speed 20000 rpm

An increase of the tilting speed increased the severity of splashing of the water on
the disk. An increase of the disk rotating speed for a given crucible tilting speed was accompanied by a more even spreading of the water, but the nature and severity of the splashing of the water was not significantly changed.

Figure 7.12 Photo showing the existence of a hydraulic jump on a stagnant disk when a well defined water stream was delivered on to the centre of the disk (D=0.2 m) with Q=6.61x10^{-6} m^3/s and delivery tube diameter of 0.005 m (side view)

Figure 7.13 Calculated water film thickness on a stagnant disk for the same conditions as in Figure 7.12
When a disk was stagnant the hydraulic jump of water hitting the disk could be observed (Figure 7.12).

Figure 7.13 shows that the film thickness increases towards the edge of a disk, when the disk is stagnant. This is in agreement with the observation shown in Figure 7.12.

![Graph showing the film thickness increases towards the edge of a disk.](image)

Figure 7.14 The effect of disk speed and flow rate on the film thickness compared to that shown in Figure 7.12 (\(\Delta\): \(Q=33.05 \times 10^{-6}\) m\(^3\)/s and \(\omega=0\) rpm, \(\square\): \(Q=6.61 \times 10^{-6}\) m\(^3\)/s and \(\omega=500\) rpm, \(-\times-\): \(Q=6.61 \times 10^{-6}\) m\(^3\)/s and \(\omega=1000\) rpm, and \(-\bullet-\): \(Q=6.61 \times 10^{-6}\) m\(^3\)/s and \(\omega=5000\) rpm)

Figure 7.14 shows the effect of disk speed and flow rate on the film thickness of water on the disk. At low disk speed there is also a hydraulic jump. With increasing disk speed the hydraulic jump moved towards the centre of the disk and then gradually disappeared.

### 7.3.2 Experiments using water stream of well defined diameter

Following the preliminary experiments described in above sections it was concluded that a well defined diameter of the liquid stream can not be achieved with the tilting crucible. The liquid stream diameter is a process parameter which is known, at least in the case of gas or water atomization, to be an important parameter controlling
powder size. Thus, it was decided to proceed with a second set of experiments where
water streams of different diameter could be delivered (i) to the centre of disk and
(ii) off the centre of the disk. The disk was positioned at 5 cm below the tube orifice.
Tubes of diameters of 1.5, 2.5 and 5 mm were used.

a) disk speed 4500 rpm, $Q=30.74$ cc/s and tube diameter 2.5 mm (side view)

b) disk speed 15000 rpm, $Q=30.74$ cc/s and tube diameter 2.5 mm (side view)
c) disk speed 20000 rpm, Q=21.55 cc/s and tube diameter 2.5 mm (top view)

Figure 7.15 Good atomization achieved using a delivery tube

When water was directed to the centre of the disk, the water was evenly distributed on the disk. It spread out along the surface of the disk and formed a thin film on the disk. When the water reached the edge of the disk it broke up into droplets. A number of good atomization conditions have been obtained (e.g., see Figure 7.15).

Figure 7.16 shows the calculated film thickness of water on the disk for the conditions given in Figure 7.15b. It can be seen that at the edge of the disk the calculated film thickness is about 10 microns. Figure 7.17 shows the radial velocity profiles at different positions on the disk. With increasing distance from the centre of the disk the radial velocity slightly decreases since towards the edge of the disk the flow area increases. The velocity profiles are nearly parabolic (see also Figure 3.15).

The calculations also show that for the conditions given in Figure 7.15 the water showed break up in the film formation regime, which is in agreement with Figure
Chapter 7  Water Atomization: Experiment and Observations

7.15a. Table 7.3 summarizes the atomization data.

![Figure 7.16](image)

Figure 7.16 The calculated film thickness of water for the conditions given in Figure 7.15b

![Figure 7.17](image)

Figure 7.17 Radial velocity profile of water at different positions on the disk (Δ: r/R=0.25, ○: r/R=0.5, ■: r/R=0.75 and ×: r/R=1)
Table 7.3 Atomization data for water for the conditions given in Figure 7.15b

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\omega=10000$ rpm</th>
<th>$\omega=15000$ rpm</th>
<th>$\omega=20000$ rpm</th>
<th>$\omega=25000$ rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film extent (mm)</td>
<td>0.31</td>
<td>0.155</td>
<td>0.097</td>
<td>0.067</td>
</tr>
<tr>
<td>Droplet size (µm)</td>
<td>23.0</td>
<td>13.9</td>
<td>9.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>

The data in Table 7.3 shows that film extent and droplet size decrease with increasing disk rotating speed, in qualitative agreement with the observations.

At low flow rates and low rotating speeds the water broke up just at the edge of the disk in DDF mode (Figure 7.18). With increasing disk rotating speed and flow rate the water break up mechanism changed to the ligament formation regime (Figure 7.19) and to the film formation mode (Figure 7.15b).

Figure 7.18 Droplets forming at the edge of a disk for the condition: disk speed 278 rpm, $Q=20.89 \times 10^{-6}$ m³/s and delivery tube diameter: 2.5 mm (top view)
Figure 7.19 Photo showing ligaments forming at the edge of a disk for the condition: disk speed: 2222 rpm, \( Q=28.50\times10^{-6} \text{ m}^3/\text{s} \) and tube diameter: 2.5 mm (top view).

At high disk speeds a lot of water mist formed at the edge of the disk (Figure 7.15b).

Table 7.4 summarizes the atomization data for the break up of water in the different atomization regimes. It can be seen that the calculations are in qualitative agreement with the experimental observations.

**Table 7.4 Atomization data for the break up of water in different atomization modes**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DDF: ( Q=20.8 \text{ cc/s} ) ( \omega=278 \text{ rpm and} ) ( D=0.2\text{m} )</th>
<th>LF: ( Q=28.5 \text{ cc/s} ) ( \omega=2222 \text{ rpm and} ) ( D=0.2\text{m} )</th>
<th>FF: ( Q=30.74 \text{ cc/s} ) ( \omega=15000 \text{ rpm} ) and ( D=0.2\text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{opt}/n_f/\text{film extent} )</td>
<td>( K_{opt}=61.46 )</td>
<td>( n_f=487.8 )</td>
<td>0.155 mm</td>
</tr>
<tr>
<td>( \text{Droplet size}(\text{mm}) )</td>
<td>3.1</td>
<td>0.2</td>
<td>0.014</td>
</tr>
</tbody>
</table>
At high flow rates there was also some splashing as the water hit the disk (Figure 7.20).

Figure 7.20 Splashing of water at high flow rates (side view)

a) disk speed 20000 rpm, $Q=88.23\times10^{-6}$ m$^3$/s and delivery tube diameter 2.5 mm

b) disk speed 15000 rpm, $Q=186.77\times10^{-6}$ m$^3$/s and delivery tube diameter 5 mm

The severity of splashing depended on the flow rate of the water or the velocity of
the water stream exiting from the tube orifice. For a given disk speed there would be some splashing when the flow rate exceeds a certain value (Figures 7.20 and 7.21). Approximate critical values for splashing were determined for water stream diameters of 1.5, 2.5 and 5 mm and these are given in Table 7.5.

Figure 7.21 Spreading of water on a disk rotating at 10000 rpm at different flow rates with a delivery tube diameter 2.5 mm (top view)
a) no splashing ( \( Q=30.91 \times 10^{-6} \text{ m}^3/\text{s} \) )

b) some splashing ( \( Q=116.28 \times 10^{-6} \text{ m}^3/\text{s} \) )

Figure 7.22 Spreading of water on a disk rotating at 10000 rpm at different flow rates with a delivery tube diameter 5 mm ( top view )

At flow rates or velocities below the critical ones there was no splashing. It seems that the velocity of water exiting from the delivery tube is more suitable to describe...
the critical condition by comparing the differences of the critical flow rates and the critical velocities. Table 7.5 shows the estimated critical velocities for the transition. It was not so easy to observe the transition by naked eye at high velocities, therefore further experiments with appropriate instrumentation are required in order to determine accurately the transition conditions.

<table>
<thead>
<tr>
<th>Water stream diameter (mm)</th>
<th>Critical flow rate of water ($\times 10^6$ m$^3$/s)</th>
<th>Critical velocity of water (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>12.7</td>
<td>7.2</td>
</tr>
<tr>
<td>2.5</td>
<td>38.5</td>
<td>7.8</td>
</tr>
<tr>
<td>5.0</td>
<td>112.0</td>
<td>5.9</td>
</tr>
</tbody>
</table>

When the water stream was directed off the centre of the disk, splashing was also observed (Figures 7.23 and 7.24). For a given stream diameter splashing occurred at low flow rates. This is the same as for the case when the stream was directed on to the centre of the disk but the splashing occurred at lower flow rates than in the former case (compare Figure 7.23 and Figure 7.21a). The critical splashing off centre distance, $r_{ck}$, where the water stream hit the disk, depended on the flow rate and disk rotating speed. As the flow rate or disk rotating speed increased, splashing occurred at lower $r_{ck}$ values. A comparison of Figure 7.24a and b suggests that a higher rotating speed causes a more serious splashing.

When the tilting crucible mode was used, a funnel positioned below the crucible was used to improve the atomization condition. Figures 7.25 and 7.26 showed that a good
atomization condition could be achieved.

Figure 7.23 Photo showing the splashing when water stream was delivered off the centre of the rotating disk for the condition given in Figure 7.21a (side view)

a) disk speed 5555 rpm
b) Disk speed 15000 rpm

Figure 7.24 The effect of disk speed on the splashing off the centre of the disk (side view)

Figure 7.25 Spreading of water on the disk when using the tilting crucible mode with a funnel positioned below the crucible for tilting speed setting 80 and disk speed 15000 rpm (side view)
Figure 7.26 Spreading of water on the disk when using the tilting crucible mode with a funnel positioned below the crucible for tilting speed setting 80 and disk speed 20000 rpm (side view)

7.4 Conclusions

1. The pouring of liquid using the tilting crucible method did not lead to an efficient atomization. This is expected to lead to the development of a broad and multimoded size distribution of powder particles due to the formation of powder particles during the spreading of the liquid and via atomization of the liquid at the edge of the rotating disk.

2. High disk rotating speed was beneficial to achieving a better (i.e., more even) spreading of the water and to more efficient atomization.

3. An increase of crucible tilting speed tended to adversely affect the atomization conditions and led to less efficient atomization.
4. Mechanism/s for delivering the liquid to the centre of the rotating disk with a well defined diameter of the liquid stream should ensure a better atomization at the edge of the rotating disk.
Chapter 8
Preliminary Experiment of Melt Atomization

8.1 Introduction
In view of the observations discussed in the previous chapter, it was decided to perform a preliminary atomization test of a low melting point metal using an induction furnace instead of the water cooled copper crucible because of time limitations, the re-engineering of the crucible holding and tilting assembling and the centring of the tilting of the crucible and the requirements for balancing the rotating disk and motor assembly. The results of these preliminary experiments are presented below and compared with the results of calculations discussed in chapters 3 to 6 as well as with previous experimental work.

8.2 Experiment
The modified Surrey centrifugal atomizer was used to atomize an Al melt. The water cooled copper crucible and the plasma torch melting assembly were removed and in their place was located a vertical tube induction furnace with a stopper rod for lifting, which was placed 10 cm above the centre of the disk, see Figure 8.1. A charge of about 360 g was melted and poured onto the centre of the disk via a melt orifice of 4 mm diameter when the furnace temperature was about 1138 K. The disk speed setting was 85 (about 5000 rpm). The atomized product was collected and examined using microscopy techniques and particle size analysis.

8.3 Results and Discussion
The atomized products are shown in Figure 8.2. These could be classified in six groups, according to their morphology: (1) Large solidified lumps on the disk (Figure 8.2 A), (2) Thin acicular particles (Figure 8.2 B), (3) "Snowflake" like particles which were formed when the melt hit the walls of the atomizing vessel and which
stuck on the wall of the vessel (Figure 8.2 C), (4) Irregular particles (Figure 8.2 D) and (5) "Raindrop" like particles collected at the bottom of the atomizer (Figure 8.2 E) and (6) Fine powder particles.

Figure 8.1 The Furnace, support system and the solidified melt on the disk
The fine powder particles were separated into three size ranges, under 355 μm, between 355 μm and 100 μm and sub 100 μm, by sieving. About 50% of the particles were above 355 μm. Size analyses using a Malvern Master Sizer gave a mass median powder size of about 360 μm. This matches the calculated particle size of 420 μm. However, this size should be considered with caution, since the particles were not spherical, see Figures 8.3 to 8.5, and also the sizes present exceeded the maximum size that the instrument can measure (600 μm).

As discussed in Chapter 4, solidification of melt on the disk is possible for a given mass flow rate and disk rotation speed, and depends both on melt superheat and the heat transfer conditions upon pouring of the melt on the disk and during the spreading of melt on the rotating desk. The observation of solidification of Al on the disk (see Figure 8.1) is in agreement with observations reported by Mizukaki et al (1995), see Figure 8.6 and the experience with centrifugal atomization of Ti alloy melts for centrifugal spray casting at the IRC, University of Birmingham (Johnson, 1998, private communication), see also Figure 2.11ii.
Figure 8.3 Thin acicular showing the movement of the melt on the rotating disk

Figure 8.4 "Snowflower" flakes forming on the inner surface of atomizer chamber

The trajectory of melt flow on the disk can be deduced from Figure 8.3. It is seen that under the action of centrifugal forces the melt flow occurred in the direction of
rotation (as expected) leading to the formation of a thin solidified layer on the disk.

Figure 8.5 The "Raindrop" collected from the bottom of the atomizer

Figure 8.6 The solidified shell of Ti-6Al-4V alloy on a water-cooled disk (After Mizukami et al, 1995)

"Droplets" forming at the edge of the disk flew off the disk and solidified either in
flight or after impact with the walls of the atomizing vessel. Table 8.1 shows the solidification times and flight distances of different powder particle sizes at different melt superheats for the basic conditions in our atomization experiments. It can be seen that the solidification times and solidification flight distances are longer than the diameter of the atomizing vessel available at Surrey. These results would therefore explain the formation of flakes during our atomization experiments.

Table 8.1 The effect of powder particle size and melt superheat on the solidification times and flight distances

<table>
<thead>
<tr>
<th></th>
<th>dp=300μm, ΔT=70 K</th>
<th>dp=350μm, ΔT=70 K</th>
<th>dp=416μm, ΔT=70 K</th>
<th>dp=418μm, ΔT=30 K</th>
<th>dp=419μm, ΔT=10 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight time at T_m</td>
<td>0.0094s</td>
<td>0.012s</td>
<td>0.0169s</td>
<td>0.0072s</td>
<td>0.0024s</td>
</tr>
<tr>
<td>Flight distance at T_m</td>
<td>0.43m</td>
<td>0.548m</td>
<td>0.76m</td>
<td>0.35m</td>
<td>0.12m</td>
</tr>
<tr>
<td>Flight time at f=1</td>
<td>0.076s</td>
<td>0.098s</td>
<td>0.141s</td>
<td>0.126s</td>
<td>0.118s</td>
</tr>
<tr>
<td>Flight distance at f=1</td>
<td>1.94m</td>
<td>2.43m</td>
<td>3.33m</td>
<td>3.16m</td>
<td>3.06m</td>
</tr>
</tbody>
</table>

When the droplets in the liquid or semi-solid state hit the inner surfaces of the atomizer chamber, they deformed and either stuck on the wall and further piled up, giving a "Snowflower" like particle, or fell down to the bottom of the atomizer. The latter produced the "Raindrop" like particles.
Chapter 8  Preliminary Experiment of Melt Atomization

The piling up phenomena of droplets can be seen in Figure 8.4. The "Snowflower" like particles exhibited a rough outside surface. The "Raindrop" like particles appeared with a smooth surface and were 5 mm to 10 mm long and about 0.2 mm thick.

Figure 8.7 SEM morphology of powder particles under 355 μm

Figure 8.8 SEM morphology of powder particles between 355 μm and 100 μm
Figures 8.7 to 8.9 shows the morphology of the fine powder particles. The powders in all three size ranges were irregular. This is in agreement with the results of Dogan and Saritas (1994), who also studied the atomization of Al using the rotating disk method, see section 2.4.3 and Figure 2.14.
Chapter 9
Conclusions and Suggestions for future work

9.1 Conclusions

Based on experimental observations of the atomization of both normal liquids and metallic melts, models have been developed in this thesis to study the rotating disk centrifugal atomization technique. The basic phenomena associated with the centrifugal atomization have been systematically studied from the spreading of melts on a disk to the formation and morphology of powders in the atomization vessel. The models also provided some guidelines for the design and operation of the process.

The experiments and observations of water atomization have shown that the method for delivering a liquid to a rotating disk affected the distribution and disintegration of the liquid. When pouring method with tilting a crucible is used, the distribution of liquid on a disk is uneven. Consequently, there was more liquid to be disintegrated downstream than upstream the disk. When a delivery tube is used, a well defined stream and therefore a uniform distribution of liquid on the disk can be obtained.

After the melt is directed near the centre of a disk, it spreads out and forms a thin film on the disk. During spreading out the melt loses heat to the gas atmosphere and the disk by conduction, convection and radiation. Depending on the operating conditions, some solidification can take place on the disk. This affects the delivery of melt to the edge of the disk and the atomization of the melt at the edge of the disk. The preliminary experimental work on the centrifugal atomization of aluminium has confirmed the above. Therefore, it is necessary to prevent the melt partially freezing on the disk in order to get a good atomization condition. The models have shown that melt superheat, mass flow rate, disk diameter, disk rotating speed and disk material have a role to play in controlling the solidification on the disk. A high
melt superheat and large mass flow rate and a small diameter of the disk are expected to avoid the freezing of the melt on the disk.

The melt at the edge of a rotating disk disintegrates into droplets according to one of three basic modes. At low flow rates and low rotating speeds the melt breaks up in the form of direct droplet formation. In this mode the waves forming at the edge of the disk are responsible for the disintegration. Wave theory has been used to analyse the process of disintegration and a model has been proposed to calculate the powder particle size. The calculated fastest-growing wave numbers and powder particle sizes as a function of atomizing parameter are in good agreement with experimental results in the literature. A high disk rotating speed and a large diameter of disk can be used to obtain fine powders. Particle sizes also depends on the type of material to be atomized. A high ratio of density to surface tension of melt is expected to produce fine powder particles.

At high flow rates and high disk rotating speeds the melt goes beyond the disk, extends to a certain distance and then breaks up into ligaments, the latter further disintegrate into droplets. The sheet wave theory of Dombrowski and Johns has been applied to analyse the break up of the melt in this regime and a method has been put forward for the calculations of the film extent and powder particle size. The calculated film extents and powder particle sizes have been compared with experimental data in the literature and showed a good agreement. The studies of atomizing parameters showed that a high disk peripheral speed can be used to produce fine powders and that a high mass flow rate of melt gives coarse powder particles and is expected to result to a unsatisfied atomization condition.

At median flow rates and median disk rotating speeds melt breaks up into droplets in the form of ligament formation. The position where the ligaments collapse and how the waves form on the ligaments still needs to be studied. As a first approximation mass conservation and the wave theory of Weber have been used to evaluate the powder particle sizes.
Once droplets form at the edge of a rotating disk they are thrown away from the disk. During flight droplets lose their momentum, heat content and solidify into powder particles. Disk diameter, disk rotating speed, melt superheat, melt mass flow rate, the properties of the atomizing gas and melt and the nucleation condition influence the dynamics and solidification history of a droplet. Modelling of droplet dynamics and solidification has shown that the nucleation undercooling is a function of particle size, disk speed and nucleant potency, the latter as measured by the wetting angle. Large undercoolings are achieved in small particles, where nucleation of solidification is affected by nucleants of low potency (large wetting angle). The cooling rate for centrifugal atomization using the rotating disk method is about $10^4$ K/s and significantly depends on the disk speed, particle size and atomized material. The flight time/distance for complete solidification of a droplet depends on the disk diameter, disk speed, melt superheat, melt mass flow rate, atomized material, atomizer atomosphere and nucleation condition.

In summary the following conclusions can be made for the work presented in this thesis:

1) A well-defined diameter of the liquid stream and a controlled mechanism for delivering the liquid to or near the centre of a disk are necessary in order to achieve a good atomization condition and to obtain a narrow distribution of powder particles.

2) A small diameter disk which is rotating at high speed can be used to produce fine powder particles and to avoid the freezing of melt on the disk.

3) Control of heat transferred through the disk, of melt superheat and melt flow rate are important for good atomizing conditions.

4) The large diameter of the atomization vessel is very important, especially for powder production since one needs to prevent the splatting of droplets hitting the wall of the atomization vessel before they fully solidify.
5) The cooling rate achieved in centrifugal atomization with a rotating disk depends on the material to be atomized, the atmosphere in the atomization vessel, the disk design and operating conditions. High cooling rate can be achieved using large disks rotating at high speeds.

9.2 Suggestions for future work

Modelling provides a very powerful tool for the development and design of new processes. In our case it has helped to understand the basic processes that occur in centrifugal atomization and to get a good insight into the effects of various process and design parameters on centrifugal atomization. It also provides a means to avoid unnecessary waste of labour and financial resource. However, some assumptions made in our modelling work were based on theoretical considerations or previous or similar experimental findings. Therefore, the modelling results need to be further verified by experiments. This is specially true for the development of new materials technology. Modelling and experimental work should be considered as two basic aspects in scientific research. It will be better if one could combine both of them for the research.

It is suggested to further test our models for the calculation of powder particle sizes and of the starting point of partial solidification on the disk. Further experimental equipment allowing a good control of melting temperature, melt flow rate and good delivery of the melt to the disk is required. On the basis of the results discussed in chapters 7, 8 the surrey centrifugal atomizer has been modified to allow for better and more controlled delivery of the melt on the centre of the disk. There are still some problem on the control and accurate measurement of melt flow rate for our atomizer.

In our present solidification model only the solidification of droplets of pure metals formed in the direct droplet formation regime has been studied. It is suggested to study the solidification of droplets formed in the other two regimes as well as alloy.
APPENDIX I

Dispersion equation of disturbances at the edge of a rotating disk

Consider the formation and growth of a wave at the edge of a rotating disk, shown in Figure 5.1, assuming that displacement of disturbances is described by

\[ y = (r-R) = a \cos K(\theta - \omega t) \]  \hspace{1cm} (I-1)

The disturbance potential can be derived from Laplace's equation and is given by

\[ \Phi = a_r r \cos K(\theta - \omega t) \]  \hspace{1cm} (I-2)

Disturbances may increase and cause liquid to break up or may decay and eventually damp out, mainly depending on the forces acting on the film. At the edge of a rotating disk, four forces are working on the film. The centrifugal force tries to throw the film away from the disk while the surface tension and viscous forces try to keep the film on the disk. A force balance allows the dispersion equation to be derived (Kayano and Kamiya, 1978).

Kinetic energy

The kinetic energy per wavelength is given by

\[ E_k = \frac{\rho \omega^2 R^2}{2K} \int_{-\pi/K}^{\pi/K} \int_{-\pi/K}^{\pi/K} \cos^2 K(\theta - \omega t) \, d\theta \]  \hspace{1cm} (I-3)

The mean kinetic energy of disturbances per unit area is obtained by dividing equation (I-3) by \( 2\pi R/K \):

\[ E_k = \frac{\rho \omega^2 R^2}{4K} \]  \hspace{1cm} (I-4)

208
Appendix 1  Dispersion Equation of Disturbances at the Edge of a Rotating Disk

Surface energy

Since disturbances occur at the exterior circumference of the disk, surface tension works on both sides of the film. The surface energy per unit area can be obtained directly in the same manner as equation (1-5)

\[ E_s = \frac{K \alpha}{\pi R} \left[ \int \left( 1 + \left( \frac{\partial y}{\partial \theta} \right)^2 \right) R d\theta - \int R d\theta \right] = \frac{K \alpha}{2 \pi R} \left[ \int_{-\frac{\pi}{K+\omega t}}^{\frac{\pi}{K+\omega t}} \frac{\rho^2 K^2}{R^2} \sin^2 K(\theta - \omega t) R d\theta \right] \]  

Energy of centrifugal force

The average energy of centrifugal force acting on unit area is obtained by multiplying the centrifugal force working on the edge of the disk by the displacement and is given by

\[ E_c = \frac{\rho \omega^2 K}{2 \pi} \int y^2 R d\theta = \frac{\rho \omega^2 K a_2}{2 \pi} \left[ \int_{-\frac{\pi}{K+\omega t}}^{\frac{\pi}{K+\omega t}} \cos^2 K(\theta - \omega t) d\theta \right] = \frac{1}{2} \rho \omega^2 R a^2 \]  

Energy lost in unit time by viscous force

The energy lost with resistance to deformation due to the viscous force is obtained by determining the radial and tangential velocities of disturbances from the disturbance potential, multiplying the radial velocity by the stress component in the radial direction and tangential velocity by the stress component in the tangential direction and summing these produces.

\[ E_v = \frac{K}{2 \pi R} \left[ \int_{-\frac{\pi}{K+\omega t}}^{\frac{\pi}{K+\omega t}} \left( P_{r2} + P_{t2} \right) R d\theta \right] = \frac{2 \mu (K-1)}{R} a_r^2 + \frac{\mu}{2R} a_t^2 = \frac{\mu}{2R} (4K-3) a_t^2 \]
Appendix 1 Disperssion Equation of Disturbances at the Edge of a Rotating Disk

where

\[ P_{rr} = -p + 2\mu \frac{\partial u}{\partial r} = -p + 2\mu \frac{(K-1)}{R} a_t \cos \theta \omega t \]  \hspace{1cm} (I-8)

\[ P_{\theta \theta} = \mu \left( \frac{\partial v}{\partial r} + \frac{\partial u}{\partial \theta} \right) = - (2K-1) \mu \frac{a_t}{R} \sin \theta \omega t \]  \hspace{1cm} (I-9)

By equating the rate of dissipation of kinetic energy, surface energy, and viscous deformation energy of disturbances to the motive power by centrifugal force the equation for the motion of the interface is

\[ \frac{d}{dt} \left[ \frac{1}{2} \rho \omega^2 R a^2 \right] = \frac{d}{dt} \left[ \frac{\rho R}{4K} \left( \frac{da}{dt} \right)^2 + \frac{\kappa^2 a}{2R^2} a^2 \right] + \frac{\mu}{2R} (4K-3) \left( \frac{da}{dt} \right)^2 \]

From this, the following linear equation can be obtained

\[ a_{tt} + K(4K-3) - \frac{\mu}{\rho R^2} a_t + 2 \left( \frac{\sigma}{\rho} \frac{K^3}{R^3} - \kappa \omega^2 \right) a = 0 \]  \hspace{1cm} (I-11)
Dispersion equation for disintegration of viscous liquid sheet

Consider a two-dimensional thin liquid sheet of density $\rho$, viscosity $\mu$, surface tension $\sigma$ and thickness $h$ moving with a velocity $v$ through a stationary gas of density $\rho_{\text{gas}}$ shown in Figure A-1. When a disturbance forms on the sheet, the equation of motion of the neutral axis mid-way can be derived by balancing the forces acting on the sheet (Dombrowski and Johns, 1963). Four forces are working on the sheet. They are gas pressure, surface tension, viscous and inertial forces.

$$\rho = -\rho_{\text{gas}} v^2 k \delta$$  \hspace{1cm} (II-1)

where $\delta$ is the displacement of a disturbance from its mean position and $k$ is the...
Appendix II  Dispersion Equation for Disintegration of Viscous Thin Sheet

wave number.

Assuming that the motion of the sheet is a growing sine wave the pressure on the upper interface is given by

\[ p = \rho_{gas} v^2 k (y_1 - h/2) \]

and the pressure force from the gas is therefore

\[ \rho_{gas} v^2 k (y_1 - h/2) z dx = \rho_{gas} v^2 k y z dx \]

Similarly the force of the lower interface is given by

\[ \rho_{gas} v^2 k (y_2 + h/2) z dx = \rho_{gas} v^2 k y z dx \]

Thus the total force caused by gas pressure is

\[ F_p = 2 \rho_{gas} v^2 k y z dx \]  \hspace{1cm} (II-2)

Surface tension force

The force caused by surface tension has a component in the y-direction given by

\[ \sigma z \frac{\partial y_1}{\partial x} + \sigma z \frac{\partial y_2}{\partial x} = 2 \sigma z \frac{\partial y}{\partial x} \]

Thus the net force caused by the difference in the surface tension components along a length \( dx \) is

\[ 212 \]
Appendix II  
Dispersion Equation for Disintegration of Viscous Thin Sheet

\[ F_e = -\frac{\partial}{\partial x} \left( 2\sigma z \frac{\partial y}{\partial x} \right) dx \]  \quad (II-3)

**Inertial force**

The inertial force is given by the rate of change of momentum of the liquid element.

\[ F_I = -\frac{\partial}{\partial t} (\rho z h dx \frac{\partial y}{\partial t}) = -\rho \left( \frac{\partial^2 y}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t} \right) z dx \]  \quad (II-4)

**Viscous force**

The shear stress at \( x \) is

\[ \mu \frac{\partial^2 y}{\partial t \partial x} \]

Thus the shearing force is

\[ \mu \frac{\partial^2 y}{\partial t \partial x} z h \]

and the net force along a length \( dx \) is

\[ F_v = \frac{\partial}{\partial x} \left( \mu z h \frac{\partial^2 y}{\partial t \partial x} \right) dx = \mu \left( \frac{h \partial^3 y}{\partial t^3} + \frac{1}{v} \frac{\partial h}{\partial t} \frac{\partial^2 y}{\partial t} \right) z dx \]  \quad (II-5)

Hence the total force on the length, \( dx \) is

\[ F_p + F_o + F_v + F_I = 2 \rho_{gas} v^2 k y z dx + 2 \alpha \frac{\partial^2 y}{\partial x^2} z dx - \rho \left( \frac{h \partial^3 y}{\partial t^3} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t} \right) z dx + \mu h \frac{\partial}{\partial t} \]

Rearrangement of the above equation gives
Appendix II  

Dispersion Equation for Disintegration of Viscous Thin Sheet

\[ 2 \rho_{\text{gas}} v^2 k y + 2 \sigma \frac{\partial^2 y}{\partial x^2} - \rho \left( h \frac{\partial^2 y}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t} \right) + \mu h \frac{\partial^3 y}{\partial t \partial x^2} = 0 \quad (\text{II-7}) \]

The above equation describes the motion of thin liquid sheet caused by a disturbance. Following the traditional practice for the description of waves, we assume that the wave can be expressed as

\[ y = a \exp(ikx) = a_0 \exp(\beta t) \exp(ikx) \quad (\text{II-8}) \]

Then, equation (II-7) becomes in terms of amplitude of wave

\[ 2 \rho_{\text{gas}} v^2 k a - 2 \sigma k^2 a - \rho \left( h \frac{\partial^2 a}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial a}{\partial t} \right) - \mu hk^2 \frac{\partial a}{\partial t} = 0 \quad (\text{II-9}) \]

or in terms of growth rate of wave

\[ 2 \rho_{\text{gas}} v^2 k - 2 \sigma k^2 - \rho \left( h \beta^2 + \frac{\partial h}{\partial t} \beta \right) - \mu h k^2 \beta = 0 \quad (\text{II-10}) \]

Since the second term in the coefficient of \( \rho \) is small compared to the first term, the equation can be further reduced to

\[ 2 \rho_{\text{gas}} v^2 k - 2 \sigma k^2 - \rho h \beta^2 - \mu h k^2 \beta = 0 \quad (\text{II-11}) \]
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215
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