Investigating the effect of an alternative feedstock on the performance of sludge powered generators: developing a theoretical model and analysing trial data

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Abstract

Trials performed by Thames Water on a Sludge Powered Generator (SPG) have used sludge from a Thermal Hydrolysis Process (THP) as feed. Data from the trials with THP product sludge at Thames Water’s Crossness SPGs was subject to data analysis by converting the trial data into flows of operating cost. Sludge is a mixture of many chemicals and these would be very time consuming to analyse for combustion performance in full detail. Therefore sludge has been simplified to a mixture of water and a single combustible chemical component (coniferyl alcohol) with the same heat of combustion as water-free sludge and roughly the right elemental analysis. This simplification enables the thermal behaviour of the combustion, including its tendency to extinguish without support fuel, to be captured. Both the simplified model and the data analysis from the trial show the THP product sludge is a viable fuel which produces a net financial benefit to the SPG’s operation.

Introduction

Thames Water operate two Sludge Powered Generator (SPG) plants at their Crossness and Beckton sites. The feed to the SPGs since commissioning has been raw sludge (a mixture of primary sludge and secondary activated sludge). However, Thames Water was considering installing anaerobic digestion in the form of the Thermal Hydrolysis Process (THP) at the Crossness and Beckton sites. THP generates large amounts of biogas which can be used in CHP engines to generate electricity, in doing so the calorific value of the sludge is reduced. This reduction in calorific value may adversely affect the performance of the SPGs if they were to be used for the post-digestion sludge disposal. Fortunately the sludge product from THP plants is more easily dewaterable, especially if the Bucher press, as trialled by Thames Water (Perrault, Mills, Fountain, & Thorpe, 2013), is utilised. In order to investigate the impact of the change of fuel on the SPGs, Thames Water has run trials at their Crossness site. The purpose of this study was to investigate the change in two ways: (1) a theoretical model of the SPGs was produced and (2) a financial analysis of the trial data from Thames Water’s SPGs was performed and thus help Thames Water in its decision to proceed with the introduction of THP at Crossness and Beckton.

One of the key operational problems of Thames’ SPGs is the tendency for combustion to extinguish because the wetness of the sludge fuel is too great. In order to avoid this event, which is costly, support fuel is supplied to the unit in the form of natural gas. It therefore seemed that the key thermal analysis that needed to be conducted with respect to the...
change in fuel was the one that examined the tendency of the SPGs to extinguish. Sarvanathan (Sarvanathan, 2013) had explored this problem using an autothermal analysis, a concept first developed by Heerden (Heerden, 1953) for the tendency of chemical reactors to extinguish, but without complete success. His autothermal model was intended to be a tool capable of indicating how the SPGs respond to changes in the feedstock or operating conditions. He attempted to model the SPGs using the ChemCad chemical process simulation package, which can in principle cope with much of the chemical complexity of sludge but had trouble converging the simulation. In the work presented here the model was therefore simplified to make Microsoft Excel the simulation engine, in the hope this would provide reliable convergence.

In parallel THP sludge was fed to a combustor at Crossness to discover the effect on the operability of the unit. During the trial the unit continued to operate as normal with operator interventions. This led to a complex data output (see Figures 1, 2, & 3) that is difficult to interpret unambiguously. Aoki and Thorpe (Aoki, 2013) created a simplified analysis of some dried fuel trials run by Thames Water by turning operating stream data into a flow of financial benefit. This study redeveloped this methodology and applied it to the THP trials.

**Data analysis methodology**

During the alternative feedstock trials which were run by Thames Water on the SPGs, THP sludge was fed into one of the fluidised bed combustors (FBCs) in addition to the normal flow of primary sludge of 7 t/h. The flow rate of the THP sludge, which was brought in from another sewage treatment works (STW), was an additional 2 t/h. Operational data was automatically gathered by a SCADA system and some of it saved on to a computer by the 'Historian' software. In this study the data is consolidated according to the method of Aoki (Aoki, 2013) which works by calculating how the financial benefit or cost of running the SPGs fluctuates with time.

The financial benefit is calculated from variable costs only i.e. it excludes capital and fixed costs e.g. labour and the (operationally constant) electrical load of the air fans. This is justified because the excluded costs are not expected to be impacted by changing the fuel.

Financial Benefit = Value of electricity generated + Income from renewable incentives + Savings on liming and disposing of the feedstock - Cost of natural gas

These values are calculated from the trial data at every minute to show how the benefit varies with change of feedstock during the trial. However, none of these variables are directly measured; the methods used for calculating them are discussed below.

**Cost of natural gas**

Natural gas is burnt to pre-heat the combustion air before it enters the bed and also occasionally injected into the bed via lances; this is done at start up and by plant operator intervention if the bed begins to get too cold. If an alternative feedstock is a better fuel then the amount of natural gas required to sustain the combustion will reduce and thus increase the net benefit. The flows of gas to the lances and to the air pre-heaters were calculated separately, as discussed below.

*Calculation of the gas used for air pre-heating*

The amount of gas used for the air pre-heat was not measured and recorded directly, so this has to be calculated by using the measured temperature difference across the air pre-heater. The heat supplied by the natural gas is calculated from the air mass flow rate and the difference in the temperatures of the air before and after the burners, using \( Q = m \ C_p \ \Delta T \) where \( m \) is the molar flow rate of air calculated from the measurement of the normal volumetric flow rate of air, then density of natural gas (unitrove, n.d.) and the \( C_p \) of air is...
taken as 1.005 kJ/kg/°C (Mayhew & Rogers, 1995). $Q$ is the amount of heat produced per second by combustion of the flow of natural gas to the burners and this can be directly priced using the cost of £40/MWh supplied by Thames Water.

*Calculation of the gas used in the lances*

The flow of natural gas to the lances heating the fluidised bed was measured and available in the data. However only a measure of the actual volumetric flow rate was available, so an estimate of the temperature and actual pressure of the natural gas was required before this flow could be priced using the cost in £/MWh. The temperature was assumed to be ambient and it was possible to estimate the pressure of this stream from the recorded operating data of neighbouring instruments on connected lines. Using this information it is simple to calculate the normal volumetric flow of natural gas and using a heating value for natural gas of 50,000 kJ/kg (Tiwari & Mishra, 2012) the usage in MWh and hence the cost can be found.

*Calculation of electricity generated*

As there are two fluidised combustors at Crossness both of which feed steam to the turbine generator set, the amount of electricity produced by the combustor running the trial had to be calculated indirectly. This was done by calculating the amount of steam produced and subtracting the steam used in pre-heating the air with steam. A realistic efficiency was then applied to the steam flow through the turbine.

Steam production was calculated from the drop in the flue gas temperature in the waste heat recovery unit. Using $Q = m C_p \Delta T$, where: $m$ is the mass flow of flue gas calculated from the sum of the bed feeds (sludge, natural gas and air), the $C_p$ is estimated to be 1.4 kJ/kg/°C (based on typical flue gas composition) and the change in temperature is the recorded value.

Using the same methodology as that used to find the amount of energy provided by gas for the burners, the amount of steam used to pre-heat the air is found from the temperature difference across the steam heater used for air pre-heat. From the steam flow rate an electricity production estimate is found by applying a steam turbine efficiency of 15%. This efficiency was calculated by comparing the steam energy produced by both the incinerators on non-trial days with the published amount of electricity produced by the steam turbines in the month of November (Variable Pitch, n.d.). The low efficiency is believed to be caused by the steam turbine being over-sized for the actual amount of steam produced.

*Income from renewable incentives*

The incineration of sludge to produce electricity was at the time of the study subsidised with Renewable Obligation Credits (ROCs), this additional income was factored into the net benefit calculated. The income from ROCs was directly proportional to the amount of electricity produced and was £45/MWh.

*Income via savings on liming/disposal of sludge*

If sludge at Crossness is not burnt in the SPGs, it has to be disposed of by treating it with lime and distributing it to agricultural land. Avoiding this costly process by incinerating the sludge creates savings which are reflected in this analysis. The savings on liming and disposing of the sludge is calculated based on the amount of dried solids burnt in the incinerator. This is calculated with an assumed 30% dry solids content and using a price of £75/tonne of dry solids for liming and disposal to agricultural land.
Results of the data analysis

Trials were run on the 8th and the 14th of November and data for the 18th November when no trial took place was supplied for comparison. This data has been analysed and the resulting graphs (Figures 1, 2, & 3) are shown on the following pages. The vertical bars show max/min ranges during that hour and not errors.

Discussion of Trials

Owing to the variable nature of the SPGs feed it is difficult to draw completely clear conclusions from the financial analysis results. It can clearly be seen from the day without a trial (Figure 3) and from the parts of Figures 1 & 2 before the THP sludge was introduced that it is quite usual for the net benefit to fluctuate by a few pounds per minute during a day. This is thought to be caused by variability in the sludge, which is known to vary in both calorific content and water content over these sorts of timescales.

It isn’t clear whether the THP feed is increasing the electricity production or decreasing the natural gas demands. However it is making a positive impact because the beds are a method of disposal for the sludge and increasing the amount of sludge which can be incinerated per day will result in substantial savings elsewhere.

Concerning the effect the trial has on the gas usage, it can be seen that on the 8th of November (Figure 3) the addition of the THP feedstock did completely remove the need to have the gas lances on. Interestingly although the gas lances also turned off when the trial began on the 14th they were not turned back on after the trial and thus this change could be caused by a change in the quality of the feedstock. It should also be noted that during the two off-trial days the gas lances can be seen to be used very little, so perhaps the feedstock on the two trial days was lower quality than the SPG’s typical feedstock. Therefore it is not clear how the THP fuel is effecting the natural gas requirement but it certainly seems to increase the potential throughput for the SPGs.

It is evident that the net benefit does increase during the two trials by approximately £2/min. However this benefit can partly be attributed to the increase in flow rate to the bed (the two tonnes/hr of THP feed is fed in addition to the normal primary sludge flow) which increases the savings on liming and alternative disposal. This effect can be stripped out as follows: The net benefit produced by the SPG outside the trial is £4/min. In terms of net benefit per tonne of ‘fuel, that’s 4x60/7 = £34/t. During the trial, the net benefit increased by £2/min. In terms of net benefit per tonnes of THP sludge provided that’s 2x60/2 = £60/t. Therefore approximately half of the increase in net benefit can be attributed to the change of fuel.

Thus the benefit over primary sludge is £1/min which equates to more than £500,000 per year per SPG; when the THP is implemented full time at Crossness this will result in a £1,000,000 benefit per year to Thames Water from the SPGs alone¹ (not accounting for the benefit derived from the biogas from the THP process itself). Additionally if a THP plant is constructed at the Beckton site it can be assumed a similar benefit to Thames Water would be produced by running the Beckton SPGs on the THP sludge.

¹ Assuming that the THP feed is fed to the SPGs at the proportions used during the trial
Figure 1: Hourly benefit for the THP feedstock trial on the 8th November
Figure 2: Hourly benefit for the THP feedstock trial on the 14th November
Figure 3: Hourly benefit for the 18th November (no THP trial)
SPG model methodology

The theoretical model of the SPGs was developed based on the principle established in the autothermal analysis of an isomerisation reaction in a CSTR (Continuous Stirred Tank Reactor), as first developed by Heerden (Heerden, 1953) and discussed by Levenspiel (Levenspiel, 1999). The original model has a number of assumptions which must be relaxed for this application, including:

- No phase change in the range of temperatures being modelled,
- No inert compounds that require heating but do not participate in the reaction(s),
- One reactant making one product, and
- Equal specific heat capacity of reactant and product, both constant with temperature.

The real situation (i.e. the SPG combustor) has:

- Phase changes from solid to liquid and from liquid to gas,
- Solid inerts (e.g. mineral content of sludge) and gaseous inerts (e.g. nitrogen),
- Many reactants making at least three products, H₂O, CO₂ and CO, and
- Unequal specific heat capacity, not constant over the temperature range of interest.

The assumption of a CSTR type reactor is a reasonable simplification for a fluidised bed combustor operating well above minimum fluidisation, such as the SPGs, especially if above bed-burning is added as an extra stage (Davidson & Harrison, 1963, Levenspiel, 1999, Yates, 1983).

All of the complexities required by the real situation as outlined above are, in principle, coded into process simulation software such as ChemCad, but this approach had failed. The challenge therefore was to introduce sufficient complexity for the analysis to be adequately representative of the behaviour of the SPGs but not so much that would render a fully coded approach using for example Microsoft Excel too large a task. It was therefore decided to represent the sludge feed as a combination of one chemical component to represent the fuel content in combination with water (representing itself) and nitrogen (representing inerts) which is then burnt with a mixture of oxygen and nitrogen (representing air) and methane (representing natural gas). Coniferyl alcohol (4-(3-hydroxy-1-propenyl)-2-methoxyphenol) was selected the best chemical to represent the fuel content of the sludge, as it is an organic compound with similar heat of combustion and atomic make up to that of the fuel elements in sludge which undergoes phase change across the relevant range of temperatures.

Coniferyl alcohol is a monomer of lignin and was selected for its likeness to chemical components that are present in sludge as listed by Werther & Ogada (Werther & Ogada, 1999). In addition to being a substance that may be found in sludge it was also selected as its lower heating value and elemental composition are similar to those of the combustible components of sludge (Voitkevich et al., 2012) (Perrault et al., 2013). The heating value in the model was fine-tuned to the correct value, which was determined experimentally, by adjusting the proportion of the sludge which was inert/ash; by starting with a compound with a heat of combustion close to that of sludge, such as coniferyl alcohol, it was possible to keep the ‘ash’ content within the realistic limits. Coniferyl alcohol also had the benefit of being solid under normal conditions, as most of the combustible components of sludge are.

Sludge ash is a mixture of inert solid minerals, largely silicon oxide and various metal oxides which do not change phase in the combustor (Shao, et al., 2010) (Werther & Ogada, 1999) becoming the fly ash captured in filters that are part of the SPG. In the interest of keeping the model simple extra inert nitrogen was added to the air to act as an ash; nitrogen also does not change phase in the temperature range found in the combustor. For this the average molecular weight and heat capacity, over the expected operating temperature of the
model, of ash was found and from this the required number of moles of nitrogen per mole of ash could be calculated.

**Principal mass and energy balance derivations**

Assuming there are no heat losses, an accurate assumption for large well insulated units such as fluidised bed combustors, the energy balance for the SPG is: ‘Heat released by combustion = heat required to raise temperature of products’. This can be rephrased in terms of \( x \) (the fractional conversion of fuel) to give:

\[
x = \frac{(\text{heat required to raise the products to reactor temperature})}{(\text{the heat released by the feed at full conversion})} = \frac{-C_p (T_{\text{out}} - T_{\text{in}})}{\Delta H_{rx}^{298}} \text{ in simplest case}
\]  

Equation 1

It is in the detailed coding of equation 1 for the more complex case that the effects of latent heat, non-constant and non-equal specific heat capacities are captured (see the Appendix).

The mass balance for the fuel in the system is ‘in = out + reacted’, or for simplicity let us consider Heerden’s simple isomerisation reaction of \( A \rightarrow B \), then Equation 2 can be derived:

\[
F C_{A0} = (1-x) \ C_{A0} F + (1-x) \ C_{A0} kV
\]

Equation 2

In equation 2, a first order reaction, rate constant \( k \), based on concentration of \( A \) and volume of reactor, \( V \), has been assumed. (This assumption is open to debate in the fluidised bed combustor but no alternative simple enough to yield a result was evident.)

Introducing the Arrhenius form of the temperature dependence of \( k \) and defining a characteristic time \( \tau \) defined as volume, \( V \), divided by volumetric flow rate of fuel, \( F \), Equation 2 can be simplified and rearranged to make \( x \) the subject giving Equation 3.

\[
x = 1 - \frac{1}{1 + \tau a e^{E/(RT)}}
\]

Equation 3

Where: \( E \) is the activation energy, \( a \) is the Arrhenius coefficient, \( T \) is the absolute temperature.

Thus plotting \( x \) from Equation 1 against a range of temperatures will show the ‘heat consumption rate’ at that reactor temperature and plotting Equation 3 will show the ‘heat production rate’ at that reactor temperature. An example of this plot is shown in Figure 4; this shows that there can be three ‘solutions’ for this type of reactor where the heat production is equal to the heat consumption which must be true at steady state. The high conversion/temperature solution corresponds to the reactor ‘flame alight’ and stable, the low conversion solution corresponds to the reaction extinguished and stable. The centre steady state is an unstable solution; this is known to be unstable because Perlmuter (Perlmutter, 1972) has shown that a stable steady state solution only exists where the gradient of the heat balance/heat consumption line is greater than that of the mass balance/heat production line on the van Heerden diagram, which is not true for the central solution.

If the dashed line, which is the graphical representation of Equation 1, moves to the left, the alight solution and the unstable middle solution move closer together. When they coincide, any deviation from steady state can result in the reactor extinguishing itself by movement to the low conversion solution. Therefore the distance between the dashed line and this critical point where the dashed line becomes a tangent to the solid line represents the ‘margin’ for the operator to take action to prevent the reactor extinguishing itself.
The model developed was built up in levels of complexity starting from the simple isomerisation equations 1 & 3 (Heerden, 1953) and (Levenspiel, 1999) to the final model that included phase changes, incomplete combustion and multiple reactants and reactions. The final model represents a CSTR with 3 feeds; a sludge stream, an air stream and a natural gas stream (for the lances) entering the reactor and an effluent flue gas stream composed of combustion products, inert components, above bed burning products.

The three chemical species that participate in the combustion are oxygen (part of the air feed), methane (natural gas) and coniferyl alcohol according to the chemical reactions.

\[
C_{10}H_{12}O_3 + 11.5O_2 \rightarrow 10CO_2 + 6H_2O \quad \text{Equation 4}
\]

\[
CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \text{Equation 5}
\]

\[
CO_2 \rightarrow CO + 0.5O_2 \quad \text{Equation 6}
\]

The fractional conversion of equation 4 is the unknown \( x \). The fractional conversion of equation 5 was set at 100%. Equation 6 was used to adjust for small amount of incomplete combustion within the fluidised bed/CSTR, which combustion is completed as above bed burning. The fractional conversion used in equation 6 was 3.5% based on the measured difference in temperature between the bed and the gasses at exit from the very top of the combustor. A fixed fractional conversion for equation 6 was found to give roughly the right temperature difference for both trial on and trial off cases.

**Heat balance equations**

Different heat balance equations were necessary at different temperatures ranges of the heat balance, depending on the melting and boiling points of the components, all following the form of equation 1. There are 4 equations that were used to be able to plot the conversion against the reactor temperature they were for:
When the temperature was below the melting point of coniferyl alcohol (74°C),
- Between the melting point of coniferyl alcohol and the boiling point of water (100°C),
- Between the boiling point of water and the boiling point of coniferyl alcohol (250°C), and
- For above the boiling point of coniferyl alcohol.

These equations for these four temperature ranges are shown respectively in the Appendix. The incomplete combustion is expressed as "y" in the equations, it is the fraction of the CO$_2$ produced that is then converted back to CO. These equations represent the system as shown in Figure 5.

Over a large temperature range the heat capacities cannot be considered constant therefore the heat capacity must be expresses as a curve the simplest of which is a polynomial expansion in $T$. This is commonly done and is adopted by process simulation software:

$$C_p = A + BT + CT^2 + DT^3$$

Equation 7

The coefficients, A, B, C and D are widely available for common chemicals. In this work those published by Perry (Perry, 1999) were used.

Therefore terms like $C_p(T_2 - T_1)$ in the development of Equation 1 were replaced by

$$\int_{T_1}^{T_2} (A + BT + CT^2 + DT^3) \ dT$$

This method was used for every chemical component, apart from coniferyl alcohol, when in the gaseous phase, for which only a single value of $C_p$ could be found and this was assumed constant. All other data used in the heat balance can be found in table A1 in the Appendix.

![Figure 5 SPG schematic used for the autothermal analysis](image-url)

The Arrhenius coefficient and activation energy could not readily be found for coniferyl alcohol but it was noted that there is little variation of the Arrhenius coefficient and activation energy between different fuels and so the value for butanol were used. All the values used for the mass balance equation are shown in Table 1.
Table 1 Constants used for the application of the mass balance line to the combustion of coniferyl alcohol

<table>
<thead>
<tr>
<th>Variable</th>
<th>$a$</th>
<th>$E$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>s$^{-1}$</td>
<td>J/mol</td>
<td>s</td>
</tr>
<tr>
<td>Value</td>
<td>$10^{22}$</td>
<td>400,000</td>
<td>50</td>
</tr>
<tr>
<td>Reference</td>
<td>(Sarvanathan, 2013)</td>
<td>Assumed value - found to be negligible on the final result</td>
<td></td>
</tr>
</tbody>
</table>

In this way Heerden diagrams were plotted for the SPGs. It is simple to plot multiple diagrams using different properties or inputs, to investigate how these changes in properties effect the position of the solutions. Figure 6 shows three different energy balance or heat consumption lines. Energy balance ‘A’ shows a case where the fuel is not viable and the only steady state solution is no conversion. Energy balance ‘B’ and ‘C’ both show three steady state solutions but it can be seen that case ‘C’ is further from potential extinction and that the lit combustion steady state for case ‘B’ is further from 100% conversion. Thus this analysis can be used to conclude which feedstock makes the better fuel for the SPGs.

Figure 6: Example Heerden diagram showing various different scenarios

**Autothermal model results**

**Model base case**

Using the trial data, a base case was developed to represent the typical operating scenario; the parameters selected for the base case are shown in Table 2. This set of parameters was chosen using the data provided by Thames Water for the financial analysis. Average
operating parameters were taken from between 0430 and 0830 on 08/11/13 just before the THP was fed into the FBC. This time period was chosen because operation was most steady at this point and being close to when the THP trial was beginning it makes it easier to compare the effect of this sludge on the behaviour of the SPG.

Table 2 Parameters used for the base case of the autothermal model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating value (Primary sludge/THP sludge)</td>
<td>20/14</td>
<td>MJ/kg dry solids</td>
</tr>
<tr>
<td>Dry solids (Primary sludge/THP sludge)</td>
<td>30/45</td>
<td>wt. %</td>
</tr>
<tr>
<td>Primary sludge flow rate</td>
<td>1.86</td>
<td>kg/s</td>
</tr>
<tr>
<td>THP flow rate</td>
<td>0.56</td>
<td>kg/s</td>
</tr>
<tr>
<td>Air flow rate</td>
<td>6.8</td>
<td>kg/s</td>
</tr>
<tr>
<td>Lance natural gas flow</td>
<td>0.6</td>
<td>wt. % of primary sludge</td>
</tr>
<tr>
<td>Air burner natural gas flow</td>
<td>1.4</td>
<td>wt. % of primary sludge</td>
</tr>
<tr>
<td>Air temperature after steam preheat</td>
<td>533</td>
<td>K</td>
</tr>
<tr>
<td>Sludge and natural gas feed temperature (assumed)</td>
<td>288</td>
<td>K</td>
</tr>
<tr>
<td>Incomplete combustion in the freeboard</td>
<td>3.5</td>
<td>%</td>
</tr>
<tr>
<td>Incomplete combustion in the reactor bed</td>
<td>8.5</td>
<td>%</td>
</tr>
</tbody>
</table>

The SPGs consist of two separate sections: the fluidised bed and the freeboard; owing to above bed burning, the freeboard temperature is always higher than that recorded for the bed. The amount of incomplete combustion for the freeboard was easily calculated as the carbon monoxide emissions from the bed are recorded. The incomplete combustion in the reactor bed was estimated so that the temperature difference between the bed and the freeboard was consistent with the measured data.

The base case result for primary sludge is shown in Figure 7. The fluidised bed and freeboard temperatures were predicted by the model to be 40°C higher than those measured in the trial. This is understandable as the model is simplified and does not factor in any heat losses. Strictly the freeboard line is not proper as the freeboard is not part of the zone of mixing within the unit.

The combustion is predicted to be stable with adequate room to cope with variations in the quality of the feed. This has been achieved by the operators, from experience and not analysis, and is achieved by using quite a lot of support fuel. The vertical jump in the heat balance lines shown in Figure is caused by the vaporisation of the feed.
Predicting the trial performance

With this calibrated base-case model the performance of the trials could be predicted. During the THP trials the SPGs were run as normal but an additional 2 tonnes/hr of THP feedstock was fed to the bed. Figure 8 shows three scenarios for the heat balance: the primary sludge flow only, the trial case of primary sludge with additional THP sludge and a flow of 100% THP sludge.

Figure 8 shows that, both in terms of reactor temperature produced and the distance on the diagram from the point of extinction (instability at steady state), the trial feedstock (a mix of additional THP and primary sludge) is a more viable fuel that the primary sludge as it produces a larger amount of heat which will be available for steam generation. The pure THP feed, which is the proposed future of Crossness and Beckton, shows the same superiority as a fuel/feed to the SPGs.

When the model predictions are compared to the recorded trial data it can be seen that the predicted reactor temperatures are higher than those recorded. In the case shown in Figure 8 the model predicts a bed temperature of 1230K but the measured temperature is 1150K. This is a slightly greater difference than was found in the base-case but does not suggest that the autothermal modelling is badly flawed.
Investigating the effect of dry solids content on the SPG performance

As the THP fuel differs from the typical primary sludge in two ways (dry solids content and energy content), the model was also used to investigate the impact of the dried solids content of the fuel in the base case scenario.

Figure 9 shows the impact of the dried solids content of the sludge feed to the SPGs. It can be seen that the combustion is very sensitive to the dry solids content, in the case of 25% dried solids content the system is very close to extinction. This would probably have been detected by the operators who would have increased the amount of support fuel.

Combining the autothermal model with the financial analysis methodology

Using the autothermal model with the recorded trial data it was possible to make predictions for the trial outcome. Two scenarios were selected from the trial data, one during a trial and one prior to a trial: the morning of the 8th of November (0430 – 0830) was selected as a suitable stable trial off scenario and the beginning of the trial on the same day (0900 – 1030) was selected as a comparable trial on period3. The recorded data from the trial results was input into the model and the predicted reactor temperatures were then used in the financial model.

The resulting net benefits for the trial off and trial on scenarios were found to be £3.78 /min and £5.59 /min respectively. The actual net benefits at these times calculated using the trial data for the trial off and trial on scenarios were £3.37 /min and £5.27 /min. Therefore the predicted increase of net benefit was £1.90 which compares very well with that obtained from the data analysis which was £2 per minute.

\(^2\) Note that the primary and THP mixture shown here has a higher flow rate than the other two streams to represent the trial conditions which cause it to reach a higher temperature than the pure THP.

\(^3\) The trial on scenario had to be kept this length because at 1030 the sludge flow rate to the SPG was increased.
Figure 9: Autothermal analysis showing the effect of dried solids content in the feedstock on the base case scenario

Conclusions

In this study two methods have been proposed and created which can be used to predict and analyse the performance of Thames Water’s SPGs and the effect of changing the feed to the SPGs from primary sludge to sludge exiting a THP process.

Through both theoretical prediction and the analysis of data gathered during the Thames Water trials, this study has found that THP sludge is a viable feedstock for SPGs and additionally THP sludge improves the performance of the SPGs compared with the typical primary sludge feed. It is believed that introducing the use of THP fuel could result in a financial benefit of more than £0.5m per year per SPG to Thames Water; a total of £1m per year for the Crossness site alone. The change of fuel will not adversely affect the operational stability of the SPGs.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>$a$</td>
<td>Arrhenius coefficient</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$A$</td>
<td>Flow of air or coefficient in eqn. 7</td>
<td>mol/s or J/(mol K)</td>
</tr>
<tr>
<td>$B$</td>
<td>Coefficient in eqn. 7</td>
<td>J/(mol K$^2$)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>$C$</td>
<td>Coefficient in eqn. 7</td>
<td>J/(mol K$^3$)</td>
</tr>
<tr>
<td>$C_{p,xy}$</td>
<td>Heat capacity in phase x (s- solid, l- liquid, v- vapour) of component y</td>
<td>J/(mol K)</td>
</tr>
<tr>
<td>$C_{xy}$</td>
<td>Concentration of component x (F = coniferyl alcohol, C = carbon dioxide) in stream y</td>
<td>mol.m$^{-3}$</td>
</tr>
<tr>
<td>$D$</td>
<td>Coefficient in eqn. 7</td>
<td>J/(mol K$^4$)</td>
</tr>
<tr>
<td>$E$</td>
<td>Activation energy</td>
<td>J/mol</td>
</tr>
<tr>
<td>$F$</td>
<td>Flow rate</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$k$</td>
<td>Reaction rate constant</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$m$</td>
<td>Molar flow rate</td>
<td>mol/s</td>
</tr>
<tr>
<td>$P$</td>
<td>Flow of flue gas</td>
<td>mol/s</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat flow</td>
<td>J/s</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant</td>
<td>J/(mol K)</td>
</tr>
<tr>
<td>$S$</td>
<td>Flow of sludge</td>
<td>mol/s</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_{bpx}$</td>
<td>Boiling point of component x</td>
<td>K</td>
</tr>
<tr>
<td>$T_{mpx}$</td>
<td>Melting point of component x</td>
<td>K</td>
</tr>
<tr>
<td>$T_x$</td>
<td>Temperature of inlet x (i-sludge and methane, iA- air)</td>
<td>K</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
<td>m$^3$</td>
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<tr>
<td>$x$</td>
<td>Fractional conversion</td>
<td>-</td>
</tr>
<tr>
<td>$y$</td>
<td>Fraction of incomplete combustion (fraction of CO$_2$ converted back to CO)</td>
<td>-</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Characteristic time (=V/F)</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$\Delta H_{fusx}$</td>
<td>Heat of fusion of component x</td>
<td>J.mol$^{-1}$</td>
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<tr>
<td>$\Delta H_{rx298}$</td>
<td>Heat of reaction of component x at 298 K</td>
<td>J.mol$^{-1}$</td>
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<tr>
<td>$\Delta H_{vapx}$</td>
<td>Heat of vaporisation of component x</td>
<td>J.mol$^{-1}$</td>
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</tbody>
</table>

**References**


APPENDIX

Table A1 Constants used for the application of the heat balance line for the combustion coniferyl alcohol

<table>
<thead>
<tr>
<th>Variable</th>
<th>ΔH_{M298}</th>
<th>ΔH_{C298}</th>
<th>ΔH_{F298}</th>
<th>ΔH_{fusF}</th>
<th>ΔH_{vapF}</th>
<th>ΔH_{vapW}</th>
<th>C_{p,FW}</th>
<th>C_{p,sF}</th>
<th>C_{p,lF}</th>
<th>C_{p,vF}</th>
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<tr>
<td>Units</td>
<td>J.mol(^{-1})</td>
<td>J.mol(^{-1})</td>
<td>J.mol(^{-1})</td>
<td>J.mol(^{-1})</td>
<td>J.mol(^{-1})</td>
<td>J/mol.K</td>
<td>J/mol.K</td>
<td>J/mol.K</td>
<td>J/mol.K</td>
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<tr>
<td>Value used</td>
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<td>283000</td>
<td>-4523400</td>
<td>21780</td>
<td>46012</td>
<td>40683</td>
<td>75.32</td>
<td>240</td>
<td>447</td>
<td>379</td>
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</tbody>
</table>

Equation A1

\[
x = -\left[\frac{SC_{FS}C_{p,FS}(T - T_i) + SC_{WS}C_{p,FW}(T - T_i) + SC_{AS}C_{p,FW}(T - T_{fa}) + AC_{OA}C_{p,vO}(T - T_{fa}) + AC_{NA}C_{p,vN}(T - T_{fa}) + AC_{CA}C_{p,vc}(T - T_{fa}) + AC_{WA}C_{p,vW}(T - T_{fa}) + MC_{MM}C_{p,vm}(T - T_i)}{SC_{FS}C_{p,FS}(298 - T) + 11.5 \times C_{p,vO}(298 - T) + \Delta H_{F298} + 10 \times (1 - y)C_{p,vc}(T - 298) + 6 \times C_{p,vW}(T - 298)} \right]
\partial + MC_{MM}[C_{p,vm}(298 - T) + 2 \times C_{p,vO}(298 - T) + \Delta H_{M298} + (1 - y)C_{p,vc}(T - 298) + 2 \times C_{p,vW}(T - 298)]
\partial + y(10 \times SC_{FS} + MC_{MM})[\Delta H_{C298} + C_{p,vCO}(T - 298) + 0.5 \times C_{p,vO}(T - 298)]
\]
Equation A2

\[
x = - \left[ SC_{FS}[C_{psf}(T_{mpf} - T_i) + DH_{fusf} + C_{pif}(T - T_{mpf})] + SC_{WS}[C_{plw}(T - T_i) + SC_{AS}[C_{pvn}(T - T_{ia})
+ AC_{OA}[C_{pvO}(T - T_{ia}) + AC_{IA}[C_{pvN}(T - T_{ia})] + AC_{CA}[C_{pvc}(T - T_{ia})] + AC_{WA}[C_{pwm}(T - T_{ia})] + MC_{MM}[C_{pvm}(T - T_i)]
\right.
\]

Equation A3

\[
x = - \left[ SC_{FS}[C_{psf}(T_{mpf} - T_i) + DH_{fusf} + C_{pif}(T - T_{mpf})] + SC_{WS}[C_{plw}(T_{bpw} - T_i) + DH_{vapf} + C_{pwm}(T - T_{bpw})] + SC_{AS}[C_{pva}(T - T_{ia})
+ AC_{OA}[C_{pvO}(T - T_{ia})] + AC_{IA}[C_{pvN}(T - T_{ia})] + AC_{CA}[C_{pvc}(T - T_{ia})] + AC_{WA}[C_{pwm}(T - T_{ia})] + MC_{MM}[C_{pvm}(T - T_i)]
\right.
\]

Equation A4

\[
x = - \left[ SC_{FS}[C_{psf}(T_{mpf} - T_i) + DH_{fusf} + C_{pif}(T_{bpf} - T_{mpf})] + DH_{vapf} + C_{pva}(T - T_{bpf})] + SC_{WS}[C_{plw}(T_{bpw} - T_i) + DH_{vapf} + C_{pwm}(T - T_{bpw})] + SC_{AS}[C_{pva}(T - T_{ia})
+ AC_{OA}[C_{pvO}(T - T_{ia})] + AC_{IA}[C_{pvN}(T - T_{ia})] + AC_{CA}[C_{pvc}(T - T_{ia})] + AC_{WA}[C_{pwm}(T - T_{ia})] + MC_{MM}[C_{pvm}(T - T_i)]
\right.
\]