The Development of an Ultra-Superheated Steam Gasifier for Efficient Embedded Power Generation

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Introduction

This research investigates the design and operation of a novel gasifier that utilises *ultra-superheated steam* (USS) in lieu of the partial combustion used in conventional systems to obtain the heat energy necessary for the endothermic reactions of gasification.

➤*Project Aims*:

- To develop a novel gasifier for the gasification of coal using ultra-superheated steam (USS).
- To investigate the mechanisms of introducing the coal and the USS.
- To compare the efficiencies of different burner designs.
- To obtain comprehensive data on the flame shape, temperature and stability to determine the optimum running conditions.
- To monitor emissions of carbon monoxide, hydrogen and oxygen from the gasifier.
- To model the flame and gasifier using CFD codes.
- To investigate the gasification of different UK and world-traded coals.
- To evaluate, economically, the feasibility of incorporating such a gasifier into a waste incineration plant to utilise the steam generated.

Ultra-Superheated Steam (USS)

USS can be generated in any conventional gas burner that fires a gaseous fuel such as methane or propane. The oxidiser in the combustion reaction is a mixture of oxygen and steam instead of air, with the components proportioned similarly to air, *i.e.* nominally 79% steam and 21% oxygen by volume. This mixture is referred to as *synthetic air*. The flue gas from this combustion is the USS.

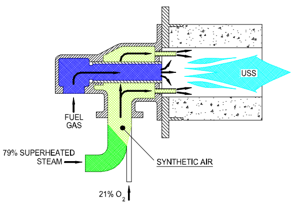

Figure 1: *USS Generator*

Figure 1 illustrates the generation of USS. For methane – synthetic air (21 mol% oxygen) combustion at stoichiometric proportions the USS consists of:
•90 mol% steam
•10 mol% CO_2

The USS flame (*Figure 2*) is colourless. The yellow colour on the burner port is due to the glowing ceramic rather than being the flame colour.

Although the USS flame is non-luminous in nature, it consists of H_2O and CO_2 which generate non-luminous radiation for the transfer of heat energy in a gasification process.

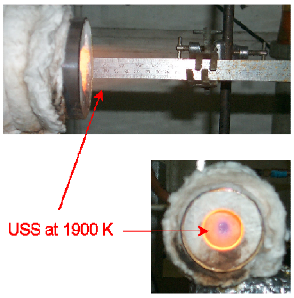

Figure 2: *USS Flame*

USS Temperature and Gasification

The temperature of a flame is dependent upon the stoichiometry of the fuel and oxidiser mixture. It is possible to vary the USS flame temperature by changing the O_2 content of the synthetic air.

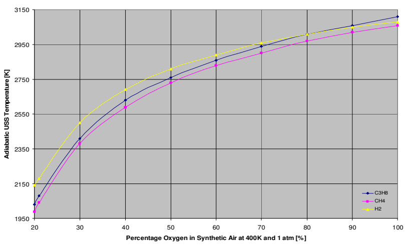

Figure 3: *Adiabatic USS Temperature vs Synthetic Air Composition*

A calculation of the equilibrium adiabatic flame temperatures for propane,methane and hydrogen – synthetic air combustion at varying oxygen content yielded the temperature profiles shown in *Figure 3*.

Real flame temperatures are however not as high as the adiabatic flame temperatures.

The flame temperature is a critical variable in determining the heat transfer from the USS to the load, which is the fuel particles undergoing gasification.

➤*Main reactions of gasification*:

a) Partial combustion
$C + \frac{1}{2}O_2 \Leftrightarrow CO$ $\Delta H = -123.1$ kJ/mol

b) Combustion
$C + O_2 \Leftrightarrow CO_2$ $\Delta H = -405.9$ kJ/mol

c) Gasification with Carbon Dioxide (Boudouard reaction)
$C + CO_2 \Leftrightarrow 2CO$ $\Delta H = +159.7$ kJ/mol

d) Gasification with Steam (Water-Gas reaction)
$C + H_2O \Leftrightarrow CO + H_2$ $\Delta H = +118.9$ kJ/mol

e) Gasification with Hydrogen (Hydrogasification)
$C + 2H_2 \Leftrightarrow CH_4$ $\Delta H = -87.4$ kJ/mol

In USS gasification the USS generation can be considered to be complete before gasification takes place.This means that no oxygen enters the gasification zone, and so there are no *Reactions (a)* and *(b)* to provide the heat energy needed for the endothermic reactions *(c)* and *(d)*. The heat energy is provided by the USS in an allothermic process.

A proposed gasification cycle for the USS process is shown in *Figure 4*.

With treatment, the syngas it can be recycled as the start-up fuel for the USS generation.

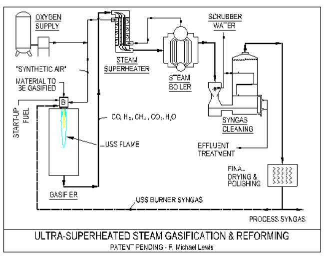

Figure 4: *Proposed USS Gasification Cycle*

Experimental Rig

The burner selected for the generation of USS and subsequent USS gasification was a dual-fuel burner. Its design capacities are a maximum air flow of 0.0322 m^3/s (1935 l/min) and a heat output of 120 kW (410 000 Btu/h). This burner was chosen because, being manufactured for dual fuel operation it could be easily adapted for the USS gasification by either replacing the liquid fuel pipe with one suitable for the supply of granular material for the gasification of solids, or by just using the burner as supplied for the gasification of liquid or slurry material.

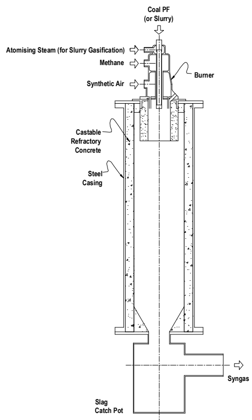

Figure 5: *Cross-Section of the USS Gasifier*

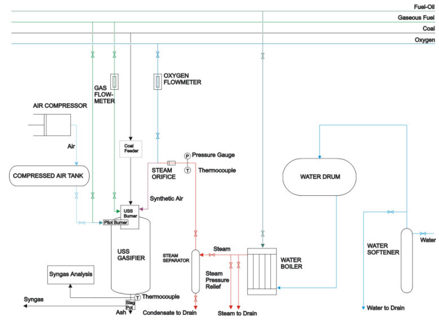

Figure 6: *Rig Layout*

The USS gasifier (*Figure 5*) is composed of two distinct parts; the USS generator (a burner) and the gasification chamber. *Figures 6* and *7* show the layout of the entire experimental rig.

The gasification chamber is composed of a mild steel shell, lined with 50 mm thick fused alumina-based castable refractory with high abrasion resistance. The internal dimensions of the gasification chamber are 1250 and 285 mm in height and diameter, respectively.

There is a catch pot at the foot of the gasifier to collect ash or unburned material. Syngas samples are also drawn at the exit of the gasifier for a GC analysis.

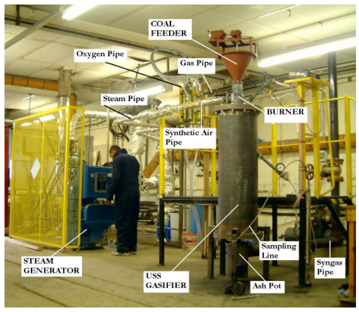

Figure 7: *Rig Photograph*

USS Gasification and Comparisons

For the gasification of a low volatile bituminous coal with the cumulative size distribution shown in *Figure 8*, the syngas yield is shown in *Figure 8*.

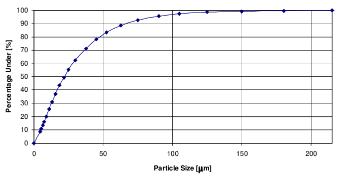

Figure 8: *Cumulative Size Distribution of the Coal*

The USS for this gasification was generated with a synthetic air composed of 40 mol % O_2 and 60 mol % steam and C_3H_8 as fuel.The USS was at an estimated temperature of 2630 K.

Figure 9 presents the results of the USS Gasification along with other entrained flow gasification processes for comparison purposes.

The USS process can be used for both particulate and slurry gasification. It can also be used to gasify waste materials as part of their disposal.

GASIFIER	USS	Shell	Koppers-Totzek	Texaco
Coal	Low vol bituminous	Illinois bituminous	Illinois bituminous	Illinois bituminous
Oxidant	USS	oxygen	oxygen	oxygen
Feed	dry	dry	dry	slurry
Ash	dry	slag	slag	slag
T_{exit} *(K)*	1083	1703	1223	1643
P *(atm)*	1	25	1	42
O_2/coal *(kg/kg)*	0.93	0.76	0.74	0.76
H_2O/coal *(kg/kg)*	0.79	0.05	0.12	0.32
H_2O/O_2 *(kg/kg)*	0.85	0.07	0.16	0.42
Syngas composition, vol %				
H_2	38.4	26.7	21.1	30.3
CO	31.0	63.1	43.8	39.6
CO_2	25.2	1.5	4.6	10.8
CH_4	2.2	0.0	0.0	0.1

Figure 9: *USS Gasification along Other Entrained Flow Processes (Source of Other Processes, Kristiansen [1996])*

Conclusion and Future Work

The test rig has been used to acquire preliminary results on the parameters that are important in the gasification, and the work done so far in the research can be summarised as follows:

- A gasifier was designed and constructed.
- The 285 mm diameter by 1250 mm height (internal dimensions) USS gasifier constructed is capable of gasifying coal at a rate of 10g/s.
- The syngas achieved using the above conditions was found to contain about 38% H_2 and 31% CO.

Work remaining in this project includes detailed CFD calculations, gasification of different coal types and an economic assessment on the feasibility of incorporating such a gasifier into a waste incineration plant

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