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Development of a novel solids feed system for high pressure gasification

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ABSTRACT

The Hydraulic Lock Hopper (HLH) embodies a high pressure dry feed system that uses water as an incompressible fluid to bring about compression. No pressurising gas is required, so commonly used inert gases such as nitrogen and carbon dioxide are conserved. The HLH has successfully demonstrated the feeding of solid fuels such as wood pellets to pressures as high as 25 barg in two modes of operation. Energy requirements of 15.51 kJ/kg (Mode 1) and 20.61 kJ/kg (Mode 2) have been recorded which translate to significant energy savings of 81.9% and 75.9% compared to conventional lock hoppers. Energy savings have been projected to increase for Mode 2 where lock gas contamination with syngas takes place, and the mass flow rate has been shown to operate independently of pressure varying between 2 and 2.5 tonnes/day. The HLH has also been shown to have a negligible effect on the fuel moisture content with moisture content increases being recorded to be consistently less than 1 wt.%.

1. Introduction

In recent years there has been an increased drive to produce energy from renewable sources. However, conventional fuels such as coal, oil and gas still dominate the landscape in terms of energy production and account for approximately 87% of the world's total energy supply [1]. Gasification poses as a technology that can provide both a carbon free power supply where biomass is used, and a more efficient power supply using conventional fuels when integrated as a combined cycle (IGCC). However, in order to operate combined cycle processes effectively, the feed stream has to be pressurised prior to use in the gas turbine stage. This presents two options for operation: either the gasifier operates at atmospheric pressure and the syngas produced is pressurised to the desired pressure for operation post gasification, or the gasifier operates at elevated pressure to produce a syngas product at pressure ready to be utilised in a gas turbine. The latter route both presents savings in the energy required for syngas compression and allows a reduction in equipment size [2–4]. It is for this reason that practically all modern gasifiers operate at pressures above that of the atmosphere, typically between 25 and 40 bar [4,5].

However, at the expense of increased operating efficiency comes increased process complexity; not least with the way in which the solid feedstock is introduced to the process at pressure. Where gasification at elevated pressure is concerned, the feeding system has been cited as one of the most common causes of process downtime [6,7]. Added to this the fact that current feeding systems are typically inefficient and present a burden on the overall efficiency of the gasification process highlights the need for alternative devices to be developed.

1.1. Scientific background

High pressure solids feeders can be split into six categories: rotary valves, lock hoppers, plug-forming feeders, piston feeders, dynamic feeders and slurry feeders [8–15]. Amongst these, lock hoppers and slurry feeders are the most common and established feed systems; however, neither system is without its operational drawbacks [3,4].

The principal drawback of lock hoppers is their inefficient operation due to a large reliance on gas used for pressurisation. The largest portion of the power required to facilitate the feeding operation is used in this step and is ultimately wasted during the depressurisation stage [12,16]. Both the power used for pressurisation and the gas used are wasted due to pressurisation cycling, and losses are seen to increase dramatically with increasing pressure.

Slurry feeders look to counter issues regarding inefficient feeding through the adaptation of conventional liquid pumps. However, the large amount of water used to make up the slurry, typically 60–70 wt.% solids in the case of coal [9] and 10–15 wt.% solids in the case of biomass [17], poses as the main drawback in their operation. Gasification only requires a small portion of the water present in slurries for steam formation and use in the water-gas shift reaction, and the remaining water or moisture content serves to decrease the overall efficiency of the gasification process. A large amount of energy is required to vaporise any excess moisture present in the fuel and this in turn increases oxygen consumption and leads to decreased cold gas efficiencies. In practice, dry fed gasifiers have a 20–25%

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lower oxygen consumption for this reason alone [4]. The disadvantage of slurry feeding is particularly felt where the gasification of biomass and low rank coals is concerned, as such fuels inherently contain high levels of moisture. It is generally accepted that combustion and gasification reactions cannot proceed where moisture contents exceed 60–65 wt.% [18,19]. Given that the internal moisture content of a fuel does not contribute towards the moisture required to make up a slurry leads to the conclusion that feeding biomass and low rank coals as a slurry is not a viable option [4].

A number of feed systems within the remaining categories have been developed to counter the drawbacks stated and are present in the literature [8–10,15]. However, the majority of devices developed have failed to reach a commercial stage, leaving lock hoppers and slurry feeders as the two most common types of feed system in the gasification industry. The objective of this study is to develop a solids feed system for efficiently feeding solid fuels to high pressure processes, and to counter the common drawbacks experienced in current systems.

2. Materials and methods

2.1. Hydraulic Lock Hopper

The Hydraulic Lock Hopper (HLH) takes the form of a new lock hopper that utilises water as an incompressible fluid. Water is used to minimise the amount of work required in the compression stage of the feeding operation by displacing gas at high pressure. Therefore, the bulk of the compression work is carried out by the water and in turn the pump used to introduce the water into the high pressure environment. A high pressure water pump provides the only mechanical action during the feeding operation and is used in place of a compressor as found in conventional gas compression cycling. A schematic diagram of the HLH and the experimental rig is shown in Fig. 1.

The HLH consists of two hoppers equal in volume, a high pressure collection vessel and a high pressure water pump. As the feeding system operates as a batch process, the role of the collection vessel is to act as a destination to be fed to at pressure. In reality the collection vessel can act as a "live bottom" feeder using a variety of established feed systems to provide continuous feeding of solid fuel to the desired downstream process. Feeding devices such as metering bins and screw feeders are routinely used in such scenarios and have been demonstrated specifically by the lock hopper developed by Thomas R. Miles Consulting Engineers for such a purpose [13,14].

The atmosphere and the top hopper are separated by a ball valve (V1), the top and bottom hopper are separated by a ball valve (V2) and similarly the bottom hopper and the collection vessel are separated by another ball valve (V3). Further to this, the top and bottom hopper are connected by an external pipe outside of the main body of the feeding system which contains an isolation valve (V4). This connecting pipe is used for pressure equalisation and recompression. Another connecting pipe is fitted to the top hopper which contains three valves (V5, V6 and V7). Water is fed from the high pressure water pump to the top hopper via V5 and V6 and is drained via V5 and V7 to a water collection chamber. A third and final pipe containing a valve (V8) is added to the top hopper in the form of a syphon which serves to reduce the volume of water retained in the top hopper to a minimum after the water drainage stage.

2.2. Modes of operation

The HLH can be operated in two separate modes: Mode 1 and Mode 2. Mode 1 requires a volume of water to be pumped to the top hopper that is approximately equal to that of the void space present between the fuel; this typically varies between 40 and 60% for most solid fuels [20]. Assuming a voidage of 50% would require the top hopper to be half filled with water to compress the fuel to the desired operating pressure. In Mode 1, the HLH begins its cycle with the top hopper at atmospheric pressure, the bottom hopper at the desired operating pressure, and both hoppers empty of fuel. All valves start in the closed position, and therefore the opening of V2 brings about pressure equalisation between the top and bottom hopper prior to the pumping of water in the compression stage of the feeding operation.

Mode 2 is more energy intensive than Mode 1 and requires the top hopper to be completely filled with water; this minimises the volume of gas at pressure vented to the atmosphere during the decompression stage. Contrary to Mode 1, V3 is left in the open position at all times during Mode 2 as to avoid a considerable over pressure in the bottom hopper; in Mode 2 the bottom hopper only acts to increase the volume of the collection vessel. A slight net increase in the overall process pressure is encountered during this mode of operation due to the volume taken up by the fuel fed. However, such an increase is considered to be negligible when the overall volume of the downstream process being fed to is taken into consideration. Like Mode 1, the HLH begins its cycle with the top hopper at atmospheric pressure, both hoppers empty of fuel, and all valves aside from V3 in the closed position.

The reason for the hoppers of equal volume (top, H1 and bottom, H2) becomes apparent when the compression work required by the HLH is examined alongside a conventional single lock hopper with a varying volume ratio of H2:H1 (Fig. 2). In the case of Mode 1, the energy saving increases with a decreasing volume of the vessel being fed to, which brings about a minimum volume equal to the hopper located immediately upstream. The opposite of this is found to favour Mode 2. Therefore, leaving V3 open provides a more efficient way in which to operate Mode 2 as the bottom hopper acts to increase the total volume of the collection vessel.

3. Results and discussion

3.1. Cycle analysis and operation

The principle of the HLH was assessed using 6 mm wood pellets made available by CPL Distribution Ltd. The pellets used were produced from chemically untreated residues from the wood processing industry and to satisfy the standard ENplus A1.

The HLH is a batch feeding system and therefore the geometry of the system governs the mass flow rate and how it is operated. A maximum of three batches of fuel can be fed across the pressure boundary during one *complete* cycle (defined as system pressurisation, fuel feeding and system depressurisation) and therefore results relating to cycle operation are presented as such.

Fig. 3 provides an overview of the internal pressure and temperature readings during operation in a 25 barg case for Mode 1 and Mode 2. The temperature changes observed in the top hopper, bottom hopper and collection vessel are due to the changes in pressure brought about through the compression and expansion of air. The expansion and compression in this instance represents a polytropic process approximating an isothermal process as temperature changes are observed with little net change in the overall temperature over extended periods of time.

In the case of Mode 1, temperature variations are recorded by TC3 and TC2 in the top and bottom hopper respectively, while the temperature in the collection vessel is seen to stay constant. The temperature changes observed in this case can be attributed to the large changes in pressure observed in the top and bottom hopper during operation. Similarly, the constant temperature reading in the collection vessel denotes a stable and constant pressure as is observed.

In the case of Mode 2, temperature variations similar those observed in Mode 1 are found. However, temperature variations are also observed in the collection vessel and can be broadly compared to those found in the bottom hopper. During Mode 2, V3 is left open throughout operation and the bottom hopper acts to increase the volume of the collection vessel. Larger temperature variations are recorded by TC2 in the bottom