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High Pressure Solids Feeding Using a Lockhopper System: Design and Operating Experience

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ABSTRACT

The feeding of solids into a high pressure reactor has always been difficult because of both high equipment costs and poor material characteristics. As part of the Solar Energy Research Institute's investigation into the acid hydrolysis process, a lockhopper system was developed to feed wood into a vessel operating at 160°C (320°F) and 1.12 MPa (150 psig). Preliminary results show that the lockhopper operates successfully at temperature and pressure for a limited amount of time on wood sawdust. However, a problem that must be watched during operation is plugging of pneumatic lines by wood dust.

Index Entries: Solids feeder; high pressure feeder; lockhopper; wood feeding; acid hydrolysis.

INTRODUCTION

The need for a high pressure feeder stems from the Solar Energy Research Institute's (SERI) involvement in acid hydrolysis process for the production of alcohol. This process converts cellulosic feedstocks to glucose (via acid hydrolysis), for fermentation to ethanol. Ethanol has received attention as a substitute for petroleum-derived fuels and can be used for octane enhancement in unleaded gasoline. Although corn has been the primary feedstock for ethanol production, its cost is too high to be competitive in the present fuel market. Cellulosic feedstocks are cheap, but pose processing and conversion problems that first must be solved.

SERI is completing work on the plug flow acid hydrolysis process. The rationale for this work is described elsewhere (*1*). Previous work on the plug flow process (*2,3*) has used wood slurries of 10% by weight solids. A recently completed study for SERI (*4*) concludes that a solids level of 20% and a prehydrolysis step is required to make the process economically attractive. However, since pumping a 20% slurry is difficult, a prehydrolysis step was proposed to partially liquefy the wood, effectively decreasing the solids concentration at the pump (*4*).

Figure 1 shows the basic configuration of the plug flow acid hydrolysis experiment. Briefly, water is heated to prehydrolysis reaction temperature by direct steam injection and empties into a 190 L (50 gal) vessel after addition of concentrated sulfuric acid. Then wood must be added to the reactor, maintained at 1.12 MPa, at a controlled feed rate. After a residence time of 5–10 min, the now partially hydrolyzed mixture is pumped to the hydrolysis reactor by the Moyno pump. Direct steam injection heats the mixture to hydrolysis reaction temperature for 4–20 sec before it flashes into a separation vessel. Liquid product (5–8% glucose) is taken from the bottom of the separator, cooled, and routed to a storage vessel. The vapor product, rich in furfural, is condensed and also routed to a storage vessel.

In previous work (*2*), a 10% wood slurry was premixed in a large tank and then pumped to the hydrolysis reactor. Currently, we are at-

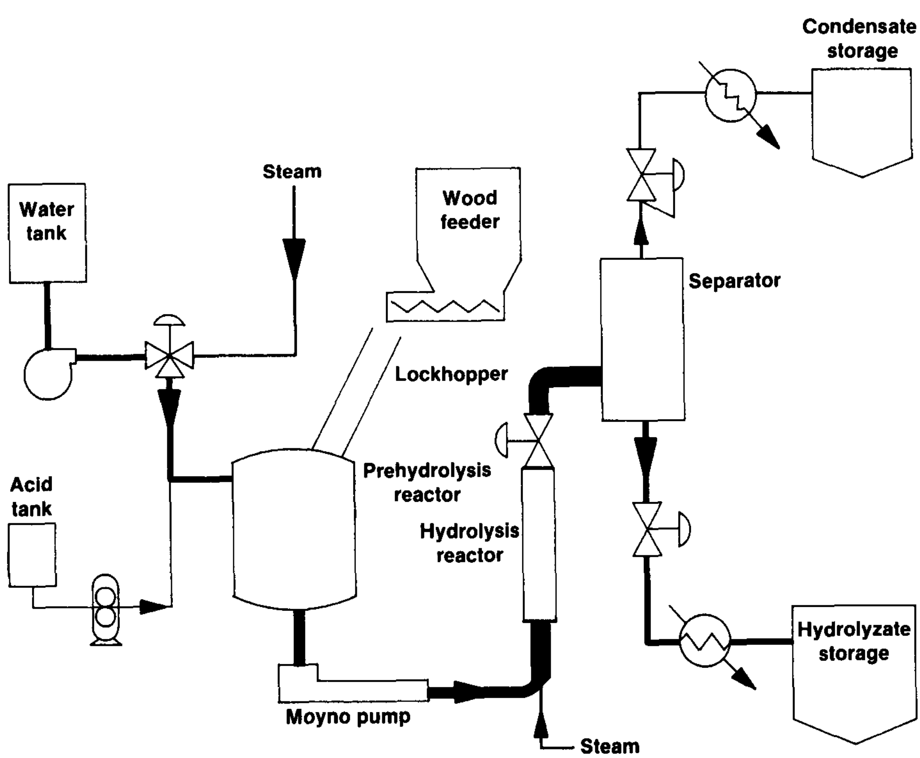

Fig. 1. SERI plug flow acid hydrolysis experiment.

tempting to pump a 20% prehydrolyzed slurry to the hydrolysis reactor. A 20% slurry contains very little free water, is easily dewatered, and is not pumpable; the dry wood must be added to the liquid contents of a vessel maintained under 1.12 MPa of pressure. Thus, a high pressure solids feeder was required that could deliver a variety of feedstock sizes to a vessel at elevated temperatures and above atmospheric pressure.

HIGH PRESSURE FEEDERS

Feeder types are broken down into two classes: those that make a pressure seal mechanically, such as lockhoppers and piston feeders, and those that use the feed material to make a pressure seal, such as plug feeders. The former are less sensitive to material characteristics, whereas the latter must achieve a compressed plug of material that partially blocks the escape of gases back through the feeder. Much of the information presented below on feeder types is abstracted from a review of high pressure feeders by Guzdar and Harvey, and was presented at the Biomass-to-Methanol Specialists' Workshop (5).

Lockhopper

Conceptually, the lockhopper is the simplest system to design and operate. Material is fed into an intervening chamber located between the high pressure reactor and atmospheric pressure. The chamber is pressurized to reactor pressure, the seal (valve) to the reactor is broken, and the material then gravity feeds into the reactor. Operationally, the system is known to suffer from problems, such as sealing valve failures, solids holdup, and decreasing system reliability. Furthermore, large operational costs are associated with the requirement for pressurized gas and related support hardware.

Despite these problems, lockhoppers are one of the few commercially available systems for feeding biomass. The Miles Biomass Gasifier Feeder (5), shown in Fig. 2, is one such system that can feed various types and sizes of chips. Tom Miles uses knife gate valves to maintain the seal between atmospheric pressure and the high pressure reactor. A "Live Bottom Hopper," consisting of screws, is used for metering and injection into the gasifier. In another application (6), Kamyr ball valves have been used for lockhoppering peat.

Recent work (7) by the US Department of Energy (DOE) has focused on improving the reliability and operating characteristics of lockhopper valves. A test program identified the major failure modes of lockhopper valves as poor quality control, design problems, and solid related problems. Some generalizations for improving the performance of lockhopper valves were to provide an unrestricted flow path, to keep critical surfaces clear, to maintain contact between the seat and closure member, to watch

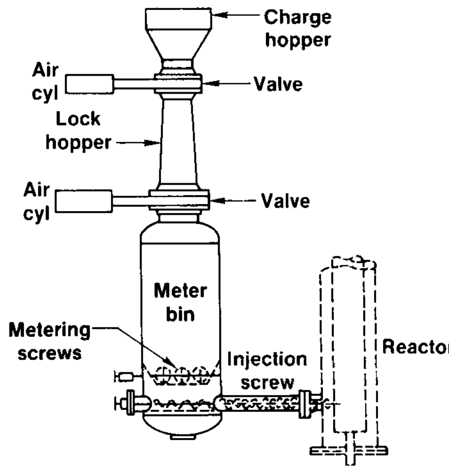

Fig. 2. Miles biomass gasifier feeder (5).

tolerances between seat and the body, to size actuators properly, and to maintain quality control.

Piston Feeder

The operating cycle of a piston feeder is essentially the same as the lockhopper, except that compression by a piston is used to reduce gas consumption. A typical operating cycle consists of filling the chamber, trapping the contents, pressurizing with the piston, opening a valve and dumping the contents, displacing gas from the chamber with the piston, shutting off the chamber, and re-expanding the chamber's volume. Although most of the development work on piston feeders has been for high pressure coal feeding, if positive material flow is assured they have an obvious use as a biomass feeder.

Many piston type feeders have been developed, but only two machines will be discussed here. One machine that has been developed by Conspray Construction Systems, Inc., is an adaptation of their commercial wet concrete pump, shown in Fig. 3. A unique feature of this machine is a retracting sleeve at the bottom of the fill hopper that traps the material into a chamber. A piston and central rod then discharge the material from the chamber through a slide valve. Actuation is hydraulic and controlled by a microprocessor, and the system can use more than one piston to obtain nearly continuous material flow.

Another machine shown in Fig. 4 developed by Ingersoll-Rand for DOE uses two opposing pistons, one for material transport and one for gas exclusion. Material is loaded into a chamber created by the two pistons and transported to a drop chute. At the same time the pistons move together, equalizing the pressure. As material gravity feeds into the reactor, the pistons move completely together, excluding the gas, and then move back to the loading position while separating to create the cham-

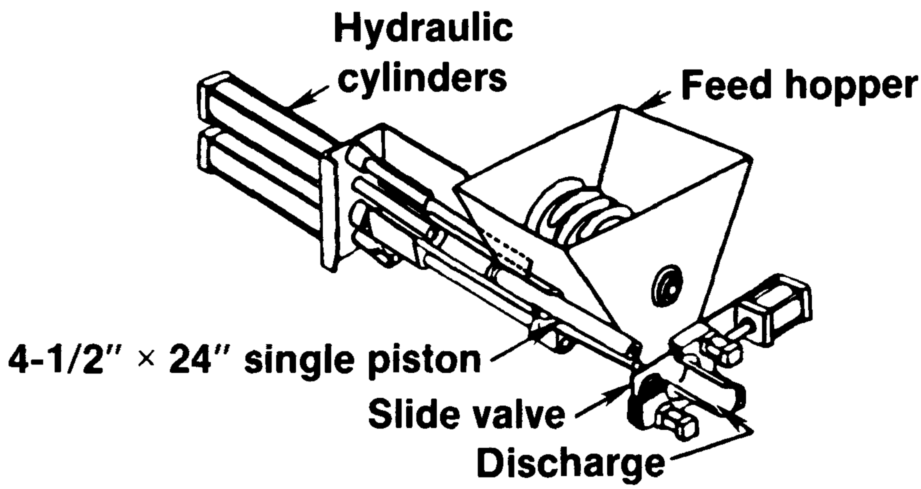

Fig. 3. Conspray piston pump (5).

ber. The pistons are again hydraulically actuated and are always in a position that blocks gas leakage from the reactor.

Pocket Feeder

The most common type of pocket feeder is the rotary airlock, shown in Fig. 5. Material is gravity fed to a pocket created by rotating vanes. Rotation of the vanes creates a seal with the valve body and transports the material to the high pressure zone. Gravity then causes the material to feed into the reactor. During further rotation, the pocket is vented and

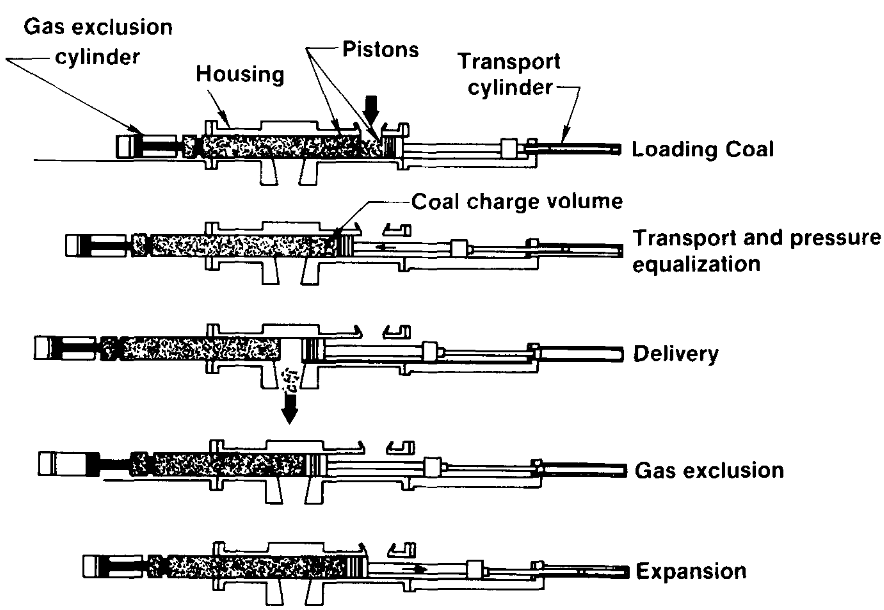

Fig. 4. Ingersall-Rand dual piston feeder (5).

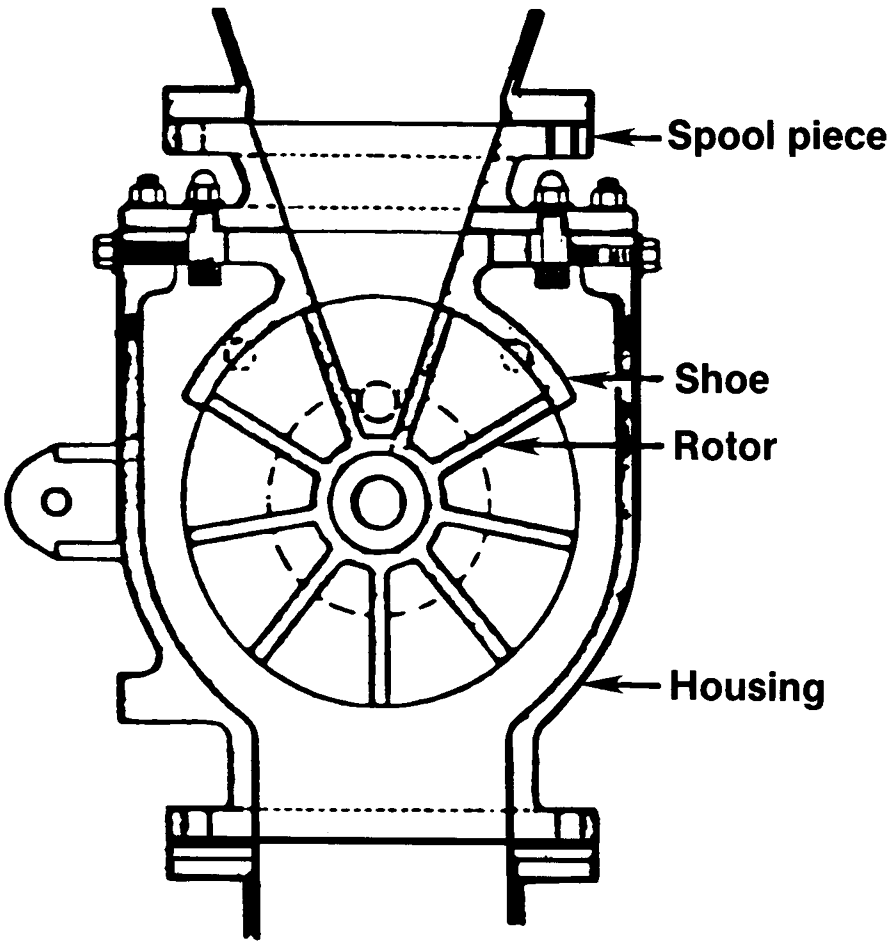

Fig. 5. Rotary airlock feeder (5).

is ready again to receive more feed material. Applications have been limited to less than 690 kPa because of gas leakage past the vanes.

An adaptation of the rotary airlock feeder to a linear version is shown in Fig. 6 and is called the Linear Pocket Feeder. It consists of a tubular conveyor in which a series of pistons are connected together with a chain to form the pockets. Material gravity feeds into a pocket, which enters a conveyor to form the pressure seal. Further along the conveyor the material gravity feeds into the reactor and the pocket is displaced with gas. Later in the cycle, the gas is displaced by water and returned to the reactor. This system has several advantages—it has no cyclic valves or controls in its operation; it has a fail safe design, so no leakage occurs when running or stopped; and gas compression is supplied by a water pump.

Screw Feeder

The screw feeder is part of the class of plug feeders that uses the feed material to form the pressure seal. The feed material is conveyed down a

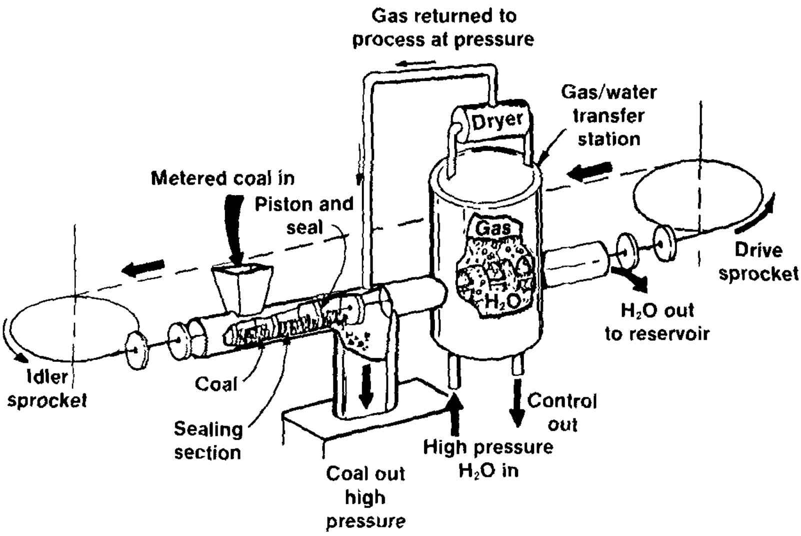

Fig. 6. Linear pocket feeder (5).

barrel and compressed at the end of a screw with enough pressure to form a plug. A single screw having a decreasing pitch can be used for low pressures. High pressures have been obtained using two corotating screws that wipe each other and the barrel to keep the material moving. The disadvantages of screw feeders are that they tend to compact the material into pellets or logs, they are sensitive to the size and shape of the solids, they have a high specific energy consumption, and they are very expensive.

One machine described in a patent (*8*) avoids compressing the material into logs by using a rotating choke at the end of the barrel. The choke is spring loaded to maintain pressure in the barrel and has fins to break up the plug as it passes out of the barrel and into the reactor.

The twin screw extruder, Fig. 7, has been used to both pump and hydrolyze biomass on a small scale (*9*). New York University has fed diverse feedstocks such as newsprint, peanut hulls, corn bran, and sawdust into the barrel of a nominal 1.0 metric ton/d extruder. Once sufficient pressure is obtained (3.2 MPa), acid and steam are introduced into the barrel of the extruder, and, with the positive conveyance and mixing of the screws, the mixture is quickly brought up to reaction temperature. After a known reaction time determined by the screw speed, the mixture is flashed to atmospheric pressure.

Ram-Type Plug Feeders

The ram-type feeders avoid the high energy usage of the screw feeders by pushing the material into a plug. One such machine has been developed by Stake Technology, Inc., of Canada, and consists of a reciprocating rotating screw that pushes the plug formed by the screw. A choke at the end of the barrel maintains pressure and breaks up the material.

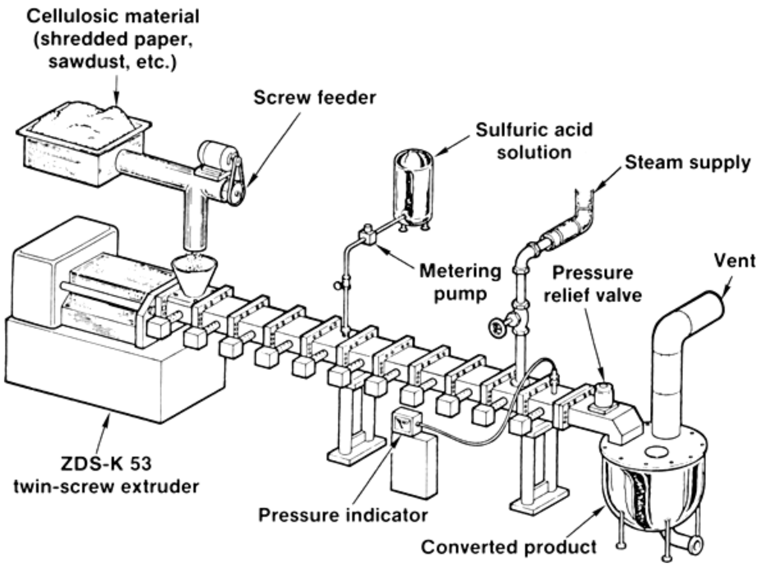

Fig. 7. Acid hydrolysis of biomass using a twin screw extruder (*9*).

This machine is used in a pretreatment process to feed cellulosic material into a digester (*10*).

Another system for coal feeding, Fig. 8, has been developed by Ingersoll-Rand under sponsorship from DOE. This system also uses a reciprocating and rotating screw to form a plug of feed material. First, the screw rotates and retracts at the same time, feeding material to the seal plug at the end of the barrel. When the screw is fully retracted, the screw stops rotating and is pushed forward, compacting and injecting material into the reactor. When the screw is fully extended, the cycle is ready to begin again.

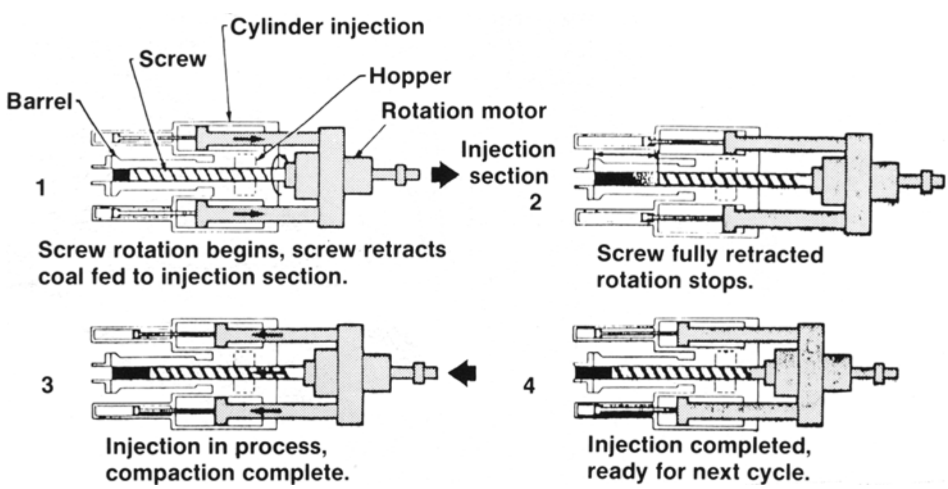

Fig. 8. Ingersall-Rand screw extruder (*5*).

Centrifugal Plug Feeder

Figure 9 show a centrifugal plug feeder developed by Lockheed, also under sponsorship of DOE. Material enters through the center of a rotor and is collected in one of several radial chambers. The material is then compacted by centrifugal force into a plug, which moves outward at a rate determined by the tip speed of the rotor. The material flowrate is determined by the rotor speed, centrifugal forces, and the pressure differential. The pressure capability is determined by rotor speed, the flowrate, and size and number of nozzles.

LOCKHOPPER DESIGN

The wood delivery system consists of two parts—the loss-in-weight feeder and the lockhopper. The wood feeder is a commercially available unit ordered from Vibra Screw, Inc., with a maximum flowrate of 1.4

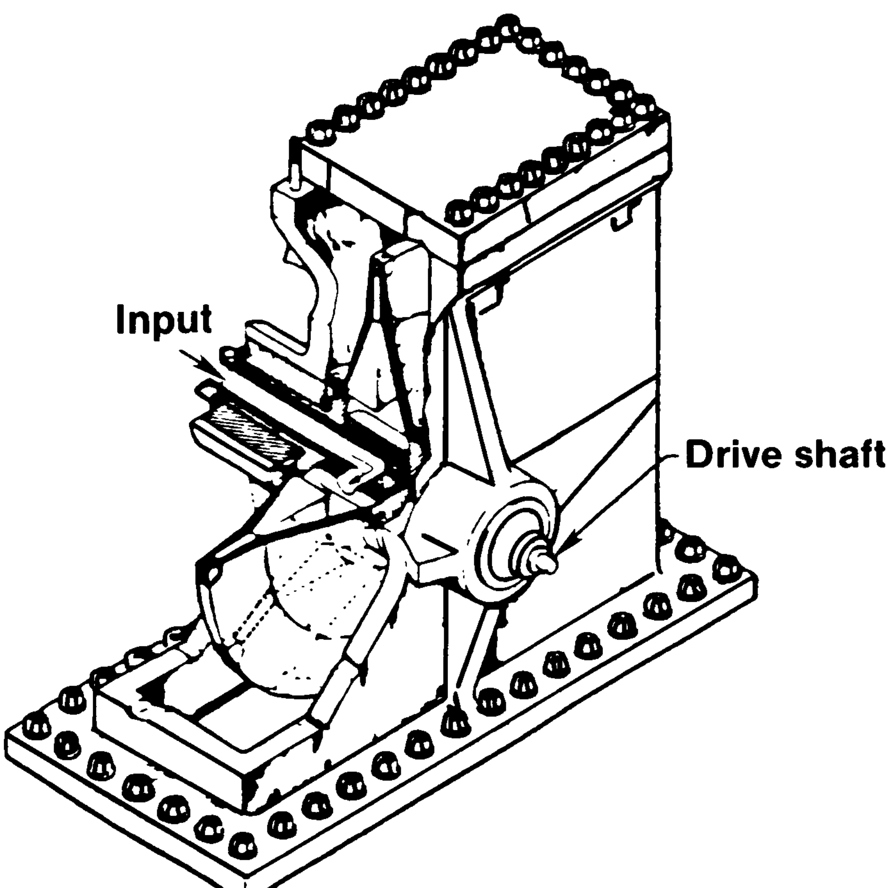

Fig. 9. Centrifugal plug feeder (5).

m^3/h (50 ft^3/h). A lockhopper was chosen because it is one of the simplest and easiest devices for bridging a pressure differential. It also has the advantage of being relatively inexpensive and insensitive to feed material. For example, the cost of the wood feeder and lockhopper was approximately $28,000, of which $2000 was for the lockhopper equipment. A plug-type screw feeder with blow back protection was quoted at near $80,000.

Lockhopper design was guided by several factors—the required material flowrate through the hopper, the pressure and temperature requirements, control element responses, and lockhopper exposure to steam from the prehydrolysis vessel. The flowrate is important for determining hopper sizes and the required cycle time. Temperature and pressure determine the hopper, valve, and seal materials. Control element responses such as valve cycle time, pressurization, and venting times all determine the overall control strategy. Consideration of steam was important because it was expected to cause the feed material (wood flour) to become "sticky," possibly adhering to the lockhopper walls and causing sealing problems. The overall design attempted to balance all these factors to obtain the best operation. For example, material will flow better through a larger hopper; however, this will also increase gas consumption.

System Description

Figure 10 is a schematic of the lockhopper, also showing elements of the electrical and pneumatic systems. The lockhopper consists of the airlock chamber, the supply hopper, and the knife gate valves. The airlock chamber is a 15.2 cm (6 in.) diameter by 30.5 cm (12 in.) long 316 L stainless steel pipe with flanges on both ends. The valves at both ends of the airlock chamber are 15.2 cm (6 in.) DeZurich knife gate valves with Viton resilient seats and 15.2 cm (6 in.) pneumatic cylinders for actuation. Resilient seats are needed to maintain pressure in the chamber, although, the temperature exceeded the 120°C rating of the seats. The supply hopper is also a 15.2 cm (6 in.) stainless steel pipe approximately 60.9 cm (24 in.) long. Since the wood feeder delivers material at a constant rate, the supply hopper's function is to catch and hold a charge for the airlock between cycles.

The pneumatic system has a threefold purpose: to supply air to the pneumatic cylinders for actuation of the knife gate valves, to provide nitrogen to the airlock for pressurization, and to provide nitrogen to the airlock and hopper for agitation of the feed material. The double-acting cylinders are supplied 740 kPa air by a 0.375 in. (0.95 cm) four-way solenoid that pressurizes one side of the cylinder's piston while simultaneously venting the other side. This causes the gate valve to be either in the open or closed position. Nitrogen for pressurization is used instead of air to exclude oxygen, which would cause undesirable side reactions with components in the prehydrolysis vessel. The nitrogen is supplied

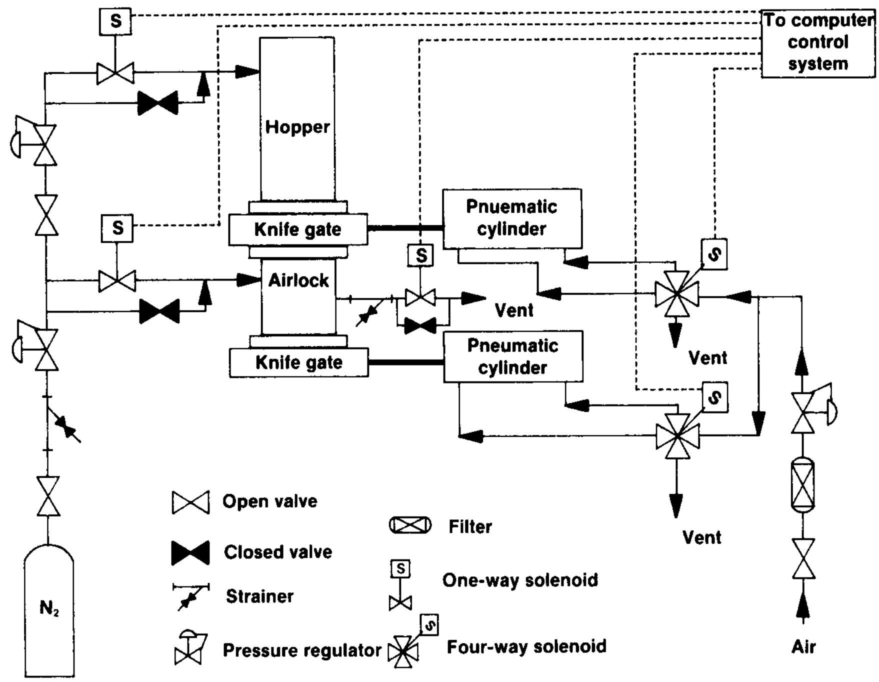

Fig. 10. Schematic of the SERI lockhopper system.

by a 0.375 in. (0.95 cm) one-way solenoid at approx. 70 kPa (10 psi) above vessel pressure. This has the dual purpose of preventing steam from entering the airlock from the vessel, before the wood has been discharged, and provides a force that helps blow the material out of the airlock. The nitrogen supply is kept on after opening the bottom gate valve to help promote wood flow and keep steam from entering the airlock. A 0.375 in. (0.95 cm) one-way solenoid is used to vent the airlock after the wood is discharged and both valves are closed. The vent is connected to a vacuum source that bleeds pressure from the airlock faster than it would discharge to atmospheric pressure. This also pulls a slight vacuum on the airlock, that, when the top valve is opened, pulls wood from the hopper into the airlock. Finally, nitrogen is supplied to the hopper at approximately 170 kPa (10 psig) for agitation of the wood, helping to promote flow into the airlock.

The pneumatic agitation of the material in the airlock and the hopper is provided by nozzles arranged inside the respective device. Figure 11 illustrates the arrangement of the airlock's nozzles. Four nozzles are placed at 90 degree intervals and staggered at different heights. Flow of nitrogen is directed downward and along the walls to push the wood out, and keep steam from entering the airlock. Additionally, a nozzle near the top directs flow through the center of the airlock, and also serves as the vent port because of a check valve placed in the line. The hopper has the same arrangement, but without the center fifth nozzle.

Control is provided by an IBM personal computer connected to a Keithley 500 Data Acquisition and Control System. Labtech Notebook

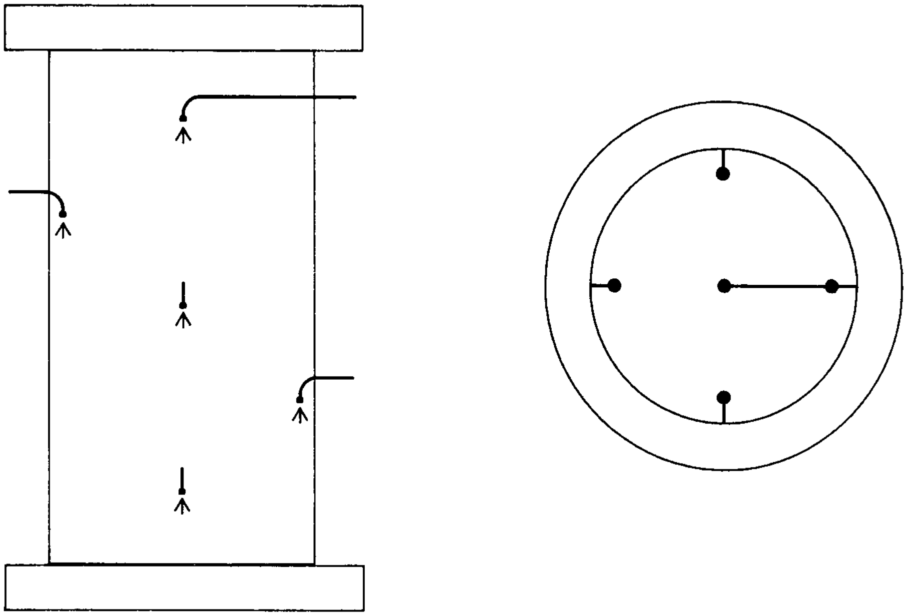

Fig. 11. Placement of the airlock's inert gas nozzles.

data acquisition software gathers data from a variety of thermocouples and transducers, and simultaneously controls operation of the airlock's solenoid valves. Low-level 5-V dc signals are sent to relays which switch 120-V ac power to the solenoids. Sequencing of the solenoid valves is user controlled with an input file that can turn each valve on or off as needed. The airlock was set up to cycle every 25 s with the following sequence of events. The top knife gate valve and nitrogen supply valve to the hopper are opened for 4 s, and wood flows from the hopper to the airlock. After the top gate valve closes, the nitrogen supply valve to the airlock is opened and in 5 s the airlock is pressurized. Then the bottom gate valve opens, while maintaining nitrogen supply to the airlock, and wood feeds into the prehydrolysis vessel. The bottom valve is closed, and a second later the nitrogen supply is turned off. Then, with both gates valves shutoff, the vent is opened for 10 s to completely depressurize the airlock, and the cycle is ready to begin again.

OPERATING EXPERIENCE

We have obtained some useful operating experience during operation of the lockhopper. Numerous trials actually flowing wood were made, each lasting from 5- to 15-min, and many more hours were logged with the lockhopper operating at temperature and pressure but without flowing wood. Some of the problems we had anticipated did not occur. For instance, both gate valves did not have any problems initially sealing against the pressure at the elevated temperature, even when wood was present. Also, wood flowed smoothly through the airlock even in the presence of steam. A layer of wood dust would build up on the airlock walls because of condensing steam, but did not grow any thicker than .5–1.0 cm.

During preliminary operation of the lockhopper using a wood flour, some problems occurred during the vent portion of the airlock's cycle. The strainer shown in Fig. 8 had to be removed because it was quickly plugged with wet wood. The vent line, which was .375 in. (.95 cm) tubing, then proceeded to quickly plug (10–15 min of operation) with wet wood. This problem was solved by increasing the vent line size to 1 in. (2.54 cm) pipe and expanding into a larger chamber, a 2 in. (5.1 cm) tee, to help collect the dust coming from the airlock. A layer of wood dust collected on the vent pipe walls as expected, but this did not reduce the venting time or cause any other problems.

The lockhopper was operated successfully for a one time, one hour test on wood flour at a relatively low flowrate of 48 kg/h (100 lb/h). Some of the airlock's nozzles did become plugged and reduced the pressure obtained in the airlock to less than reactor pressure, but this did not hinder material flow through the airlock.

More problems developed when testing was done at the desired flowrate of 96 kg/h (200 lb/h). Large quantities of wood flour were removed from the airlock by the vacuum system and the vent line solenoid plugged after approximately 10 min of operation. The difficulty in operating with wood flour prompted us to use larger wood particles and replace the vent line solenoid with a pneumatically operated 1.27 cm (.5 in.) ball valve. The new wood particles were predominantly 20–60 mesh in size, considerably larger than wood flour particles. At this point in time, a one time, one hour operation of the system with these modifications was very successful, no problems were observed with vent line plugging or material flow through the airlock.

One further problem has developed, the knife gate valve seals have begun to wear resulting in steam leakage back into the airlock. Since the lockhopper operated for only about 30 h (approx. 5 h on wood) before the problem began, this is a significant problem that will be examined in the future.

RECOMMENDATIONS

Our experiences with the lockhopper system have shown that there are many problems when using a material such as wood flour. However, when the particle size is increased, the system becomes easier and more reliable to operate. Two concerns must be addressed before the system is used in a commercial acid hydrolysis process. First, the gas consumption is high, particularly with our design, which attempts to exclude as much steam as possible from the airlock by using excess nitrogen. If an inert gas is not required, then the cost could be reduced by using cheaper compressed air. Second, the reliability of lockhopper equipment for long-term service is still in doubt (note the failure of our knife gate seals and DOE's effort to identify reliable lockhopper valves) (7). The long-term operation of a lockhopper still needs to be proven, particularly at elevated temperatures.

Some other feeders, such as screw and plug type feeders, are also probably not good choices, since they use large amounts of energy and have the undesirable trait of compressing the feed material. Rotary airlocks suffer many of the same problems as lockhoppers, even if they could be designed for high pressure applications.

The likely remaining candidates are piston feeders and the linear pocket feeder, both of which have low gas consumption. Piston feeders are promising if the material will drop from the chamber in the presence of steam and if biomass does not cause excessive seal failure. The same characteristics are also required for the linear pocket feeder. However, this device has an advantage in that it may be self-cleaning in the water displacement step and returns steam back to the process. It is also imperative to watch developments in coal handling, since a promising high pressure feeder developed for coal could also be suitable for biomass applications.

ACKNOWLEDGMENT

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