**Demonstration of a Piston Plug feed System for Feeding
Coal/Biomass Mixtures across a Pressure Gradient
for Application to a Commercial CBTL System**

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Abstract

Producing liquid transportation fuels and power via coal and biomass to liquids (CBTL) and integrated gasification combined cycle (IGCC) processes can significantly improve the nation's energy security. The Energy Independence and Security Act of 2007 mandates increasing renewable fuels nearly 10-fold to >2.3 million barrels per day by 2022. Coal is abundantly available and coal to liquids (CTL) plants can be deployed today, but they will not become sustainable without large scale CO₂ capture and storage. Co-processing of coal and biomass in CBTL processes in a 60 to 40 ratio is an attractive option that has the potential to produce 4 million barrels of transportation fuels per day by 2020 at the same level of CO₂ emission as petroleum.

In this work, Southern Research Institute (Southern) has made an attempt to address one of the major barriers to the development of large scale CBTL processes—cost effective/reliable dry-feeding of coal-biomass mixtures into a high pressure vessel representative of commercial entrained-flow gasifiers. Present method for dry coal feeding involves the use of pressurized lock-hopper arrangements that are not only very expensive with large space requirements but also have not been proven for reliably feeding coal-biomass mixtures without the potential problems of segregation and bridging.

The project involved the development of a pilot-scale 250 lb/h high pressure dry coal-biomass mixture feeder provided by TKEnergi and proven for feeding biomass at a scale up to 6 ton/day. The aim of this project is to demonstrate cost effective feeding of coal-biomass mixtures (50:50 to 70:30) made from a variety of coals (bituminous, lignite) and biomass (wood, corn stover, switch grass). The feeder uses a hydraulic piston-based approach to produce a series of plugs of the mixture that act as a seal against high back-pressure of the gasification vessel in to which the mixture is being fed. The plugs are then fed one by one via a plug breaker into the high pressure gasification vessel. A number of runs involving the feeding of coal and biomass mixtures containing 50 to 70 weight % coal into a high pressure gasification vessel simulator have shown that plugs of sufficient density can be formed to provide a seal against pressures up to 450 psig if homogeneity of the mixture can be maintained. However, the in-homogeneity of coal-biomass mixtures can occur during the mixing process because of density, particle size and moisture differences. Also, the much lower compressibility of coal as opposed to biomass can contribute to non-uniform plug formation which can result in weak plugs. Based on present information, the piston plug feeder offered marginal economic advantages over lock-hoppers. The results suggest a modification to the piston feeder that can potentially seal against pressure without the need for forming plugs. This modified design could result in lower power requirements and potentially better economics.

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Executive Summary

Due to a finite petroleum resource and increased risk of supply disruption, alternative non-petroleum sources for transportation fuels need to be developed. Coal and biomass are two of the most plausible alternative fuels for replacing petroleum as a source of transportation fuels. Coal and biomass to liquids (CBTL) refers to technologies that co-gasify coal and biomass in a high pressure gasifier and then convert the syngas produced to liquid fuels via Fischer-Tropsch synthesis. CBTL is attractive to develop since plants using 60 % coal and 40 % biomass can produce 4 Mbpd by 2020 at equivalent CO₂ emissions as petroleum without carbon capture and sequestration (CCS). This is because the use of 40 % biomass reduces the impact of the total CO₂ emissions. CBTL plants are also economically competitive with petroleum based plants at current crude oil prices. However, further performance improvements and cost reductions in CBTL plants are needed to reduce investor risk in these plants that can cost upwards of several hundred million dollars.

This report addresses a major technical barrier faced by developers of commercial CBTL plants--availability of a cost-effective and reliable feed system for feeding coal-biomass mixtures into a high pressure entrained flow gasifier. Lock hoppers, the present commercial method of feeding these fuels individually, have not yet been proven for coal-biomass mixtures. They may develop rat holes, or segregate and bridge due to compaction. Also, a number of disadvantages of lock-hopper based systems such as high capital and operating costs, and low cold gas efficiency at high pressures have encouraged the development of alternative feeding systems. These include feeders such as those being developed by General Electric, Pratt and Whitney Rocketdyne, and TKEnergi that work like solids pump rather than use an inert high pressure gas for maintaining front pressure and pushing the solids in to the high pressure gasifier.

In this work, the testing of a 250 lb/h high pressure pilot-scale piston plug feeder designed and provided by TKEnergi to Southern is described. The feeder technology from TKEnergi, based on 3 pistons operating in sequence, is an alternative to expensive and bulky lock hopper systems. The aim of the project is to demonstrate cost effective feeding of coal-biomass mixtures (50:50 to 70:30) made from a variety of coals (bituminous, lignite) and biomass (woody, corn stover, switch grass) against pressures up to 450 psig. Specific objectives include:

- Specifying an appropriate biomass pretreatment system,
- Demonstrating the ability of this pretreatment system and TKE's feed system proven for biomass to co-feed a variety of biomass and coal mixtures into a simulated high pressure environment similar to that encountered in CBTL facilities, and

- Evaluating the engineering and economic viability of the proposed co-feed system for use at large scale CBTL processes.

The equipment set up at Southern Research Institute (Southern) was intended to simulate the necessary pretreatment of biomass and mixing it with coal for feeding into a high pressure environment. A schematic of the system simulated is shown in Figure E-1.

Figure E-1: Schematic of biomass pretreatment and coal-biomass feeding system at Southern

The feeder consists of three (3) hydraulic pistons as shown in Figure E-2. They are designed so each piston compresses the feed material and moves it to the next. The first two pistons pre-compress the material and the third piston compresses the material by moving partially formed plugs into a brake, further compressing it and forming a stable plug which is then moved into a plug breaker. At any given time, there are a number of plugs in front of the third piston and at least one piston is in closed position. Examples of plugs formed from a 50-50 mixture of coal and wood as a function of hydraulic pressure on the third piston are shown in Figure E-3.

Figure E-2. Feeder showing the hopper, pistons, plug transfer to breaker and feed opening from breaker to pressure tank.

Figure E-3. Coal-wood plugs formed after the third piston at hydraulic pressures from 1200-2000 psi

The plugs at 1600 psi and higher hydraulic pressure had sufficient integrity and strength to seal against back pressures up to 500 psi or higher. Based on this finding, a number of runs of the feeder were conducted at back pressures up to 450 psi.

The most important results obtained in the project included:

- Coal-biomass mixtures consisting of 50 to 70 % bituminous coal and lignite mixed with woody biomass, corn stover, and switch grass were successfully prepared using a hammer mill. The size distribution and moisture content of these mixtures was measured.
- Feeder was demonstrated for feeding coal-biomass mixtures containing 50-70 % coal into a high pressure tank at 350-450 psig at variable speeds from 1 to 220 lb/h.

Based on the successful high pressure testing results, the potential advantages of the piston-plug feeder technology are summarized below:

- The piston-plug feeder technology does not require the use of expensive lock-hopper systems
- Bridging is not a major issue as in lock-hoppers because the feed hoppers are at low pressure
- Biomass/coal plugs of sufficient strength and density can be formed using a hydraulic pressure of 1600-2000 psi on the third piston.
- Biomass aids in the binding--no external binders are used.

Some limitations of the feeder technology that were brought to light during the high pressure tests included:

- The in-homogeneity of coal-biomass mixtures caused by particle size differences between coal and biomass and the much lower compressibility and higher density of coal as opposed to biomass can contribute to segregation in the feed hopper that leads to non-uniform plug formation. When this happened, the plugs were not able to hold the high pressure.
- A seal only at the plug needs to be proven safe for use in a combustible environment such as an entrained flow gasifier—based on a process hazard assessment carried out at Southern, it was concluded that the feeder would need modification to provide a secondary seal at the piston.
- Due to potential high power consumption and the sealing problem mentioned above, TKEnergi has discontinued the scale up of the feeder, thus rendering a detailed economic evaluation to be of little value.

TKEnergi is currently developing a feeder that seals at the pistons, does not require that the mixture be uniform, does not require forming and pushing plugs, and thus requires less energy to

operate. Southern and TKEnergi are presently discussing the potential development and testing of this new feeder in a future project.

To summarize the project at Southern,

- Biomass pretreatment system consisting of a fluidized-bed dryer and shredder and capable of processing up to 500 lb/h biomass, was commissioned at Southern
- Coal-biomass mixtures consisting of 50 to 70 % bituminous coal and lignite mixed with woody biomass, corn stover, and switch grass were successfully prepared using a hammer mill.
- TKEnergi Feeder was demonstrated for feeding a coal biomass mixtures containing greater than 50% coal into a high pressure tank at 350-450 psig at variable speeds from 25 to 220 lb/h.
- The piston-plug feeder needs to be modified to provide a secondary seal at the piston in addition to the seal formed by the plug.
- TKEnergi is developing a new feeder that
 - does not require the formation of plugs
 - uses significantly less energy than the present piston-plug feeder design
 - Southern and TKEnergi are presently discussing the potential development and testing of this new feeder.

Introduction and Background

Due to a finite petroleum resource and increased risk of supply disruption, alternative non-petroleum sources for transportation fuels need to be developed. Coal and biomass are two of the most plausible alternative fuels for replacing petroleum as a source of transportation fuels [1]. However, a number of technical barriers need to be overcome to make transportation fuels from coal and biomass competitive with those from petroleum. These include, among several others, a lack of biomass to liquids (BTL) and CBTL integrated demonstration, availability of a cost-effective and reliable feeder for coal-biomass mixtures into high-pressure gasifiers, and high cost associated with cleanup of syngas from gasifiers to levels suitable for fuel synthesis. Southern has a number of ongoing pilot-scale projects that address these important barriers to widespread deployment of technologies for converting coal and biomass to liquid transportation fuels.

Examples of these projects include:

- Fully integrated gasification-based thermochemical biorefinery
- Fuel preparation and feeder for coal and biomass mixtures
- Municipal solid waste conversion to mixed alcohols
- Advanced syngas cleaning and tar reforming system
- Cellulosic biomass hydrolysis to industrial sugars

The total US oil consumption is about 21 million barrels/day (Mbpd). About 14 Mbpd is used in the transportation sector with light duty vehicles accounting for about 9 Mbpd (138 billion gallons/year) [2]. Oil resources are finite and alternative energy sources need to be developed. US imports about 10 million barrels of oil each day, and 65 % of the 10 Mbpd (or 6.5 Mbpd) is imported from OPEC and Persian Gulf countries. These sources present significant risk of supply disruption and threaten the energy security of the nation. To improve energy security and reduce costs, the U.S. Air Force has set a goal to supply 50% of its fuel requirements in the lower 48 States from domestic synthetic sources by 2016 [3]. At the same time, the U.S. Department of the Defense desires to improve its environmental performance and is exploring options to reduce carbon emissions of the plants producing synthetic fuels to less than that of a conventional petroleum refinery on an energy content basis.

As an alternative to oil, the US has an abundant supply of proven coal reserves that can last for over 100 years. The infrastructure for coal mining and supply is quite good because of its significant use to produce electricity. Coal is also competitive in price but increasing its use for

converting coal to liquids (CTL) in addition to electricity is not sustainable due to increased CO₂ emissions that contribute to global climate change. Social acceptance is also an issue with increased coal use due to increased mining operations.

Compared to coal, biomass, an abundant resource, is a renewable CO₂ neutral fuel. A major barrier to increasing the use of biomass in BTL plants is the poor to non-existent infrastructure for harvesting and transporting biomass for large scale use. There is also the food versus fuel debate with the use of biomass that can be used for food. Due to these reasons, the availability of cellulosic (non-food) biomass or waste biomass for BTL plants is neither cheap nor abundant in a practical sense. It is estimated that with modern cultivating and harvesting techniques, sustainable cellulosic biomass resource can be increased to 550 million tons/year by 2020 [1].

CTL has been commercially available via the gasification/Fischer-Tropsch (FT) route for over 55 years. However, there are no commercial plants that make fuels and chemicals from coal in the US (except Eastman's coal to chemicals complex in Kingsport). This is due to a combination of several reasons including economics with respect to petroleum, high capital costs involved, and environmental and social acceptance. CTL can be commercially deployed but will not be until large scale carbon capture and storage (CCS) is commercially demonstrated.

There are no commercial BTL plants operating in the US. The Energy Independence and Security Act (EISA) of 2007 mandates increasing renewable fuels from sources such as biomass nearly 10-fold to >2.3 million barrels per day by 2022. This act has led to significant ongoing funding by the U.S. Department of Energy to promote biomass to liquids (BTL) research, development, and demonstration. BTL plants may require significant Government incentives for CO₂ reductions before any private companies assume the risks to build them.

Nonetheless, liquid fuels from biomass and coal have the potential to reduce petroleum fuel use and CO₂ emissions in the U.S. transportation sector over the next 25 years according to a recent study by the National Research Council [1]. According to the report, "A program of aggressive support for establishment of first-mover commercial coal-to-liquid transportation fuel plants and coal-and-biomass-to-liquid (CBTL) transportation-fuel plants with integrated geologic CO₂ storage will have to be undertaken immediately if commercial plants are to be deployed by 2020 to address U.S. energy security concerns and to provide fuels whose levels of greenhouse gas emissions are similar to or less than that of petroleum-based fuels." A DOE published report indicates that with a minimum of 8 % by weight biomass feed and with CO₂ sequestration, CBTL process can produce fuels which are economically competitive at crude prices above \$93

per barrel and which have 20% lower Green House Gas (GHG) emissions than petroleum fuel [4].

CBTL is attractive to develop since plants using 60 % coal and 40 % biomass can produce 4 Mbpd by 2020 at equivalent CO₂ emissions as petroleum without CCS. This is because the use of 40 % biomass reduces the impact of the total CO₂ emissions. CTL and CBTL plants are also economically competitive with petroleum based plants as seen in Table 1. However, further performance improvements and cost reductions in CBTL plants are needed to reduce investor risk in these plants that can cost upwards of several hundred million dollars.

Table 1. Comparison of \$/barrel Gasoline Equivalent Cost (CCS implies 90 % CO₂ capture and storage)*

	Without CO ₂ price	With \$50/metric ton CO ₂
CTL	65	120
CTL-CCS	70	90
Crude oil at \$60 per barrel	75	95
Crude oil at \$100 per barrel	115	135
CBTL	95	120
CBTL-CCS	110	100

*Adapted from [1]

This report addresses a major technical barrier faced by developers of commercial CBTL plants--availability of a cost-effective and reliable feed system for feeding coal-biomass mixtures in to a high pressure gasifier. Previous studies have demonstrated the ability to co-gasify biomass in entrained flow gasifiers [5-6]. However, a primary challenge related to biomass utilization is the ability to reliably feed a variety of biomass feedstocks to the gasifier as biomass-coal mixtures. Present commercial methods for individually feeding coal and biomass use lock-hoppers that are simple and can handle wide ranging particle sizes. These are in use at commercial coal gasification plants at Eastman Chemical Company and Tampa Electric Company. The Miles feeder is a commercial example of a lock-hopper based biomass feeder up to a scale of 10 ton/h. Lock hoppers, however, have not yet been proven for coal-biomass mixtures that may develop rat holes, or segregate and bridge due to compaction in the lock hoppers. Also, a number of disadvantages of lock-hopper based systems have encouraged the development of alternative feeding systems. These disadvantages that lead to high capital and operating costs, and reduced cold gas efficiency include:

- Large and tall vessel structure due to the need for long cycle times
- Use of inert pressurization gas

- Significant loss of cold gas efficiency above 500 psig
- Non-continuous feed
- Poor lock valve reliability with wet-dusty feed

The disadvantages of lock hoppers have encouraged the development of feeders that work like solids pump rather than use an inert high pressure gas for maintaining front pressure and pushing the solids into the high pressure gasifier [5-10]. Some feeders of the past that do not require lock hoppers such as the K-Tron pump and the Walden diaphragm pump however could not build sufficient pressure, and some did not work well for coal such as the Foster Miller Linear Pocket Feeder. Currently, as far as we know, only the General Electric's Stamet Posimetric Pump, the Pratt-Whitney Rocketdyne (PWR) Pump, and the TKEnergi (Southern's partner in this project) Piston-Plug feeder are under development. These systems have been under development for several years but have not reached full commercialization status.

The TKEnergi system chosen for this work has been demonstrated at a large pilot scale for biomass, but not for coal-biomass mixtures. It has been demonstrated at a scale of up to 6 ton/day biomass for feeding against pressures up to 450 psig. There is potential for the feeder to be able to feed coal biomass mixtures because biomass can potentially act as a binder of the coal particles. In this report, the testing of a 250 lb/h high pressure pilot-scale feeder designed and provided by TKEnergi to Southern is described. The feeder technology from TKEnergi based on 3 pistons operating in sequence is an alternative to expensive and bulky lock hopper systems. The aim of the project is to demonstrate cost effective feeding of coal-biomass mixtures (50:50 to 70:30) made from a variety of coals (bituminous, lignite) and biomass (woody, corn stover, switch grass) against pressures up to 450 psig.

Objectives

The goal of this project is to design and demonstrate the operability of a biomass pretreatment and a coal/biomass co-feed system. The system will be examined for use with high pressure, commercial-scale entrained gasification systems utilized in future large scale coal and biomass to liquids (CBTL) facilities. Specific objectives include:

- Specifying an appropriate biomass pretreatment system,
- Demonstrating the ability of this pretreatment system and a commercially-available feed system proven for biomass to co-feed a variety of biomass and coal mixtures into a simulated high pressure environment similar to that encountered in CBTL facilities, and

- Evaluating the engineering and economic viability of the proposed co-feed system for use at large scale CBTL processes.

The commercially-available feed system chosen for this project was a 250 lb/h piston-plug feeder system from Denmark's TKEnergi for feeding a variety of biomass/coal mixtures with at least 50 weight % coal and up to 70 % coal into a high pressure environment. This system has been proven at 450 psig for up to 6 ton/day scale for biomass.

Equipment Description

The equipment at Southern is intended to simulate the necessary pretreatment of biomass and mixing it with coal for feeding into a high pressure environment. A schematic of the system simulated is shown in Figure 1. Depending on the properties of the biomass and the state of the received coal, the type and sequence of steps may change.

Figure 1: Schematic of biomass pretreatment and coal-biomass feeding system at Southern

The feeder design capacity is about 250 pound per hour depending on the feed material density and particle size. It is designed to feed mixtures of biomass and coal at pressures of up to 500 psig. The shredder, dryer, and hammer mill are currently designed to operate in batch and can handle up to 500 pound per hour of biomass.

Shredder

The Shredder was originally designed to handle up to 135 lb/hr of as received refused derived fuel (RDF), but has demonstrated up to 500 lbs/hr capacity when shredding with maximum particle size of 6" to ½" or less. The Shredder uses a 48" wide, 9" inch diameter rotor operating at 120 RPM. Shredding is accomplished using 27 cutting teeth on the rotor, with the material driven against a ½" screen by the rotor. Material is fed into 2.9 cubic yard hopper, and is forced against the hopper by an oscillating hydraulic ram that operates at up to 2600 PSI. As the particle size is reduced to ½" or less, the material falls through the screen and out of the shredder on to a pan/try. The control parameter on the rotor relate only to the hydraulic ram timing sequence and stroke length. The shredder manufacturer is VelcoPlan and model number is RG42030 and is currently manually fed using an overhead crane.

Dryer

The dryer is a vibrating fluidized bed type designed to handle up to 500 lb/hr of wet material depending on the density of the material. It is capable of reducing moisture content from 40% down to 5% using 1800 SCFM of heated air at a maximum temperature of 325 F. The drying air is heated by a 500,000 Btu natural gas burner, which is forced into the bottom of a vibrating bed. The bed is fluidized using a 1 HP, VFD – motor with a typical bed amplitude of 5/32" to 7/32". The dryer exhaust is pulled up through a cyclone, which is powered by a 15HP air exhaust fan. The cyclone captures particulates that become entrained in the exhaust flow and collects them into a drum. The retention time of the material in the dryer is controlled by an automatic weir, which can be adjusted to control how frequently the material is released, and how long each release lasts. Once released by the weir, dried material falls into a drum at the outlet of the drier. The control parameters for the dryer include the burner temperature by means of a burner control valve, hot air flow by means of an air damper, bed vibration amplitude by means of a VFD, and material retention time, and subsequence moisture reduction by means of an electronically controlled, pneumatically operated weir. The dryer is supplied by Witte CO. and the model number is Witte 12" x 6".

Hammer Mill

The hammer mill carries out particle reduction by passing biomass through a chamber filled with hammers that force the biomass particles through a screen. The degree of reduction depends on the biomass type, the rate the rotor/hammer assembly turns, the size of screen holes, and the rate that biomass is fed into the hammer mill. It uses four ¼” by 6” hammers to pulverize the biomass. A 50HP motor operating at 3600 RPM drives the hammer mill rotor/assembly. The pulverized biomass is then forced through a 690 in² screen with 1mm openings. The feed rate is varied to control the biomass particle size. As the material reaches the approximate size, it falls through the screen to a plenum with a discharge screw to direct the milled biomass out of the hammer mill. The hammer mill is supplied by Champion and the model number is 11.5 x 22.

Feeder

Figure 3 shows the feeder and feeder housing. For dust control explosion prevention purposes and maintaining the feeder hydraulic equipment in a clean environment, the feeder system is enclosed in a shipping container. The container has two compartments, one contains the hydraulic oil reservoir and pumps and the other the feed screws, pistons, and the plug breaker. The second compartment is also equipped with an explosion vent. Figure 3 shows the Process and Instrumentation Diagram (P&ID) for the feeder system.

Dried and sized biomass and pulverized coal are weighed and transferred to a drum tumbler where they are mixed for up to 30 minutes or until they appear well mixed by visual inspection. The coal-biomass mixture is then transferred to the feed bin.

Feed Stock Bin

The bin can hold approximately 20 cubic ft of coal-biomass mixture (about 600 lbs of 50/50 mixture). The bin can only be accessed from the shipping container roof for loading feed material.

Operators responsible for filling the bin are trained in use of the crane for transporting supersacks and /or drums of feed material and are fully aware to position themselves away from the explosion vent door on the roof of the container. The vent door is chained at two positions and will not fly away and the explosion force is directed away from the location of the feed bin but operators are cautioned to stay away from the vent door during the feeder operation.

The bin is equipped with a bridge breaker, a feed screw, and high and low level sensors. The breaker should be off during the loading of the bin, operating while the feed screw is operating, and although it provides some mixing of the material, it should not be used as a mixer.

The screw at the bottom of the bin feeds the feed material to the weighing screw hopper. The feed screw is on-off controlled and will run for a different period depending on the density of the material as measured by the weighing screw.

Weighing Screw

The feed material is transferred from the feed via the feed screw to the weighing screw. The weighing screw is mounted on three (3) load cells which determine the mass of material for each cycle of the feeder. Using the mass of the feed material and the known volume of the weighing screw, the feed material density is calculated within the system controller and the weighing screw velocity is automatically varied to compensate for any change in the material density to ensure a constant mass flow. The weighing screw discharges feed material into a feed screw mounted on the stage 1 piston. This screw runs continuously after the feeder system is started.

Figure 2. Southern Research plug feeder assembly inside the shipping container

Figure 3. Plug Feeder P&ID

Piston Feeder and Brake

The feeder consists of three (3) hydraulic pistons. They are designed so each piston compresses the feed material and moves it to the next. The first two pistons pre-compress the material and the third piston compresses the material by moving partially formed plugs into a brake, further compressing it and forming a stable plug which is then moved into a plug breaker. At any given time, there are a number of plugs in front of the third piston and at least one piston is in closed position. This will minimize any leak from the pressurized vessel to atmosphere, through the feeder, due to a plug failure because the only opening for any gas to escape is the space between the piston head and the feeder body. This space is also usually filled with feed material further restricting any gas movement from the pressure vessel to atmosphere due to a potential plug failure.

The hydraulic pressure exerted on each piston is measured in forward and reverse positions. The first and second piston always move from end to end while the third piston is moved back and forth to positions determined by the properties (i.e., density) of the material being fed.

The plug brake is mounted directly to the feeder body. It is used to control the movement of the plug. The brake consists of three jaws, one fixed and two that are used to hold, compress, and release the plug. The density of the plug is adjusted to a pre-established desired value by the force exerted on the pistons acting on the two brake-jaws. A hydraulic valve is used to control the pressure on these pistons. The position of the fixed jaw can be changed manually if desired or if required due to wear of the jaws.

Plug Breaker

The plug breaker is placed directly after the brake. A rotating drum, inside the breaker housing, tears the plug apart to pieces manageable by the transport. A section of the transport screw is placed directly below the rotating drum, directing material down into the transport screw. The drum can be adjusted up and down in order to compensate for wear and to adjust the particle size of the material leaving the plug breaker. The breaker typically breaks-up the plug and reduces the particle size to its original size. However, since the feeder is a used feeder and the objective of this project was not to show actual operation in a entrained flow gasifier but to demonstrate that the pressure barrier can be overcome, the breaker was not redesigned and replaced in this phase of the project.

Transport Screw

The transport screw feeds the material from the bottom of the plug breaker into the pressure vessel located outside of the container. The transport screw housing has been pressure tested at 725 psi and the manufacture's recommended maximum operating pressure 505 psi.

Pressure Seals

The plug breaker and transport screw are both equipped with stationary double pressure balanced mechanical seals. Pressure on the barrier fluid is upheld by a hydraulic power pack.

Pressure Vessel

The pressure vessel is designed to operate at up to 600 psig at temperatures of up to 120° F. Nitrogen is used to pressurize the vessel to about 500 psig before biomass-coal mixture is fed into the vessel. As material is fed into the vessel and replaces the nitrogen volume, a pressure control valve will release nitrogen to maintain the vessel pressure. The pressure vessel is also equipped with pressure and temperature indicators for analytical purposes. A pressure transmitter will pause the feeder in case the system pressure exceeds 501 psi. For personnel safety and protection of equipment, a rupture disc set at 600 psig will protect the pressure vessel from any accidental pressurization beyond its design capabilities. The pressure vessel is designed to hold feed material for up to four hours of continuous feeding, depending on the material density. A level switch will pause the feeder to prevent the vessel from overfilling. Overfilling the vessel could interfere with the operation of the transport screw feeder and cause plugging of the feed line. The vessel is also designed to allow injection of inert detectable gases. Gas monitors located within the feeder container at various locations on the feeder system (i.e., before and after the break) will be used to detect any gas that may leak from the pressure vessel into the feeder system.

Experimental

The specifications of the biomass pretreatment equipment are provided in Table 2. Fuel preparation consists of biomass pretreatment and mixing with pulverized coal. As received biomass is received and transferred to a shredder. The shredded biomass is dried using a fluidized-bed dryer down to 3-7 % moisture. The sequence depends on the biomass. It has been found that this sequence works well for woody biomass; whereas drying followed by shredding works better for stalk and stringy biomasses like corn stover and switch grass. The shredded biomass is hammered down to less than 1 mm and mixed with the coal in the required proportion prior to pumping it into the high pressure chamber. This is the sequence to be followed for lignite as it is received pre-pulverized. On the other hand, the bituminous coal was received as lumps. So the lumps were broken down to 0.5 to 1 inch sizes and mixed with the shredded biomass. The hammer mill was used to reduce the size of the mixture to less than 1mm.

Table 2: Biomass Pretreatment Equipment Specifications

-
- Shredder
 - Designed for 135 lb/hr RDF; capable of 500 lb/hr Biomass size reduction to < 1/2"
 - 9"rotor, 120 RPM, 2600 PSI hydraulic ram drives material against rotor, through screen
 - Control parameters: stroke length and speed
 - Target: 250 lb/hr shredded wet biomass reduced to 1/2" nominal length

 - Dryer
 - Vibrating fluidized bed designed for 500 lb/hr using 325°F air @ 1800 SCFM
 - 500,000 Btu natural gas burner with 7.5 HP blower, feeds hot air into bottom of bed
 - Heated air pulled up through media into 15 HP exhaust cyclone
 - Control parameters are retention time by weir and bed vibration frequency
 - Target 250 lb/hr biomass reduced to <10% moisture

 - Hammer Mill
 - 50 HP, 3600 RPM motor driving four 6" by 1/4" hammers
 - Pulverized materials falls through 690 in2 screen with 1mm holes
 - Control parameters: none (on / off)
 - Target: 250 lb/hr milled biomass and coal mix to < 1mm
-

Equipment for biomass pretreatment system was commissioned and demonstrated. Southern demonstrated a hammer mill, including the necessary equipment for biomass conveyance and dust collection, such that the system would yield bulk biomass and coal with an average particle size less than 1mm (woody biomass, switch grass, and corn stover). Hazardous operations reviews were conducted to ensure that safety issues were identified early and integrated into the as-built system and operating procedures. Additional safety and environmental issues were identified and addressed during process hazard analysis reviews and in discussions with permitting authorities.

A total of nine (9) tons of raw biomass was purchased from Department of Forestry at NC State University. These included switch grass, corn stover, and wood chips. Three (3) tons or 11 bales of switch grass, three (3) tons or 5 bales of corn stover, and three (3) tons of woody (pine) chipped biomass in super sacks were obtained. Also 3 tons of WVa bituminous coal was purchased from a local vender (Bridgers Coal Supply) and delivered as large particles with many pieces surpassing 16 inches. These pieces were crushed into 0.5-2 inches pieces in preparation for mixing with the shredded /dried biomass and hammer milling. Also, 1 ton of pulverized North Dakota lignite was obtained from the Environmental Protection Agency. Each biomass

type was processed through the pretreatment system to ensure the proper functioning of the equipment.

Generally, biomass samples were taken before and after the shredder/ dryer. The samples were analyzed for moisture content and particle size distribution. After the shredder, biomass was reduced to particle size on average: woody biomass – 0.5 inch, corn stover – 0.5 inch, and switch grass – 1 inch. Southern completed proximate and ultimate analyses of corn stover, woody biomass, and bituminous coal which were available at the time. Photographs of the equipment and some representative photographs of biomass pretreatment and coal biomass mixture preparation are shown in Figures 4 to 18.

Figure 4: As received 1200 lb bails of corn stover

Figure 5: Corn Stover before it is shredded

Figure 6: Fluidized-bed drier

Figure 7: Biomass shredder

Figure 8: Corn stover being shredded

Figure 9: Shredded corn stover stored in super sacks

Figure 10: Woody biomass (NC pine) as received in super sacks (the high pressure tank and the feeder container is in the background)

Figure 11: Woody biomass chips as received

Figure 12: Woody biomass being shredded

Figure 13: Woody biomass after shredding

Figure 14: As received WVa bituminous coal

Figure 15: Crushed WVa bituminous coal

Figure 16: 50-50 mixture of crushed coal and shredded biomass

Figure 17: Hammer mill (front view)

Figure 18: Hammer mill (side view and size indication)

Biomass was dried to a moisture content of 3 – 7 % using the dryer. Then, a portion of shredded and dried biomass was mixed together with crushed coal to prepare a 50/50 mixture by weight. Then the mixture was processed using a hammer mill to bring particle size to less than 1 mm. A size distribution analysis for the 50/50 coal/wood mixture was performed. Milled mixtures were

stored in 55 gallon drums and sealed in order to protect against moisture. All drums contained about 120 lb of mixed materials. Bulk density was determined to be 16.3 lb/cf.

Piston-Plug Feeder and Pressure Vessel

The 4.0 inch nominal size piston plug feeder was supplied by TKEnergi from Denmark. It works on the principle of using three pistons in series in a timed sequence to compress solid particles to form and move nominally 4.0 inch diameter cylindrical plugs, that form a seal against high back pressure. The length of the plug depends on the timing between the piston strokes. The plugs formed first are pushed by the plugs formed later. Eventually the plug enters a plug breaker where the plug is broken back to particles of original size. These particles are then transported using a screw conveyor in to a high pressure vessel. The specifications and features of the feeder are summarized in Table 3.

Table 3: Piston-Plug Feeder Specifications and Features

-
- 250 lb/hr mass flow, 3-stage piston plug feeder
 - Biomass / Coal plug in 3rd stage piston provides seal against high pressure environment
 - ‘Weigh Screw’ located before pistons measures mass flow (screw mounted on load cells)
 - Plugs created at hydraulic brake on 3rd stage piston
 - Plug hardness can be adjusted in feeder controls (increases or decreases hydraulic brake pressure)
 - Plug weight can be adjusted in feeder controls (increases or decreases piston 3 stroke into lump breaker; higher plug weight equates to more mass of a plug sent to lump breaker)
 - Plugs crushed for feeding into vessel by plug breaker (‘Lump Breaker’ – vertical grinding block at outlet of 3rd stage piston)
 - Feed screw transports crushed material from lump breaker to vessel
-

As described earlier, the feeder was housed in a 20 ft x 8 ft container, with hydraulics and electrical equipment on the right and the pistons on the left as was shown earlier in Figure 2. The system included a day hopper; a multi-piston drive plug feed system, screw feeders, and a plug breaker. The container was purged and was equipped with dust filters and an explosion vent.

A number of photographs of the feeder and associated equipment are shown in Figures 19 to 22. A three dimensional cut-away drawing of the feeder system before assembly shown in Figure 23 shows the hopper, the three pistons, and the plug breaker and how they connect together. The material is fed through the hopper and the first two smaller pistons, with strokes at 90 degrees to

each other, bring the material in the path of the third 4 inch piston that then compresses it in to a plug at a hydraulic brake.

Figure 19: The feeder: hopper, pistons, and transfer screw installed in container

Figure 20: The feeder: coal-biomass plug reciever and breaker for feeding the powder in pressurized tank

Figure 21: The feeder: hydraulic pump section

Figure 22: Feeder showing the hopper, pistons, plug transfer to breaker and feed opening from breaker to pressure tank.

Southern commissioned and tested the feeder system designed for biomass/coal feeding at high pressures. The feeder was run with biomass first, and then with coal-biomass mixtures. All the controls and instrumentation were tested and commissioned. The ability of the piston plug-feeder system to create a compressed plug for demonstration of transfer of biomass-coal blend to high pressure environments was demonstrated.

The pressure tank for conducting the high pressure tests was positioned as shown in Figure 22 for connecting it to the feeder outlet. It had a flanged access as shown for removing the solid

Figure 23: High pressure vessel, 4 ft diameter x 10 ft high, positioned in place adjacent to the feeder discharge from the feeder container

materials following the runs. The tank was designed for operation up to 600 psig and had built-in safety features such as rupture disc and pressure relief valve. The pressure was built using a bank of pressurized nitrogen cylinders and controlled using a back pressure control valve. A shut off valve on the inlet and the outlet allowed a leak check on the system. The leak rate was found to be essentially negligible. The measured leak rate was used as a benchmark for the high pressure coal feeding runs.

The feeder sequence was controlled using a control panel with programmable logic control (PLC). Photographs of the integrated system and control panel display are shown in Figures 24 to 26.

Figure 24. Preparation for pressure run

Figure 25. Coal biomass mixture drums, control panel display, and pressurizing N2

Results and Discussion

Proximate and Ultimate Analyses

Four of the fuels were sent to an outside testing lab for measurement of proximate and ultimate analyses. These included wood (NC pine), corn stover, North Dakota lignite, and WV a bituminous coal. The proximate and ultimate analyses of these samples are shown in Table 4.

Table 4: Proximate and Ultimate Analyses of Fuels (Dry basis except moisture, wt %)

	Wood (NC Pine)	Corn Stover	WV a Bituminous Coal	North Dakota Lignite
Moisture	18.6	13.9	2.7	27.2
Volatile matter	82.0	80.5	36.5	54.9
Fixed carbon	17.4	18.5	58.3	29.7
Ash	0.56	1.0	5.1	15.5
Sulfur	<0.01	0.06	0.82	1.1
Carbon	51.0	47.0	81.8	62.3
Hydrogen	5.8	5.6	5.0	4.7
Nitrogen	0.1	0.46	1.4	1.2
Oxygen	43.0	44.6	6.4	15.1

It is instructive to note the large differences between the biomass sample and the coal samples for these analyses. The most notable differences are the much higher volatile matter and oxygen content of biomass and their much lower sulfur contents.

System Commissioning

The initial experiments concentrated on commissioning the integrated system and determining the conditions to form reasonably strong coal-biomass mixture plugs. For these experiments, the bituminous coal and the wood (NC pine) were chosen. Wood was shredded and dried to 3 to 7 % moisture. The shredded and dried wood was mixed with ½ to 1 inch pieces of coal and then fed into the hammer mill to prepare the required mixture. A reasonably large 1 mm screen was used to reduce the power requirements for comminution and to ensure that all the particles in the mixture were smaller than 1 mm. The bulk density of the mixture prepared was 16.3 lb/cf. Photographs of the mixtures prepared are shown in Figure 27. The size distribution is shown in Table 5.

Figure 27. Bituminous coal and wood mixtures prepared

Table 5: Size Distribution of 50-50 Coal-Wood Mixture Prepared for Feeding

Sieve No	Hole size (micron)	Empty Wt (g)	After Shake (g)	Difference (g)	Percentage	Cumulative	Appearance
Total	Total	2881.9	3315.1	433.2	100%		
12	>1700 μm	444.1	444.6	0.5	0.1%	0.1%	more biomass pieces
20	>850 μm	403.8	405.7	1.9	0.4%	0.6%	biomass
40	>425 μm	368.5	400.3	31.8	7.3%	7.9%	biomass
50	>300 μm	372.3	441.4	69.1	16.0%	23.8%	mostly biomass, some coal
70	>212 μm	351.7	405.8	54.1	12.5%	36.3%	mostly biomass, some coal
140	>106 μm	336.4	439.1	102.7	23.7%	60.0%	mixed coal/biomass
270	>50 μm	328.3	419.9	91.6	21.1%	81.2%	mostly coal
Pan	<50 μm	276.4	357.9	81.5	18.8%	100.0%	Coal dust

It is to be noted from Table 5 that coal tended to get more reduced in size than wood in the hammer mill. Biomass appeared to concentrate in the larger sizes whereas coal appeared to concentrate in the smaller sizes falling through the 1mm screen in the hammer mill. This was because they are inherently different materials. Coal is more brittle and tends to be hammered to smaller particles, whereas wood is more compressible and thus harder to pulverize.

The initial feeder commissioning experiments were of necessity run against ambient pressure because of a need to collect the plugs. These experiments evaluated plug integrity during feeding as a function of pump hydraulic pressure. To physically remove and examine a compressed mixture (plug), it was necessary to remove the plug breaker after the third piston during operation of the feeder. This allowed direct observation of plug size and density using various system parameters such as system pressure and time delays. An example of a wood plug as it forms after the third piston is shown in Figure 28. Third piston hydraulic compression pressures of 1200, 1600, and 2000 psi were tested with the 50/50 coal/wood mixture. Compressed plugs were collected and examined. The feeder built strong plugs and successfully worked for 2 hours at a feed rate 220 lb/hr. Plugs at the three pressures shown in Figure 29 were examined visually for integrity and mechanical strength. Based on the integrity of the plugs, it was concluded that plugs made with 1600 psi hydraulic pressure were of sufficient strength that would allow operation of the feeder at pressures up to 500 psi or higher back pressure.

Figure 28: Direct observation of a wood plug formed after the third piston

Figure 29: Coal-wood plugs formed after the third piston at hydraulic pressures from 1200-2000 psi

Following the tests to determine the required hydraulic pressure, tests were conducted to examine the feeder's capability to run against up to 450 psig backpressure. An experimental matrix of mixtures was prepared as shown in Table 6.

Table 6: Proposed Experimental Matrix of Coal-Biomass Mixtures

50-50 Mixture Feeding Tests at 450 psi	
	Bituminous coal-wood
	Bituminous coal-corn stover
	Bituminous coal-switch grass
	Lignite-wood
	Lignite-corn stover
70-30 Mixture Feeding Tests at 450 psi	
	Bituminous coal-wood
	Lignite-wood

All of these mixtures were prepared and characterized. The mixtures prepared and their particle size distributions are provided in Appendix A. All materials were dried to 3-7 % moisture prior to feeder testing. The average particle sizes of the mixtures ranged from 72 to 120 microns.

Following the atmospheric pressure runs, a number of high pressure runs were carried out. In carrying out these runs, a number of problems associated with the feed system program were revealed and solved. A detailed log of the program fixes and runs carried out is presented in Appendix B.

A number of challenges were encountered in making the TKEnergi feeder operational. It was a used feeder that was employed in Europe originally. The feeder wiring and motors had to be

thus changed for US voltage and frequency. Also a number of undersized electrical components had to be replaced. The hydraulic reservoir for one hydraulic pack was a little bit undersized which caused overheating. We decided to leave the reservoir as is and cool it with a nitrogen purge on the hydraulic motor. This kept temperatures below the shutdown level. After a few days of testing, we discovered a problem with material feeding. We found that when the feeder did not discover one of these two conditions after feeding, the system will go into shutdown mode:

- The feeder must detect a loss of weight after running the weight screw
- The feeder must detect a gain in weight after running the material bin screw

The clumping or bridging of material due to in-homogeneity caused the density of the plug to be lower. Also the errors would tend to shut the feeder down. Our solution was to eliminate the error in the software and monitor the system closely. This resulted in a less dense plug, which resulted in blowouts at lower pressures. The ultimate solution to the bridging problem was to add a purge into some areas of the feeder, and have personnel manually stir the material bin at 15 minute intervals during operation. Another problem was due to using bottled N₂ as a pressure source that resulted in long pressurization times of 4-5 hours due to the size of the tank. The slow pressurization also exacerbated the variance in coal-biomass feed rates.

Here we summarize one of the runs that were conducted after overcoming most of the problems. The run was carried out with the 50-50 coal wood mixture followed by the 70-30 coal wood mixture on 3/17/2011. The run began with a 50/50 bituminous coal and wood mixture. The mass flow rate was kept at 25 lb/hr during plug formation and primary pressurization using 150 psi nitrogen from a liquid nitrogen source. The system back-pressure was raised slowly. The program fixes worked as they should as the back pressure was increased and the brake pressure set-point was maintained at 1850 PSI. After running for a little over 3 hours, the biomass type was switched to 70/30 bituminous coal and wood blend. The N₂ source was also switched to a high pressure nitrogen 16-pack with the back pressure at 115 PSI. At these low pressures and low mass flow rate, very little material bridging was observed compared to material bridging at higher flow rate. The mass flow rate was increased gradually from 25 lb/hr to its maximum flow of 220 lb/hr over the next 3 hours. A view of the control panel at this point is shown in Figure 30.

Figure 30. Feeding 220 lb/h of a 70-30 coal-wood mixture against 450 psi back pressure

The targeted mass flow rate of 220 lb/h had been achieved with the back pressure maintained at 450 psig. However, as the mass flow rate increased so did the frequency of coal-biomass mixture bridging. The backpressure of 450 psig was maintained for about an hour when the plug was blown back, caused by availability of insufficient material due to bridging. This limitation might be remedied by adding a nitrogen purge to the weigh screw bin to keep the biomass from bridging. The bridging appears to have contributed to a non homogeneous plug that was blown back potentially due to material segregation leading to a lower amount of biomass than that needed for binding the coal particles. The problem of segregation leading to non homogeneous plugs continued to pose a problem of blowback of the plugs.

For safe operation, we believe the feeder either needs to use a uniform mixture (unlikely) or must be able to form a secondary seal against pressure at the piston in case the plug is not able to hold the pressure and allows leak. One way to do that might be to use piston rings similar to those used in cars. Another idea would be to somehow pressurize the back side of the plug with nitrogen at a slightly higher pressure than the vessel. This would ensure no leakage from the outside – in. This would require similar modifications to all three pistons as well. Our feeder partner TKEnergi [10] recognized the problem of forming plugs of non uniform materials and

claims to have now developed a new feeder as described in the reference that (i) seals at the piston, (ii) does not require plugs to be formed, and (iii) thus does not require a plug breaker.

Preliminary Engineering and Economic Evaluation

A high-level analysis of the scaling of feeder size and the potential competitive economics with existing systems was recommended by the peer review committee based on the presentation given during the review in 2009. An economic analysis for commercial coal gasification sized systems (e.g., 50,000 barrels per day of CBTL liquids) can guide development paths and risks; such feeder units typically last for months, not years, so a clear economic analysis is necessary.

A preliminary techno-economic analysis for a large pilot scale 5 ton per hour system was presented earlier and is shown in Table 7. This analysis showed that the cost of the plug feeder was similar to lock hopper systems and to other feeders, and the operating cost was lower than lock hoppers. A preliminary assessment of the techno-economic efficacy of the feed system for application to a commercial scale entrained flow gasifier system operating at pressures up to 450 psi was attempted. In this analysis, the piston plug feeder concept was to be incorporated into an existing CBTL facility design for comparison with other high-pressure feeders in both scale-up ease and overall cost. Among the various dry feed

Table 7. Techno-economic comparison of various feed systems

Feed System	Piston Driven Plug Feeder	Lock Hopper System	Rotary Valve	Screw Plug Feeder
2007 Cost (5 tons per hour @ 5 – 30 bar)¹	\$1,610,472-\$2,013,090	\$939,442 (single stage) \$1,610,472 (two stage)	\$1,342,060 - \$1,610,472 (not available at high pressure)	\$1342,060 (larger capacity, not available at high pressure)
Maintenance cost	Low – mainly related to piston front and liners.	Low—mainly related to the valves	High – due to wear on the rotary drum	High
Operating cost (incl. bleed gas)	Low	High	High	Medium
Risk of bridging and rat holing	Low	High – can be reduced by proper design	Medium – material can bridge in the chamber	Low
Maximum Capacity (Tons/Hour)	Up to 10	> 50	10 - 50	10-25

¹ Converted from Euros to Dollar using June 2007 exchange rate of \$1.34206/ Euro.
(<http://www.x-rates.com/d/USD/EUR/hist2007.html>)

systems for high pressure gasifiers, none have been demonstrated commercially for coal-biomass mixtures, and for feeding of coal alone, the only dry system that has been used in large scale gasifiers is based on lock hoppers. However, lock hoppers suffer from a number of operating disadvantages, including their height that would be as much as three times that for plug feeders, and use of large amounts of inert gas for pressurization and transfer. Also since the valves between hoppers are subject to use in the presence of large amounts of solids, they are subject to sticking and seal failure. The plug feeder has advantages in the above aspects, but appears to suffer from larger power consumption due to the requirement of moving plugs through pistons in a manner similar to extrusion. Also, the plug feeder required the coal-biomass mixture to be very consistent and homogenous in order to form plugs of sufficient integrity to form a pressure seal.

A detailed economic analysis of the plug feeder could not be carried out due to lack of supporting data for scale up from the manufacturer. Also the fact that the feeder would need modifications makes the economic evaluation for the current feeder of little value. TKEnergi [9,10] has terminated the scale up of the plug feeder and has been developing a new feeder based on pistons and a sealing ring described in patent application WO2011/04491 A2 that can move powders into high pressure environments and does not depend on formation of a plug to provide a seal. This patent application is attached in Appendix C. Clearly if the mixture can be fed without the need for forming plugs, the feeder would have significant advantages. Not only would the power consumption be low because there would not be a need for forming and pushing plugs through pistons, there would not be a need for the material being fed to be uniform. Because of significant capital and operating cost advantages, this feeder would be far superior versus lock-hoppers. However, the performance of the modified feeder is yet to be verified.

Conclusions and Summary

The most important results obtained in the project included:

- Coal-biomass mixtures consisting of 50 to 70 % bituminous coal and lignite mixed with woody biomass, corn stover, and switch grass were successfully prepared using a hammer mill. The size distribution and moisture content of these mixtures was measured.
- Feeder was demonstrated for feeding coal-biomass mixtures containing 50-70 % coal into a high pressure tank at 350-450 psig at variable speeds from 1 to 220 lb/h.

Based on the successful high pressure testing results, the potential advantages of the piston-plug feeder technology are summarized below:

- The piston-plug feeder technology does not require the use of expensive lock-hopper systems
- Bridging is not a major issue as in lock-hoppers because the feed hoppers are at low pressure
- Biomass/coal plugs of sufficient strength and density can be formed using a hydraulic pressure of 1600-2000 psi on the third piston.
- Biomass aids in the binding--no external binders are used.

Some limitations of the feeder technology that were brought to light during the high pressure tests included:

- The in-homogeneity of coal-biomass mixtures caused by particle size differences between coal and biomass and the much lower compressibility and higher density of coal as opposed to biomass can contribute to segregation in the feed hopper that leads to non-uniform plug formation. When this happened, the plugs were not able to hold the high pressure.
- A seal only at the plug needs to be proven safe for use in a combustible environment such as an entrained flow gasifier—based on a process hazard assessment carried out at Southern, it was concluded that the feeder would need modification to provide a secondary seal at the piston.
- Due to potential high power consumption and the sealing problem mentioned above, TKEnergy has discontinued the scale up of the feeder, thus rendering a detailed economic evaluation to be of little value.

TKEnergi is currently developing a feeder that seals at the pistons, does not require that the mixture be uniform, does not require forming and pushing plugs, and thus requires less energy to operate. Southern and TKEnergi are presently discussing the potential development and testing of this new feeder in a future project.

To summarize the project at Southern,

- Biomass pretreatment system consisting of a fluidized-bed dryer and shredder and capable of processing up to 500 lb/h biomass, was commissioned at Southern
- Coal-biomass mixtures consisting of 50 to 70 % bituminous coal and lignite mixed with woody biomass, corn stover, and switch grass were successfully prepared using a hammer mill.
- TKEnergi Feeder was demonstrated for feeding a coal biomass mixtures containing greater than 50% coal into a high pressure tank at 350-450 psig at variable speeds from 25 to 220 lb/h.
- The piston-plug feeder needs to be modified to provide a secondary seal at the piston in addition to the seal formed by the plug.
- TKEnergi is developing a new feeder that
 - does not require the formation of plugs
 - uses significantly less energy than the present piston-plug feeder design
 - Southern and TKEnergi are presently discussing the potential development and testing of this new feeder.

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Appendix A: Coal-biomass Mixture Properties

The particle size distribution, average particle size, and moisture content of the various coal biomass mixtures are shown in Table A-1.

Table A-1: Coal-biomass Mixture Properties (sample key provided in Table A-2)

Screen Weights								Mean Size Average (microns)	Sample
50	70	140	200	270	325	500	Pan		
297	210	105	74	53	44	25	0		
0.00%	25.60%	22.35%	14.08%	11.17%	11.80%	14.63%	0.38%	78.50	BW5-1
13.96%	10.19%	20.22%	14.20%	11.50%	8.84%	20.47%	0.61%	72.88	BW5-2
31.09%	17.26%	22.83%	10.75%	6.47%	3.60%	7.62%	0.39%	117.97	BW5-3
15.15%	11.23%	21.25%	13.82%	11.20%	8.84%	18.16%	0.35%	77.57	BW5-4
14.22%	10.55%	20.77%	14.19%	11.62%	8.35%	19.85%	0.46%	74.68	BW5-5
17.43%	14.18%	24.62%	13.36%	9.46%	6.27%	14.31%	0.36%	88.33	BW5-6
18.08%	11.96%	22.02%	13.39%	10.69%	7.69%	15.84%	0.33%	83.36	BW5-7
11.60%	10.04%	20.63%	14.86%	12.91%	9.77%	19.84%	0.36%	72.62	BW5-8
15.71%	11.88%	21.21%	13.96%	11.45%	8.21%	17.18%	0.41%	79.29	BC5-1
13.56%	11.59%	20.92%	13.92%	12.07%	9.18%	18.12%	0.66%	75.26	BC5-2
13.30%	11.11%	21.79%	14.78%	12.64%	8.52%	17.11%	0.74%	76.08	BC5-3
12.86%	11.27%	21.55%	14.61%	12.13%	8.61%	18.19%	0.78%	74.71	BC5-4
14.80%	11.31%	21.41%	13.84%	11.92%	8.22%	17.92%	0.59%	76.92	BC5-5
18.45%	15.44%	23.81%	12.88%	9.68%	6.20%	13.03%	0.50%	90.45	BG5-1
22.29%	16.90%	22.59%	11.28%	8.90%	5.91%	11.67%	0.45%	96.62	BG5-2
15.65%	13.69%	23.82%	13.69%	11.18%	7.78%	13.82%	0.36%	85.64	BG5-3
17.43%	13.74%	21.39%	13.23%	11.04%	9.19%	13.64%	0.34%	85.29	BG5-4
22.70%	16.79%	23.45%	12.19%	8.91%	5.63%	9.94%	0.39%	100.95	BG5-5
23.02%	17.03%	23.32%	11.71%	8.56%	5.48%	10.49%	0.37%	100.78	BG5-6
7.97%	14.62%	35.02%	17.87%	8.21%	5.11%	11.02%	0.18%	93.41	LW7-1
20.69%	15.76%	24.12%	12.33%	8.04%	4.66%	12.93%	1.46%	88.87	LW7-2
13.06%	14.23%	27.61%	13.16%	8.21%	4.59%	18.67%	0.47%	82.13	LW7-3
8.66%	11.46%	27.47%	17.02%	11.17%	7.03%	16.97%	0.21%	79.13	LW7-4

Table A-2: Sample Key

Sample Source Key
B = Bituminous Coal
L = Lignite
W = Wood
C = Corn Stover
G = Switch Grass
5 = 50% coal
7 = 70% coal

Photographs of the various coal-biomass mixtures

50/50 Bituminous Coal and Wood Mix

50/50 Bituminous Coal and Switch Grass Mix

70/30 Bituminous Coal and Wood Mix

50/50 Lignite and Corn Stover Mix

Appendix B: Run Log Book

The issues encountered were simple program startup issues with the feeder caused by slow VFD startup. These errors were resolved by clearing the errors using remote software and will need to be repeated every time a new program is loaded. Motors in areas “F” and “G” also experienced errors caused by a bad fuse and a single faulty fuse holder. These errors were resolved by replacing the appropriate components. When the system was first pressurized, it was determined that any error will stop the compression feeder, brake pressure will be lost, and a blowout can occur. The only way to currently address this problem is to avoid system errors, and material bridging has been the primary source of these errors. When weigh-screw bin weight decreases over many cycles and feed-screw “A” cannot add material due to bridging, an error count is increased which will eventually stop the system. This problem has been addressed by repairing the “stirrer” in bin “A” and manually agitating the material by hand during normal operation. This seems to have eliminated the bridging problems. However, the spool piece connecting the pressure vessel and the compression feeder is also likely to collect biomass and can eventually create flow blockage. Overheating was experienced with motor G.M1 due to spool blockage. As a result, the spool was removed, cleaned and replaced. The blockage was most likely caused by multiple plug blowouts, and has not been experienced a second time. The final problem encountered involves the maximum brake pressure. As the brake PrV hydraulic temperature increases, the brake becomes less capable of reaching the desired set-points. This creates softer plugs that are unable to hold the required backpressures. The selected test materials seem to enhance the problem since there is little material expansion observed once the biomass is compressed. This creates a situation where brake pressure needs to be maintained in order to hold a proper seal. However, as the plug size increases, the brake must be released to push a predetermined length through the system to avoid binding. This brake pressure must then be increased to its original state, but is unable to do so quickly because of software coding. In an attempt to alleviate the inability to quickly reapply brake pressure, the control software has been modified to wait for P3 to reach a higher set-point before brake pressure is reduced, and the plug size decrease has been lowered to shorten the amount of time that the brake is not fully pressurized. The PrV return set-point will also be increased to eliminate slow pressure ramping.

02-23-2011

-System parameters-

Plug weight: NA

Brake pressure: NA

Mass flow rate: NA

Mass type: NA

Pressure source: Nitrogen Dewar and HP Nitrogen pack

This trial was run to determine base leak rate for vessel V-8. The 3-stage plug feeder was disconnected from the vessel, and a blind flange was used in place of the feeder. A nitrogen dewar was used to saturate the system with nitrogen at a targeted pressure increase of 300 PSI/hr. The inline pressure regulator immediately experienced freezing and caused unregulated nitrogen flow. The nitrogen source was isolated from the vessel and the system was depressurized.

02-24-2011

-System parameters-

Plug weight: NA

Brake pressure: NA

Mass flow rate: NA

Mass type: NA

Pressure source: Nitrogen dewar and HP Nitrogen pack

This trial was a continued attempt to determine base leak rate for vessel V-8. The targeted pressurization rate was decreased to 200 PSI/hr. The regulator continued to experience freezing, so the source was isolated and the system depressurized. A regulator bypass valve was installed to eliminate freezing. The nitrogen flow was controlled using a simple needle valve. Vessel pressure was increased to ~190 PSI using the dewar. The nitrogen dewar and vessel was then isolated, and line pressure was bled upstream of the vessel. The nitrogen dewar was then replaced with a 3000 PSI nitrogen 16-pack. Vessel pressure reached 277 PSI and was then isolated in order to continue the process tomorrow. All pressure control data tags were updated and imported into the data historian.

02-25-2011

-System parameters-

Plug weight: NA

Brake pressure: NA

Mass flow rate: NA

Mass type: NA

Pressure source: Nitrogen dewar and HP Nitrogen pack

This trial was a continued attempt to determine base leak rate for vessel V-8. Vessel pressure was increased from ~277 PSI to 500 PSI in about 1 hour. The vessel was isolated at 09:11 and remained in isolation until 11:11. Over a 2 hr period there was an observed pressure decrease of 8 PSI (498.7 – 490.7). The Vessel pressure was then decreased to 450 PSI. The vessel was isolated at 13:43 and remained isolated until 15:43. Over this 2 hour period there was a pressure *increase* of 1.1 PSI (449.7 – 450.8), most likely caused by ambient temperature increase. This run confirmed that there was no leak in the system.

02-28

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1500 PSI

Mass flow rate: 220 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

This trial was run to ensure the correct functionality of the compression feeder system. The blind flange was removed, and the vessel and feeder were joined using a spool coupling. Upon startup, the error “B.M1 faulted” immediately caused the system to fail. The problem was determined to be a simple startup error. Every time the operational program is changed and/or reloaded, this error must be lifted using remote software.

03-01-2011

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1500 PSI

Mass flow rate: 220 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

This trial was a continuation to ensure the correct functionality of the compression feeder system. Startup immediately caused the errors “G.M1 motor protector tripped” and “F.M1 motor protector tripped”. The hydraulic power packs also failed to initiate. The control board was traced and all voltages were checked. The fuse holder –F10/2 was found to have a blown fuse. The fuse was replaced (3A / 600V) and was immediately blown on compression feeder startup. A new external fuse holder was purchased, and the fuse rating was increased to 5A.

The compression feeder was tested under “manual mode” and each motor functioned correctly. However, when the feeder was run in “automatic mode”, motors G.M1 and F.M1 still failed to initiate. These motors should always be activated and running under normal operation. The control program was modified to ensure that these two motors are always activated and running when the compression feeder is active. The compression feeder currently functions properly.

03-02-2011

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1500 PSI

Mass flow rate: 220 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

This trial was run to ensure the proper functionality of the pressure control system. A low pressure of ~40 PSI was applied to the system. The backflow regulator PCV-8026 failed to regulate the pressure. After careful inspection, the system component PCV-8026 was determined to be a pilot pressure controlled regulator. This part could not achieve the required functionality without significant pressure control system modifications and additions. As a result, a new regulator (spring controlled) would need to be purchased.

03-03-2011

-System parameters-

Plug weight: NA

Brake pressure: NA

Mass flow rate: NA

Mass type: NA

Pressure source: NA

The project was put on hold until the new regulator was shipped and received. Tescom back-pressure regulator 26-176524 was purchased from W. K. Hile Company Inc.

03-07-2011

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1500 PSI

Mass flow rate: 221 lb/hr – 1lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

Trial time: 08:30 – 16:30

This trial was run to determine the leak rate across a biomass plug formed under full system pressure. The new backflow regulator was installed and a plug was formed at atmospheric pressure and a feed rate of 220 lb/hr. The system was then pressurized using an N2 dewar to ~55 PSI and the backflow regulator was determined to be fully functional. Mass flow rate was decreased to 1 lb/hr and the pressure was increased until 140 PSI was reached. The vessel was isolated and the N2 dewar was replaced with a HP N2 16-pack. Pressure was applied to the vessel with a source/vessel pressure difference of ~100 PSI. The system was put into normal shutdown, at a vessel pressure of 348 PSI, as an attempt to maintain vessel pressure overnight. The vessel began to lose pressure rapidly and the system was restarted. Error “E.PT: Do not

pressurize before plug is OK” was lifted. 348 PSI Plug blowout occurred at 16:14. ESTOP manually triggered at 16:15. The Conex (compression feeder) was thoroughly cleaned, paying special attention to the load cells and piston assemblies.

03-08-2011

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1500 PSI

Mass flow rate: 221 lb/hr – 1lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

Trial time: 08:33 – 16:30

This trial was run to determine the leak rate across a biomass plug formed under full system pressure. A biomass plug was formed at atmospheric pressure and a mass flow rate of 220 lb/hr. The mass flow rate was then decreased to 1 lb/hr and the system was pressurized to ~140 PSI using an N2 dewar. The vessel was isolated and the N2 dewar was replaced with a HP N2 16-pack. Mass flow rate was increased to 2 lb/hr. Pressure was applied to the vessel with a source/vessel pressure difference of ~100 PSI. Vessel pressure reached 372 PSI. Error “B: Out of Material” occurred at 13:33. Plug blowout began at 13:33. The ESTOP was manually triggered at 13:35. The system was started under normal operation at atmospheric pressure to remove any fully formed plugs from the compression system. Conex was then cleaned.

03-09-2011

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

Trial time: 08:40 – 09:50

This trial was run to determine the leak rate across a biomass plug formed under full system pressure. TK Energy had been contacted regarding previous blowouts. They recommended increasing the brake pressure. SRI resources also recommended increasing the mass flow rate. A biomass plug was formed at atmospheric pressure and a feed rate of 220 lb/hr. The mass feed rate was then decreased to 120 lb/hr. The system was pressurized using an N2 dewar. Pressure was applied to the vessel with a source/vessel pressure difference of ~100 PSI. Error “B: Out of Material” and “A: Out of Material” occurred at 09:39. Vessel pressure reached 34 PSI. Plug

blowout occurred at 09:43. The ESTOP was triggered manually. The Conex (compression feeder) was thoroughly cleaned, paying special attention to the load cells and piston assemblies.

-System parameters-

Plug weight: 0.5 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

Trial time: 14:02 – 14:31

The previous trial was repeated and received the same errors. Max vessel pressure observed was 20 PSI.

03-14-2011

-System parameters-

Plug weight: 1 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Atmospheric

The trial procedures have remained the same with the exception of a few program changes and a plug weight increase of .5 lb. Currently, the largest concern is the decrease of the brake pressure during normal operation. This seems to be the cause of every recorded plug blowout. Possible causes include P3 pressure limits, “secure mode” parameters, and “stop mode” parameters”. The maximum limit of P3 was increased to 2700 PSI in order to stop the brake pressure from dropping to 100 PSI during normal operation. *“Secure mode” brake pressure set-point was increased from 100 PSI to 200 PSI to help identify the software routine being called when the pressure decrease occurs.*

Atmospheric trial start: 08:53

Bin weight: 240 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-08:55 error "B.out_of_material"

-08:55 system "shutdown"

Atmospheric trial start: 08:59

Bin weight: 140 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-09:20 - abnormal drop in brake pressure SP 1750 PSI --> 1600 PSI

-09:23 - abnormal drop in brake pressure SP 1850 PSI --> 100 PSI

-09:29 - "normal shutdown"

Atmospheric trial start: 10:46

Bin weight: 40 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-11:09: abnormal drop in brake pressure SP 1750 PSI --> 100 PSI

-11:10: "normal shutdown"

P3 software pressure limit changed from 2000PSI --> 2700PSI

Atmospheric trial start: 14:03

Bin weight: ~0 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-14:26: abnormal drop in brake pressure SP 1750 PSI --> 100 PSI

-14:27: "normal shutdown"

Loaded feeder bin with 2x 120lbs (BW5-5 and BW5-6)

Atmospheric trial start: 15:11

Bin weight: 240 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-15:38: abnormal drop in brake pressure SP 1899 PSI --> 100 PSI

-15:39: "normal shutdown"

Atmospheric trial start: 16:00

Bin weight: 140 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

-16:28: abnormal drop in brake pressure SP 1899 PSI --> 100 PSI

-16:29: "normal shutdown"

Every trial run this day saw a quick decrease in brake pressure set-point. The pressure of P3 had been determined to be unrelated to the brake pressure drop.

03-15-2011

-System parameters-

Plug weight: 1 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

The program has been defaulting to “secure mode” based on previous trial observations. This appears to be within normal operating parameters. The underlying cause then appears to be material bridging. The loading bin and weigh bin will be closely monitored during all following trials.

Atmospheric trial start: 11:51

Bin weight: 400+ lb

Brake pressure: 1900 PSI

Mass flow rate: 20 lb/hr

Plug weight: 1.0 lb

-16:32 error "B.out_of_material"

- Area "A" bin was visually inspected and contained an estimated 300 lbs of biomass
- The weigh screw bin was determined to have contained no biomass, possibly due to bridging
- The data trend suggests that there was little to no fluctuation of the weigh screw weight, cause remains unknown, but material bridging is likely.

-17:22 plug blow-out

03-16

-System parameters-

Plug weight: 1 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

The cause of brake pressure loss is due to bridging in area B. The weigh screw weight continually decreases and there is no observable weight increase as motor A.M1 is running. This suggests that there is material bridging. Upon further investigation, some of the material bridging was caused by broken bolts holding the agitator blades to the rotating shaft. This assembly was repaired and the system was run in “normal operation” again. Shortly after startup, the error “G.M1 Motor Protector Tripped” was displayed and the system went into “stop mode” causing the system pressure to rapidly decrease along with the decreased brake pressure. The cause was due to blockage in the spool connecting the vessel and compression system. The spool was taken off of the vessel and the blockage was removed.

03-17-2011

-System parameters-

Plug weight: 1 lb

Brake pressure: 1900 PSI

Mass flow rate: 220 lb/hr – 120 lb/hr

Mass type: 50/50 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

The brake pressure never reached its maximum set-point. This was most likely caused by the increased temperatures observed on the brake's PrV. To counter the increasing PrV temperature, nitrogen gas was applied directly to the valve. The brake still reached its maximum pressure limit near 1750 PSI, and the nitrogen seemed to have little effect. This limited the amount of backpressure that could be applied to the biomass being fed. When the PrV set-point was reduced to allow a decrease in plug length, the program slowly increased the brake pressure back to the desired set-point. This pressure increase needs to occur much quicker. In addition, the biomass continuously bridged. As a result, the bin in area “A” needed to be frequently agitated by hand (about every 10 min @ flow of 25 lb/hr). The weigh screw weight also needed to be closely monitored to ensure that mass was entering the compression system and to ensure that bridging did not also occur within the weigh bin.

Summary of events:

Default program errors and reset

Control circuits and fuses
Compression feeder startup under pressure
Material bridging and “out of material” errors
Brake pressure
Plug weight
Material properties: compression, relaxation, and frictional (adhesion to steel)
PrV temperatures and pressure limits

03-17-2011

-Trial start: 10:41

-System parameters-

Plug weight: 1 lb

Brake pressure: 1900 PSI

Mass flow rate: 25 lb/hr – 220 lb/hr

Mass type: 50/50 by weight and 70/30 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

The control program was edited to maintain a constant brake pressure when system backpressure reached a predetermined value. The purpose of this change was to ensure minimal brake pressure variance when plug length increased beyond the maximum limit. This should allow the PrV to reach its previous set-point much faster and allow for quick system recovery.

The trial began with about 160 lbs of a 50/50 bituminous coal and wood blend. The mass flow rate was kept at 25 lb/hr during plug formation and primary pressurization using an N2 dewar. When the system backpressure reached 100 PSI, the program additions worked as they should and the brake pressure set-point was fixed at 1850 PSI. At 13:58 the biomass type was switched to 70/30 bituminous coal and wood blend. The N2 source was also switched to a high pressure nitrogen 16-pack with current system pressure at 115 PSI. At these low pressures and low mass flow rate, very little material bridging was observed compared to material bridging at higher flow rates from previous trials. Backpressure continued to build to 429 PSI and then the mass flow rate began to gradually increase from 25 lb/hr to its maximum flow of 220 lb/hr. As the mass flow rate increased so did the frequency of biomass bridging. A backpressure of 450 PSI was reached at 16:00 and was maintained until 16:45. Plug blow-out occurred at 16:46. The cause of this blow-out was most likely due to a decrease in required mass flow caused by bridging at high mass flow rates. This limitation can be remedied by adding a nitrogen purge to the weigh screw bin to keep the biomass from bridging.

03-31-2011

Atmospheric trial start:

Bin weight: ~120 lb

Brake pressure: 1750 PSI

Mass flow rate: 220 lb/hr

Plug weight: 1.0 lb

A compressed air purge system was installed on the weigh bin in order to help eliminate material bridging. The compression system was run at atmospheric pressure using a 70/30 blend bit-coal and wood. The error counts remained, but were immediately lifted when the purge system moved the material from the loading bin. The data trends look very consistent, and material is being constantly fed. Although there is still bridging, the problem has been alleviated to the point that a successful trial can be run without stoppage due to lack of material flow and material bridging.

04-01-2011

-Trial start: 10:41

-System parameters-

Plug weight: 1 lb

Brake pressure: 1850 PSI

Mass flow rate: 25 lb/hr

Mass type: 70/30 by weight, bituminous coal and wood mix

Pressure source: Nitrogen dewar and HP Nitrogen pack

The purpose of this trial was to test the functionality of the compressed air purge under high system pressure. The system software continuously alerted of weigh bin errors after every load bin motor cycle. This was due to the delay caused by the new purge system. As the load bin fed biomass, the end of the feed tube would collect mass. The purge would then break the mass loose and it would fall into the weigh bin at a slow but consistent rate. Data trends showed that the biomass feeder was receiving a steady stream of biomass, and little to no bridging was occurring. Plug failure and system blowout occurred at a vessel pressure of ~360 PSI. There were no immediately noticeable actions or trends that could have caused the blowout.

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(54) Title: A PISTON MEMBER, AN APPARATUS COMPRISING THE PISTON MEMBER, AND METHODS AND USE OF THE PISTON MEMBER AND THE APPARATUS

Fig. 2

(57) Abstract: A piston member (1,1',1'') comprising a piston rod (4) provided with a piston (3,3',3'') serves for reciprocating inside a cylinder barrel (5,6,7,5',6',7',5'',6'',7''), said piston (3,3',3'') divides the cylinder barrel chamber (34a,34a',34a'',34b,34b',34b'') into a proximal cylinder barrel chamber (34a,34a',34a'') having a proximal capped end (35a,35a',35a'') opposite the piston (3,3',3'') and a distal cylinder barrel chamber (34b,34b',34b'') having a distal cylinder barrel end (35b,35b',35b'') opposite the piston (3,3',3''). The piston member comprises at least one sealing ring (8,8',8'') or seat arranged inside the distal cylinder barrel chamber (34b,34b',34b'') at the distal cylinder barrel end (35b,35b',45''). Preferably three consecutive piston members (1,1',1'') are arranged to operate in a series in an apparatus for transporting coal powder to a gasifier. The movement of the pistons inside the cylinder barrels is controlled in relation to each other to transport apportioned batches of coal powder to a high pressure reactor.

A piston member, an apparatus comprising the piston member, and methods and use of the piston member and the apparatus.

5 The present invention relates to a piston member comprising a piston rod provided with a piston reciprocating inside a cylinder barrel, said piston divides the cylinder barrel chamber into a proximal cylinder barrel chamber having a proximal capped end opposite the piston and a distal cylinder barrel chamber having a distal cylinder barrel end opposite the
10 piston.

The invention further relates to an apparatus for continuous transporting apportioned batches of material to a recipient, such as a gasifier or reactor.

15 The invention further relates to methods of continuous transporting apportioned batches of material to a recipient, such as a gasifier or a reactor under high pressure.

20 In particular the present invention relates to the use of an apparatus and methods for transporting coal powder and other solid materials.

Gasification of fossil fuels, biomass or waste is currently
25 widely used on industrial scales to generate electricity. Gasification relies on chemical processes at elevated temperatures greater than 700°C, which puts a high demand on safety regulations when the raw material are continuously fed to the gasifier, in particular due to presence of toxic and
30 explosive gases. In a gasifier, the carbonaceous raw material undergoes several different processes. First the pyrolysis process occurs as the carbonaceous particle heats up. Volatile gases are released and char is produced resulting in weight loss of coal. The process is dependent on the properties of the
35 carbonaceous material and determines the structure and composition of the char, which will then undergo gasification

reactions. Next the volatile products and some of the char reacts with oxygen to form carbon dioxide and carbon monoxide in a combustion process, which provides heat for the subsequent gasification reactions where the char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen. By introducing oxygen or air into a gasification system organic material is converted into carbon monoxide and energy, for driving a second reaction that converts further organic material to hydrogen and additional carbon dioxide.

The feeding of solids into a high pressure reactor has however always been difficult because of both high equipment costs and poor material characteristics. Lock hoppers, which are the most commonly used principle for feeding against a pressure, have serious problems in the very high consumption of inert gas used for pressurizing and transfer. This is especially the case for feeding solids with a low density or with a tendency to form bridges. One other major shortcoming of lock hoppers is that it is a batch type operation. Since the valves between hoppers must be operable with high concentration of solids while moved, the valves are subject to sticking and seal failure under the operating conditions. Both the depressurizing valve and the vent lines are subject to severe abrasive conditions as the result of the rapid movement of hard solids therethrough under the influence of the differential pressure. Such systems are thus subject to sequence control failures and unsuitable for continuous operation due to great costs.

EP 1 425 089 relates to a method and apparatus for transfer of particulate products between zones of different pressure. In a sluice system the particulate product is first transported through a portioning device, which produces a sequence of uniform product portions divided by uniform particle free spaces. Subsequently the product portions are transported individually through a sluice device, which comprises at least one sluice chamber and two pressure locks of which at least one

at any time secures a pressure tight barrier between the two pressure zones, and the product portions are force loaded from the first zone into a sluice chamber by means of a piston screw, the axis of which is practically in line with the axis of the sluice chamber, and the product portions are force unloaded from the sluice chamber and into the second pressure zone by means of said piston screw or a piston or by means of gas, steam or liquid supplied at a pressure higher than that of the second pressure zone. The sealing surfaces of the apparatus described in EP 1 425 089 are very vulnerable to wear resulting in that the apparatus is prone to leak. If gas is used as the pressure fluid the gas that is compressed in the sluice chamber must be released as the sluice chamber has to be decompressed in order to be filled again. Thus the gas from the sluice chamber will be released to the atmosphere during each piston stroke. This means that either the apparatus can only feed into atmospheres that are not combustibile, explosive or poisonous or the consumption of inert bleed gas, i.e. gas resulting from any leakage in the feeding mechanism, will be very high.

In a main aspect according to the present invention is provided a piston member, an apparatus and a method by means of which the disadvantages of the prior art can be remedied.

In a second aspect according to the present invention is provided a piston member, an apparatus and a method by means of which materials can be transported into combustibile, explosive and/or poisonous atmospheres without safety risks.

In a third aspect according to the present invention is provided a piston member and an apparatus with lower wearing-down frequency than hitherto known.

In a fourth aspect according to the present invention is provided an apparatus in which the apparatus components can be replaced at minimum costs and downtime.

In a fifth aspect according to the present invention is provided a piston member, an apparatus and a method by means of which fine particles of combustible material can be transported
5 to a recipient, including a gasifier or a reactor, without clogging.

In a sixth aspect according to the present invention is provided an apparatus for continuous transporting apportioned
10 batches of material to a hot recipient without bridging.

The novel and unique feature whereby at least one of the above aspects is achieved according to the present inventions consist in that at least one sealing ring or seat is arranged inside
15 the distal cylinder barrel chamber at the distal cylinder barrel end, preferably a ductile sealing ring or a ductile seat.

Within the scope of the present invention a "ductile material"
20 is defined as a material having the mechanical property of being deformed plastically without fracture.

The ductile sealing ring or ductile seat is hit by the piston in a forward piston stroke by means of a force resulting in
25 that the ductile sealing ring or ductile seat is deformed to such an extent that a fluid tight seal is created between the contacting surfaces of the cylinder barrel chamber, the ductile sealing ring or seat, and the piston. The seat may be constituted by an annular protrusion on the interior cylinder
30 barrel wall or may be constituted by a separately inserted sealing ring. In the first case the entire cylinder barrel part must be substituted, in the latter case only the sealing ring needs replacement. In both cases the seat or sealing ring constitutes an annular protruding end section of reduced
35 diameter of the cylinder barrel chamber, which end section, at the end of the forward piston stroke, is hit by the piston

transporting the material in front of the piston. The piston member is thus designed with a travel of piston that is longer than the axial length of the piston.

5 Due to the ductility of the material of the ductile sealing ring or ductile seat, said ductile sealing ring or ductile seat reassumes its original configuration during the return piston stroke. Thus, the ductile sealing ring or ductile seat serves as an advantageously moving seat for sealingly engaging the
10 piston and the cylinder barrel. A preferred embodiment of a piston member that creates a sufficient deformation of the ductile sealing ring or ductile seat when hit by the piston includes a piston manufactured from a hard metal, e.g. hardened steel and a ductile sealing ring or ductile seat manufactured
15 from a ductile metal, e.g. austenitic stainless steel. Austenitic stainless steels have high ductility and high ultimate tensile strength resulting in a very reliable metal-metal seal between the components of the piston member and the ductile sealing ring or ductile seat, where the ductile sealing
20 ring or ductile seat advantageously regenerates after each piston stroke. This embodiment is suitable for use for transporting solid combustible material to a high pressurized recipient.

25 In case the sealing ring or seat is manufactured of a metal that is not ductile, said sealing ring or seat may not be able to reassume its shape but the sealing capability is still present and reliable due to the intimate metal-metal seal between the components of the piston member and the sealing
30 ring or seat. In this embodiment the sealing ring or seat may be cast together with the cylinder barrel.

Irrespective of the sealing ring or seat is manufactured of a ductile material or not, the sealing ring or seat can be
35 replaced at low cost once wearing requires it to maintain

reliable sealing, in contrast to conventional apparatuses where down-time during maintenance often is prolonged.

A further advantage of such a sealing ring or seat is that deposits, aggregated matter or any foreign matter can be broken or cut without detrimental consequences for the sealing property of the sealing component, i.e. the sealing ring or seat. The edge of the sealing ring or seat serves as a cutting knife for any transported material present in the cylinder barrel when hit by the piston, thus an inherent and advantageous further property of the sealing ring or seat is as a tool for preventing clogging and accumulation in the cylinder barrel.

Advantageously, the piston may have a front nose facing towards the distal cylinder barrel chamber to compensate for differences in volume of piston and a total volume of an intermediate compartment into which material is transported on its way to the recipient. Transport may take place continuously, in consecutive apportioned batches of a volume each corresponding substantially to the volume of the intermediate compartment, in order that the transport process maintains pressure neutral. Thus the nose is preferably designed so that the total volume of the intermediate compartment becomes as close to the volume of the piston when the nose protrudes inside said intermediate compartment. The difference between volumes arises due to coupling flanges that are required when two tubular members are coupled in fluid communication with each other and due to fabrication tolerances of the piston and feed chamber. By appropriate dimensioning the protruding nose with respect to size and shape control of the above volumetric ratio between volume of piston and intermediate compartment can be obtained. The nose can have any convenient design that does not influence the piston stroke or is not in the way for the reciprocating movement of the piston, hence advantageously the pistons are also prevented from

rotating about the piston axis to further ensure clearance angle and clearance area for noses on pistons on several co-operating piston members.

- 5 In the preferred embodiment the nose has an axial cut-out or an axial concavity configured to provide space for another piston reciprocating perpendicular to the piston furnished with the nose.
- 10 An exemplary intermediate compartment is for example the temporary intermediate compartment established by consecutive reciprocation co-operating piston members arranged substantially perpendicular to each other, as will be described in more detail later. As an example of volumetric ratio, if the
- 15 ratio between the volume of the intermediate compartment and the volume of the piston is 11:10 the piston member will have zero transport of gas at a backpressure of 10 bar. Since the solid material takes up some of the volume in the intermediate compartment also it is possible to obtain a neutral pressure of
- 20 up to 100 bar reactor pressure.

Normally a sluice system of co-operating piston members that feed a pressurized reactor is not tight and induces a flow of gas with the result that either gaseous matter, such as carbon

25 monoxide, leaks to the surroundings, or atmospheric air is introduced into the operating process of the sluice system. In conventional piston member applications a drop in the functionality of linear sealing is often detected after a period of operation. When the piston is in contact with solid

30 materials that are very abrasive, such as biomass or coal powder, this period can be unacceptable short.

If a piston member suddenly stops operating in a fluid tight manner the piston member may have means for detecting leakage

35 of pressurized gas or fluid from a reactor or through a

cylinder barrel chamber in direct or indirect communication with the piston member.

5 An exemplary embodiment of the means for detecting leakage of pressurized gas or fluid may comprise a pressure measuring instrument in fluid communication with a pressurized chamber delimited by the circumferential clearance between the piston and the interior wall of the cylinder barrel and two spaced apart annular seal members arranged in or at the cylinder
10 barrel chamber wall.

For use in the present application the term "pressurized chamber" is to be understood as a chamber having a pressure above the pressure of the surrounding environment.

15 Eventually the sealing ring or seat at the end of the piston barrel chamber, i.e. the sealing ring is located at the end of the piston stroke, becomes ineffective or defect during the many piston strokes, e.g. due to wear, or is damaged due to
20 contact with harder components. At that time it is very important to immediately replace the sealing ring or the seat. Thus early detection of leakage is crucial for an effective, favorable and profitable operation of the piston member. Also, air or gas may escape from the piston member via fissures,
25 cracks, poor weldings or via poor flange couplings as well as air may enter the piston member at such places. In any of the situations the air or gas will either result in that the oil pressure in the detecting zone increases or decreases and immediately reveals that a leak has occurred. Thus any
30 indication that the pressure deviates from a fixed standard pressure or pressure interval is an indication of the presence of a leak.

If the pressure measuring instrument is in fluid communication
35 with the pressurized chamber via a pipe, the pressurized chamber, that constitutes a linear seal, may be filled with a

pressurized oil at an oil pressure that is higher than the pressure at the recipient. The spaced apart annular seal members may be arranged on opposite sides of said pipe to provide a reliable pressurized chamber with extended lifetime.

5 Opposite the sealing ring or seat the piston can be consistently oiled. Leakage in any part of the reciprocating system is detected immediately because gaseous matter will either be forced or by itself escape into the pressurized chamber via the oil pipe to the pressure measuring instrument
10 if the pressure in the reciprocating system drops below a desired level, such as the pressure at the recipient. The pressure measuring instrument may trigger an alarm or other indication that the pressure has dropped to an undesired level and that measures need to be taken to remedy the reason for the
15 leakage.

Preferably the annular seal means member is a lip seal or one or more O-rings arranged in recesses in the interior annular wall of the cylinder barrel chamber. The lip seal has a
20 flexible lip that rubs against the reciprocating piston to prevent the leakage of oil and ingress of dirt to the pressurized chamber. Once a leak is present the sealing capacity is inadequate which can have several different effects on the piston member, including affecting the travel speed of
25 the piston. The oil pressure in the pressurized chamber attempt to equalize the pressure difference which action is registered by the pressure measuring instrument. Numerous types of exclusionary lips may be used within the scope of the present invention.

30

At least one circumferential slide seals may be arranged in the cylinder barrel chamber wall interposed between a pipe inlet to the pressurized chamber and the annular seal member for facilitating a smooth reciprocating movement of the piston
35 inside the cylinder barrel and may in a preferred embodiment be a Teflon® seal.

The sealing ring or seat may be dimensioned to extend radially inside the distal cylinder barrel chamber at a distance of between 2 % - 2% of the interior diameter of the distal cylinder barrel chamber to obtain effective sealing at the distal cylinder barrel end at a transition to an intermediate compartment or other recipient for the material transported by the piston at the end of the piston stroke. This sealing capacity is further ensured if the piston member is dimensioned with a stroke length adapted to deform or contact the sealing ring to seal between the cylinder barrel chamber and the piston.

As mentioned above the invention also relates to an apparatus for continuous transporting apportioned batches of material to a recipient using at least one of the piston members described above. The recipient may for example be a gasifier or reactor combusting solid particulate material at a high pressure, however since the piston member is able just to transport and deliver material to any recipient, the recipient need not be of the kind operating at high pressure and within the scope of the present invention any kind of material can be transported to any kind of recipient in a reliable and secure manner.

An apparatus, which is particularly suited for use for continuously transporting apportioned batches of material to a recipient working at high process pressure, may comprise at least three piston members of the previously described kind. Such an apparatus advantageously serves as a sluice system where apportioned batches of material are delivered as individual portions to the recipient in a system where any fluid communication between the raw material and the recipient has been removed and excluded and where bridging cannot take place.

A preferred embodiment of such an apparatus may advantageously be configured so that

- a first piston member may receive the material to be transported, the first piston member has a first piston reciprocating inside a cylinder barrel, the first piston divides the first cylinder barrel chamber of the first cylinder barrel into a first proximal cylinder barrel chamber having a first capped end and a first distal cylinder barrel chamber having an opposite first distal cylinder barrel end,
- a second piston member may have a second piston reciprocating inside a second cylinder barrel, the second piston divides the second cylinder barrel chamber of the second cylinder barrel into a second proximal cylinder barrel chamber having a second capped end and a second distal cylinder barrel chamber having an opposite second distal cylinder barrel end,
- a third piston member may have a third piston reciprocating inside a third cylinder barrel, the third piston divides the third cylinder barrel chamber of the third cylinder barrel into a third proximal cylinder barrel chamber having a third capped end and a third distal cylinder barrel chamber having an opposite third distal cylinder barrel end, wherein
- the first piston member may, in its first forward piston stroke, transport material fed to the first distal cylinder barrel chamber, into a first intermediate compartment or sluice defined by at least the second distal cylinder barrel chamber and the third piston positioned at its third distal end, and
- the second piston member may, in its second forward piston stroke, transport material from the first intermediate compartment or sluice to a second compartment defined by the third distal cylinder barrel chamber, the distal end of the second piston and the recipient.

By means of such an apparatus it is possible to transport solid material to for example a gasifier or reactor without compressing the material and just pushing the material forward by means of the pistons of the piston members in alternating piston strokes. Due to the confined intermediate compartments or sluices defined by the controlled reciprocating movements of the sequentially working pistons inside their respective cylinder barrel chambers there is no direct communication between the raw material feeder and the recipient. Bridging can never occur and the apparatus is safer than known screw feeder systems, has a higher operating capacity and is easy to maintain in good working order. Operating trouble, such as operational failure or stoppage, is rare but if occurring fast and easy to remedy by an often very simple replacement of a component, such as e.g. a sealing ring subjected to wear. During the entire feeding cycle a superior mechanical seal against the process pressure in the recipient can be established and maintained.

The material is just pushed through the temporary intermediate compartments, one compartment after the other, in the operating cycle given by the reciprocating pistons in there respective cylinder barrel, which have been arranged in communication with each other enabling the first piston of the first piston member to deliver material to the second cylinder barrel chamber of the second cylinder, and once this has taken place enabling the second piston to deliver the apportioned batch of material into the third cylinder barrel chamber of the third piston member, the third piston of which eventually pushes the apportioned batch of material into the recipient. During an operating cycle step the next apportioned batch of material may already be progressing in the cycle making the intermediate compartments filled repeatedly. Thus the operating cycle is continuously repeated over and over again. The piston members move material forward without compressing the material and the particle size distribution (PSD) is substantially undisturbed.

The at least one sealing ring or seat, preferably manufactured of a ductile metal, contributes in providing sealing of the intermediate compartments defining the sluice system for delivering the material to the final recipient. The initial texture and particle size distribution is maintained during the entire transport.

Only one piston member is required for continuous delivering apportioned batches of material to a recipient in an operating cycle comprising the steps of

- retracting the piston to the proximal end to enlarge the distal cylinder barrel chamber,
- supplying the material to the distal cylinder barrel chamber, and
- performing a piston stroke toward the distal end of the cylinder barrel to deliver the apportioned batch of material to a recipient.

This simple method may be preferred if material is to be delivered to a recipient which is not pressurized.

A preferred method according to the present invention involving more than one piston member comprises to continuously feed apportioned batches of raw material to the first piston member of the apparatus, and operating the apparatus to transport the batches of raw material to a recipient by reciprocating the first piston of the first piston member, the second piston of the second piston member and the third piston of the third piston member in a repeated feeder cycle where the pistons are positioned to define intermediate compartments for sequences of batches of material fed to the first piston member's first distal cylinder barrel chamber.

The preferred method according to the present invention may comprise the further steps of

- (a) arranging the first piston at the proximal end of the first cylinder barrel,
- (b) arranging the second piston at the distal end of the second cylinder barrel, and arranging the third piston at the distal end of the third cylinder barrel,
- (c) supplying an apportioned batch of raw material to be delivered to a recipient under high pressure to the first distal cylinder barrel chamber while returning the second piston to the proximal end of the second cylinder barrel,
- (d) moving the first piston towards the distal end of the first cylinder barrel to feed the raw material into a first intermediate compartment in front of the second piston of the second piston member, and by means of the first piston and the first sealing ring or seat provide a first seal between the first cylinder barrel and the second cylinder barrel,
- (e) moving the third piston to the proximal end of the third cylinder barrel maintaining the first seal between the first cylinder barrel and the second cylinder barrel,
- (f) moving the second piston towards the distal end of the second cylinder barrel to provide a second seal between the second cylinder barrel and the third cylinder barrel chamber by means of the second sealing ring or seat and the second piston which feeds raw material into a second intermediate compartment in front of the third piston of the third piston member,
- (g) maintaining the second seal while returning the first piston to the proximal end of the first cylinder barrel while the third piston simultaneously is moved to the distal end of the third cylinder barrel to deliver the raw material to the recipient, and
- (h) repeating steps b-g.

In a modified method according to the present invention all piston members are open when repeating the operating cycle.

Thus in the modified embodiment the method may comprise the operating cycle steps of

- 5 (a') arranging the first piston at the proximal end of the first cylinder barrel, arranging the second piston at the proximal end of the second cylinder barrel, and arranging the third piston at the proximal end of the third cylinder barrel,
- 10 (b') arranging the first piston at the distal end of the first cylinder barrel, arranging the second piston at the distal end of the second cylinder barrel, and arranging the third piston at the distal end of the third cylinder barrel,
- 15 (c') arranging the second piston at the proximal end of the second cylinder barrel, and arranging the first piston at the proximal end of the first cylinder barrel,
- 20 (d') supplying an apportioned batch of raw material to be delivered to a recipient under high pressure to the first distal cylinder barrel chamber and moving the first piston towards the distal end of the first cylinder barrel to feed the batch of raw material into the first compartment,
- 25 (e') retracting the third piston towards the proximal end of the third cylinder barrel,
- (f') moving the second piston towards the distal end of the second cylinder barrel to feed the batch of raw material into the second compartment,
- (g') moving the third piston towards the proximal end of the third cylinder barrel,
- 30 (f') repeating steps c'-g'.

In any of the above embodiments of piston members, apparatuses' or methods the at least one piston member may be hydraulic or pneumatic.

The invention will now be described by way of example illustrating an apparatus with three piston members. It should be understood that more than three piston members may be implemented in the apparatus according to the present invention if considered appropriate.

Fig. 1 shows a perspective exploded view of a first embodiment of a piston member according to the present invention without a nose,

fig. 2 shows, in perspective, an apparatus with three piston members according to the present invention and a screw feeder, where a part of the exterior wall of the apparatus has been removed for illustrative purposes to reveal the interior structure of the apparatus,

fig. 3 shows a section taken along line III-III of the second piston shown in fig. 2,

fig. 4 is an enlarged scale view of the encircled area C1 of fig. 3,

fig. 5 is an enlarged scale view of the encircled area C2 of fig. 3,

fig. 6 shows a sectional view taken along line VI-VI in fig. 2 illustrating the pistons of the piston members in an operating step of an operation cycle of the apparatus according to the present invention, and

fig. 7 shows the same, but with the piston in another operating step.

Fig. 1 shows in an exploded view the components of a first embodiment of a piston member 1 according to the present

invention adapted for delivering material to a recipient (not shown).

5 The piston member 1 consist of a proximal end cap 2, a piston 3 with a piston rod 4, a piston barrel 5, a tubular pressurized chamber cylinder 6, a T-shaped coupling cylinder section 7, a sealing ring 8 and an exit pipe 9 with a flange 10. The total cylinder barrel available for the piston's travel consist of
10 the piston cylinder barrel 5, the tubular pressurized chamber cylinder 6, and the T-shaped coupling cylinder section 7, the latter of which forms the distal end of the total cylinder barrel.

The proximal end cap 2 has a first coupling flange 11 for
15 coupling with a corresponding first coupling flange 12a on the piston cylinder barrel 5. The piston cylinder barrel 5 has a second coupling flange 12b opposite the first coupling flange 12a for coupling with a corresponding first flange 13a on the pressurized chamber cylinder 6. Opposite the first coupling
20 flange 13a the pressurized chamber has a second coupling flange 13b adapted for coupling together with a corresponding first flange 14 on the tubular T-shaped coupling cylinder section 7. Axially opposite the first flange 14 said tubular T-shaped coupling cylinder section 7 has as second flange 15 for
25 coupling, in the case shown, to the flange 10 of the exit pipe 9. However the second flange 15 could also be provided for coupling to another coupling piece on another piston member as will be described later. Perpendicular to the axis of the tubular T-shaped coupling cylinder section 7, said tubular T-
30 shaped coupling cylinder section 7 has a coupling piece 16 with a third coupling flange 17 for coupling to e.g. a screw feeder, another piston member or other material supply system.

35 The piston member according to the present inventions consist of components that can be assembled to or used in a piston feeder for feeding raw material to a recipient. Each individual

component has an acceptable effective life but is easy to replace as well. Since the piston member is composed of easy replaceable individual smaller unit components downtime can be kept at a minimum.

5

The structure, composition, arrangement and function of the individual components of the piston member as well as of the piston member in co-operation with additional piston members will be described in further details with reference to the additional figures to further clarify to the person skilled in the art how the apparatus and method according to the present invention operates.

Fig. 2 shows a perspective view of an apparatus 18 according to the present invention with three co-operating piston members 1, 1', and 1''. The piston member 1'', seen to the upper left in fig. 2, constitutes the third piston member of the apparatus 18, and is the last in a sequential series of substantially identical piston members 1, 1', 1'' for transporting the raw material supplied by screw feeder 21 into a high pressure recipient (not shown) such as a gasifier where e.g. coal powder is converted to a gaseous fuel. The piston members 1, 1', 1'' correspond substantially to the piston member seen in fig. 1 and for like parts same reference numerals with the exception that the components of the first piston member 1 is indicated without apostrophe, the components of the second piston member 1' is indicated with one apostrophe, and the components of the third piston member 1'' is indicated with two apostrophes.

The screw feeder 21 is coupled to the third coupling flange 17 of the first coupling piece 16 of the first piston member 1 by means of a distal coupling flange 22. The screw feeder 21 consists of a screw feeder coupling piece 23 with a screw feeder coupling piece flange 24 for coupling to a raw material reservoir (not shown). The screw feeder coupling piece 23 is

35

arranged to feed raw material to the screw 25, which is rotatable arranged inside a feed tube 26 by means of shaft 27.

5 The first and the second piston member 1, 1' differ from the piston member seen in fig. 1 in that the piston 3,3' is provided with a front noses 19,19', as can be seen in the encircled cut out section at the upper right in fig. 2. The cut out section reveals the interior structure of the pressurized chamber 6' of the second piston member 1', where first and
10 second annular lip seal members 28',29' are arranged in axial distance on opposite sides of an oil inlet pipe 30' for supplying a pressurized oil to the clearance between the interior annular wall of the pressurized chamber and the piston 3'. The first and second annular seal members 28',29' are
15 accommodated in suitable recesses 30',31' made in the interior wall of the pressurized chamber 6'. The pressurized chamber could in the alternative be shifted upstream or downstream along a cylinder barrel.

20 Fig. 3 shows a section taken along line III of the second piston shown in fig. 2. The proximal end of the piston 3 has a nose 19' configured as a concave solid body for compensating for difference in volume of piston and volume of the intermediate compartment created in front of the nose in a
25 cylinder barrel, as will be described later with references to fig. 6 and 7.

As seen more clearly in fig. 4, which is an enlarged scale view of the encircled area C1 of fig. 3, the first and second
30 annular lip seal members 28',29' and the second piston member 1' are arranged in axial distance on opposite sides of the oil inlet pipe 30' in recesses 31a',31b' in the interior wall of the pressurized chamber 6'. Slide seals 32',33' are interposed between the annular lip seal member 28',29' and the oil pipe
35 inlet 30'. The entire linear seal of the pressurized chamber 6' serves expediently for both oiling the reciprocating piston 3'

and as a means for detecting leakage of gas in the reciprocating apparatus. The first piston member 1 are in a similar manner configured with an annular lip seal member 28,29, oil inlet pipe 30 in recesses 31a,31b in the interior wall of the pressurized chamber 6 as well as slide seals 32,33. Also the third piston member 1 are configured with an annular lip seal member 28'',29'', oil inlet pipe 30'' in recesses 31a'',31b'' in the interior wall of the pressurized chamber 6'' as well as slide seals 32'',33''.

Fig. 5 is an enlarged scale view of the encircled area C2 of fig. 3 and shows the sealing ring 8', which sealing ring 8' is arranged at the distal end 35b' of the cylinder barrel 5',6',7' for engaging the piston 3' to create a firm fluid tight sealing barrier between the third piston member 1'' and the second piston member 1' while the third piston 3' moves the apportioned raw material initially delivered by the first piston member 1 towards the recipient via the exit pipe 9.

Fig. 6 and 7 illustrate the operating principle of the apparatus 18 shown in fig. 2 and the method of using the apparatus 18.

The first piston 3 divides the first cylinder barrel chamber 34 in a first proximal cylinder barrel chamber 34a and a first distal cylinder barrel chamber 34b, the second piston 3' divides the second cylinder barrel chamber 34' in a second proximal cylinder barrel chamber 34a' and a second distal cylinder barrel chamber 34b', and the third piston 3'' divides the third cylinder barrel chamber 34'' in a third proximal cylinder barrel chamber 34a'' and a third distal cylinder barrel chamber 34b''.

In the operating cycle of the apparatus 18 the first piston 3 starts positioned in the first proximal cylinder barrel chamber 34a at the proximal end 35a of the first cylinder barrel 5,6,7

exposing the first distal cylinder barrel chamber 34b for receiving a batch of raw material from the screw feeder 21. The second piston 3' is positioned in the second distal cylinder barrel chamber 34b' of the second cylinder barrel 5',6',7' with the nose 19' slightly protruding into the third cylinder barrel chamber 34''. The second piston 3' is arranged substantially perpendicular to both the first piston 3 and the third piston 3'' and provides, together with the sealing rings 8,8',8'' seal towards the first piston member 3 and the third piston 3''. A feed compartment 36 is delimited by the first distal cylinder barrel chamber 34b, the first sealing ring 8, the second piston 3' and the screw feeder 21.

Once the batch of the raw material has been transferred to the receiving compartment 36, the first piston 3 with the nose 19 moves forward towards the second piston 3' until it hits the sealing ring 8 to deliver the apportioned batch of raw material into a first compartment 37.

As seen in fig. 7 the third piston 3'' moves into the third distal cylinder barrel chamber 34a'' while maintaining the seal between the first cylinder barrel 3 and the second cylinder barrel 3'. Then the second piston 3' of the second piston member 1', which initially blocks for access of material's to the second cylinder barrel chamber 34', returns to the proximal end 35a' of the second cylinder barrel chamber 34' enabling the batch of raw material from the first intermediate compartment 36 to proceed into the second distal cylinder barrel chamber 34b' in front of the nose 19' of the second piston 3'. The second distal cylinder barrel chamber 34b' delimits together with the nose 19 of the first piston 3 and the third piston 3'' a fluid tight second intermediate chamber 38.

In the next step of the operating cycle the second piston 3' is moved into the second distal cylinder barrel chamber 34b' of the second cylinder barrel 34'. At the end of the second piston

3's piston stroke a seal between the second cylinder barrel chamber 34' and the third cylinder barrel chamber 34'' is established by means of the second sealing ring 8', the second piston 3' and the third piston 3'' while the seal at the same time is regenerated, to allow for the first piston 3 to return to the proximal end 35a of the first cylinder barrel chamber 34 in a safe manner. At the same time the third piston 3'' simultaneously is moved to the distal end 35b'' of the third cylinder barrel chamber 34'' to deliver the raw material to the recipient. The feeder cycle is repeated as long as required.

Example

A pilot feeding apparatus with ductile sealing ring

A feeding apparatus that is designed to feed coal powder having a bulk density of 650 kg pr m³ and a particle density 1300 kg/m³ against a reactor pressure of 60 bar with no gas flowing in or out of the process. A first piston member is feed axially by gravity by means of a continuous screw feeder. The first piston member co-operates with a second piston member and a third piston member all having a cylinder barrel of diameter 700 mm and a stroke length of 1000 mm.

The piston speed of the second piston member and the third piston member is 250 mm/sec. during forward transport of material and 350 mm/sec. during returning and retracting the second piston and the third piston, respectively, whereas the speed of the first piston member is 350 mm/sec during forward movement and 400 mm/sec. during returning and retracting. At the end of the forward movement of the piston members the pistons hit and deform the ductile sealing rings and compresses the material to a degree sufficient to obtain a sealing capacity that prevents leakage. A piston stays in its distal forward position about 0.5 second to ensure detection of an

effective sealing, resulting in a piston stroke cycle time of about 15 - 20 seconds.

The capacity of the apparatus is 0.384 m^3 per stroke or $0.024 \text{ m}^3/\text{sec}$ for a piston stroke cycle time of 16 sec. cycle. With a
5 filling rate of 90 % the capacity will be approximately 50 tons of coal powder per hour.

10 The pistons forces the coal powder into the chamber in front of the next piston and create the seal while overcoming the process pressure and inherent forces of any matter resulting from the transported material.

15 A forward piston force of between $400\text{--}500 \text{ N/mm}^2$ is applied to the ductile sealing ring inside the cylinder barrel in the forward piston stroke. The ductile sealing ring is about 2200 mm long and engages the piston at the distal cylinder barrel end. A forward piston force application of approximate 1.1 MN holds against a process pressure that applies 2.7 MN on the 700
20 mm piston. The force that the sealing ring or seat applies on the piston, the process pressure, and any frictional forces must together be overcome. A total piston force of about 4 MN for moving the coal powder towards the distal cylinder barrel end of the respective cylinder barrel chamber is more than
25 required.

30 The piston force required for obtaining a safe and reliable seal to minimize or prevent leakage is the same for each piston, but the work required for the different pistons will be very different.

35 The first piston must overcome the transport frictional force in both directions and the large sealing force of about 4 MN will only be needed for the last 2-4 mm of the first forward piston stroke when meeting the first ductile sealing ring at the distal end of the first cylinder barrel chamber.

The second piston overcomes the transport frictional force and the process pressure at the forward stroke towards the distal end of the second cylinder barrel chamber and needs the large sealing force of about 4 MN for the last 2-4 mm of the forward stroke when meeting the second ductile sealing ring and to overcome the transport frictional forces on the return stroke towards the proximal end of the second cylinder barrel.

The third piston needs to work against the process pressure on the forward stroke towards the distal end of the third cylinder barrel chamber and the large sealing force of about 4 NM is needed for the last 2-4 mm of the forward stroke. The process pressure in the reactor into which the coal powder is delivered is advantageously utilized in the return stroke of the third piston when the third piston moves towards the proximal end of the third cylinder barrel chamber.

The pistons reciprocate with a tolerance of about 2 mm inside the respective cylinder barrels, which cylinder barrel is terminated by respective end caps to define the desired ratio between the batch of the proximal chamber of the cylinder barrel and the distal cylinder barrel when the piston is reciprocating inside said cylinder barrel chamber.

In the present example coal powder with a bulk density of 650 kg/m³ and a particle density 1300 kg/m³ is fed against 60 bar. A ratio between the two volumes of 36:35 is needed to obtain a neutral flow. If this ratio is smaller there will be a leak flow and if it is larger the piston will pump air into the process.

The piston of the piston member advantageously seals towards the cylinder barrel chamber of the next piston member at the end of the piston stroke, which next piston member is arranged in a series of consecutive operating piston members. In case of

an apparatus comprising only two piston members a transitional station must be inserted between the two piston members to avoid bridging and effectively prevent direct or indirect fluid communication between raw material supply and final recipient.

5 Thus although two piston members can be used within the scope of the present invention apparatuses with three or more piston members is more preferred.

10 In case of only one piston member, said piston member is used for supplying apportioned batches to a recipient in a single reciprocating operation. Although the sealing capability is less required in this simple embodiment the piston member is usable.

15 Preferably three consecutive piston members are arranged to operate in a series in an apparatus for transporting coal powder to a gasifier. The movement of the pistons inside the cylinder barrels are controlled in relation to each other to transport apportioned batches of coal powder to a high pressure
20 is gasifier.

Claims

1. A piston member (1,1',1'') comprising a piston rod (4) provided with a piston (3,3',3'') reciprocating inside a cylinder barrel (5,6,7,5',6',7',5'',6'',7''), said piston (3,3',3'') divides the cylinder barrel chamber (34a,34a',34a'',34b,34b',34b'') into a proximal cylinder barrel chamber (34a,34a',34a'') having a proximal capped end (35a,35a',35a'') opposite the piston (3,3',3'') and a distal cylinder barrel chamber (34b,34b',34b'') having a distal cylinder barrel end (35b,35b',35b'') opposite the piston (3,3',3''), **characterized** in that at least one sealing ring (8,8',8'') or seat is arranged inside the distal cylinder barrel chamber (34b,34b',34b'') at the distal cylinder barrel end (35b,35b',35b'').
2. A piston member (1,1',1'') according to claim 1, **characterized** in that the at least one sealing ring (8,8',8'') or seat is manufactured of a ductile material.
3. A piston member (1,1',1'') according to claims 1 or 2, **characterized** in that the piston (3,3',3'') has a front nose (19,19',19'') facing towards the distal cylinder barrel chamber (34b,34b',34b'').
4. A piston member (1,1',1'') according to claim 3, **characterized** in that the nose (19,19',19'') has an axial cut-out or an axial concavity configured to provide space for another piston (3,3',3'') reciprocating perpendicular to the piston (3,3',3'') with the nose (19,19',19'').
5. A piston member (1,1',1'') according to any of the claims 1 - 4, **characterized** in that the piston member (1;18) has means for detecting leakage of pressurized gas or fluid from a recipient or through a cylinder barrel chamber

(34a,34a',34a'',34b,34b',34b'') in direct or indirect communication with the piston member (1,1',1'').

6. A piston member (1,1',1'') according to claim 5,
characterized in that the means for detecting leakage of pressurized gas or fluid comprises a pressure measuring instrument in fluid communication with a pressurized chamber (6,6',6'') delimited by the circumferential clearance between the piston (3,3',3'') and the interior wall of the cylinder barrel (5,6,7,5',6',7',5'',6'',7'') and two spaced apart annular seal members (28,28',28'',29,29',29'') arranged in or at the cylinder barrel chamber (34a,34a',34a'',34b,34b',34b'') wall.

7. A piston member (1,1',1'') according to claims 5 or 6,
characterized in that the pressure measuring instrument is in fluid communication with the pressurized chamber via a pipe (30,30',30''), that the pressurized chamber (6,6',6'') holds a pressurized oil at an oil pressure that is higher than the pressure at a recipient and that the spaced apart annular seal members (28,28',28'',29,29',29'') are arranged on opposite sides of said pipe (30,30',30'').

8. A piston member (1,1',1'') according to claim 7,
characterized in that at least one circumferential slide seals (32,32',32'',33,33',33'') is arranged in the cylinder barrel chamber (34a,34a',34a'',34b,34b',34b'') wall interposed between a pipe (30,30',39'') inlet to the pressurized chamber and the annular seal member (28,28',28'',29,29',29'').

9. A piston member (1,1',1'') according to any of claims 6, 7 or 8, **characterized** in that the annular seal member (28,28',28'',29,29',29'') is a lip seal or one or more O-rings.

10. A piston member (1,1',1'') according to claims 7 or 8, **characterized** in that the slide seal (32,32',32'',33,33',33'') is a Teflon® seal.
- 5 11. A piston member (1,1',1'') according to any of the preceding claims 1 - 10, **characterized** in that the sealing ring (8,8',8'') or seat is dimensioned to extend radially inside the distal cylinder barrel chamber (34b,34b',34b'') at a distance of between 2 ‰ - 2% of the interior
10 diameter of the distal cylinder barrel chamber (34b,34b',34b'').
12. A piston member (1,1',1'') according to any of the preceding claims 1 - 11, **characterized** in that the piston
15 member (1,1',1'') is dimensioned with a stroke length adapted to deform or contact the sealing ring (8,8',8'') to seal between the cylinder barrel chamber (34a,34a',34a'',34b,34b',34b'') and the piston (3.3',3'').
- 20 13. A piston member (1,1',1'') according to any of the preceding claims 1 - 12, **characterized** in that the piston member (1,1',1'') is hydraulic or pneumatic.
14. An apparatus (18) for continuous transporting apportioned
25 batches of material to a recipient, **characterized** in that the apparatus (18) comprises at least one piston member (1,1',1'') according to any of the preceding claims 1 - 13.
- 30 15. An apparatus (18) according to claims 14 for continuous transporting apportioned batches of material to a recipient, **characterized** in that the apparatus (18) comprises at least three piston members (1,1',1'') according to any of the preceding claims 1 - 13.

16. An apparatus (18) according to claims 14 or 15, **characterized** in that the apparatus (18) comprises

- a first piston member (1) that receives the material to be transported, the first piston member (1) has a first piston (3) reciprocating inside a first cylinder barrel (5,6,7), the first piston (3) divides the first cylinder barrel chamber (34a,34b) of the first cylinder barrel (5,6,7) into a first proximal cylinder barrel chamber (34a) having a proximal capped end (2) and a second distal cylinder barrel chamber (34b) having an opposite first distal cylinder barrel end (35b),
- a second piston member (1') that has a second piston (3') reciprocating inside a second cylinder barrel (5',6',7'), the second piston (3') divides the second cylinder barrel chamber (34b',34b') of the second cylinder barrel (5',6',7') into a second proximal cylinder barrel chamber (34a') having a second capped end (2') and a second distal cylinder barrel chamber (34b') having an opposite second distal cylinder barrel end (35b'),
- a third piston member (1'') that has a third piston (3'') reciprocating inside a third cylinder barrel (5'',6'',7''), the third piston (3'') divides the third cylinder barrel chamber (34a'',34b'') of the third cylinder barrel (5'',6'',7'') into a third proximal cylinder barrel chamber (34a'') having a third capped end (2'') and a second distal cylinder barrel chamber (34b'') having an opposite third distal cylinder barrel end (35b''), wherein
- the first piston member (1) transports, in its first forward piston stroke, material fed to the first distal cylinder barrel chamber (34b) into a first intermediate compartment (37) or sluice defined by at least the second distal cylinder barrel chamber (34a') and the third piston (3'') positioned at the third distal end (35b''), and
- the second piston member (3') transports, in its second forward piston stroke, material from the first

intermediate compartment (37) or sluice to a second intermediate compartment (38) defined by the third distal cylinder barrel chamber (34a''), the distal end (35b') of the second piston (3') and the recipient.

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17. An apparatus (18) according to any of claims 14, 15 or 16, **characterized** in that the apparatus (18) comprises hydraulic or pneumatic piston members.

10 18. An apparatus (18) according to any of the preceding claims 14-17, **characterized** in that the recipient is a gasifier or reactor, preferably a high-pressurized gasifier or reactor.

15 19. A method of continuous transporting apportioned batches of material to a recipient by means of the piston member (1,1',1'') according to any of the preceding claims 1 - 13, **characterized** in that the method comprises an operating cycle of

20 - retracting the piston (3,3',3'') to the proximal end (35a,35a',35a'') of the cylinder barrel chamber (34,34',34'') to enlarge the distal cylinder barrel chamber (34b,34b',34b''),
- supplying the apportioned batch material to the distal
25 cylinder barrel chamber (34b,34b',34b''), and
- performing a piston stroke toward the distal end of the cylinder barrel chamber (5,6,7;5',6',7';5'',6'',7'') to deliver the apportioned batch of material to a recipient.

30 20. A method of continuous transporting apportioned batches of material to a recipient under high pressure by means of the apparatus (18) according to any of the preceding claims 14 or 18, **characterized** in that the method comprises to continuously feed apportioned batches of raw
35 material to the first piston member (1) of the apparatus (18), and operating the apparatus (18) to transport the

batches of raw material to a recipient by reciprocating the first piston (3) of the first piston member (1), the second piston (3') of the second piston member (1') and the third piston (3'') of the third piston member (1'') in a repeated feeder cycle.

21. A method according to claim 20, **characterized** in that the method comprises the further steps of

- (a) arranging the first piston (3) at the proximal end (35a) of the first cylinder barrel (5,6,7),
- (b) arranging the second piston (3') at the distal end (35b') of the second cylinder barrel (5',6',7') and arranging the third piston (3'') at the distal end (35b'') of the third cylinder barrel (5'',6'',7''),
- (c) supplying an apportioned batch of raw material to be delivered to a recipient under high pressure to the first distal cylinder barrel chamber (34b) while returning the second piston (3'') to the proximal end (35a') of the second cylinder barrel (5',6',7'),
- (d) moving the first piston (3) towards the distal end (35b) of the first cylinder barrel (5,6,7) to feed raw material into the first intermediate compartment (37) in front of the second piston (3') of the second piston member (1'), and by means of the first piston (3) and the first sealing ring (8) or seat provide a seal between the first cylinder barrel (5,6,7) and the second cylinder barrel (5',6',7'),
- (e) moving the third piston (3'') to the proximal end (35a'') of the third cylinder barrel (5'',6'',7'') maintaining the seal between the first cylinder barrel (5,6,7) and the second cylinder barrel (5',6',7'),
- (f) moving the second piston (3') towards the distal end (35b') of the second cylinder barrel (5',6',7') to provide a seal between the second cylinder barrel (5',6',7') and the third cylinder barrel

(5'',6'',7'') by means of the second sealing ring (8'') or seat and the second piston (3'), which feeds raw material into a second intermediate compartment (38) in front of the third piston (3'') of the third piston member (1''),

(g) maintaining the seal while returning the first piston (3) to the proximal end (35a) of the first cylinder barrel (5,6,7) while the third piston (3'') simultaneously is moved to the distal end (35b'') of the third cylinder barrel (5'',6'',7'') to deliver the apportioned batch of raw material to the recipient, and

(h) repeating steps b-g.

22. Use of the apparatus (18) according to any of the preceding claims 14 - 18 and/or the method according to any of the preceding claims 19 - 21 for transporting coal powder.

Fig. 1

Fig. 2

Fig. 3

Fig. 5

Fig. 4

Fig. 6