COAL COMMINUTION BY HIGH PRESSURE WATER JETS
MACHINE DESIGN CONCEPTUAL STUDY

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ABSTRACT:

In the offered paper the authors present the results of the work conducted on the coal response for high pressure water jets attack. The paper covers different types of water jets such as: solid jets, cavitating jets, and rotating jets and also the results of coal disintegration effectiveness. The concepts of the models of comminuting machines are presented. The mechanism of the coal disintegration in relationship to these models and the process efficiency are discussed.

INTRODUCTION:

With the advances in the high pressure water jet technology, one of the potential applications of this science is in the area of material disintegration. Coal was chosen as the subject of interest because of the ongoing search for an alternative source of energy. Coal has a structure that is very brittle and filled with micro-cracks. Earlier work by Mazurkiewicz [1] show that material is weaker in tension than in compression. Figure 1 shows the stresses that occur as the water jet penetrates a coal crack. The tip tension stress σ maximum is given by the equation

$$\sigma \max = \sigma_o \left(1 + \frac{2b}{a} \right) \qquad 1)$$

where σ_o is the stagnation pressure developed inside the crack by the jet, 2b the crack length and the 2a the crack width. For even hard coal with a crack dimension ratio, b/a = 10, the pressure necessary to ensure continued crack growth is 15.7 KPa.

For coal, the practical observation yields a ratio between the compression stress versus the tensile stress to be in the range of 20 to 30 times. Also, the theoretical strain energy comparisons show that the compression tension ratio for coal to be 65 in the perpendicular direction to the coal seam and 62 in the parallel direction to the coal seam. These facts combined with the ability of the water jets to penetrate the micro-cracks, creating a zone of tension at the crack tip enhances crack growth and increases the comminution effectiveness.

The theoretical model for comminution of coal by high pressure water jets was based on Griffith's theory [2,3]. Griffith considered an infinite cracked plate of unit thickness with a central traverse crack of length of 2a. The plate is under tensile stress and fixed at its ends. Crack propagation will occur if the energy released upon crack growth is sufficient to provide all the energy that is required for crack growth, which can be expressed by:

$$\frac{dU}{da} = \frac{dW}{da} \qquad 2)$$

where U is the elastic energy and W the energy required for crack growth. Griffith defined the crack driving force as $G = \pi\sigma^2 a/E$. For crack growth to occur G must exceed a certain critical value G_{IC}. Hence the condition for crack growth

$$G_{IC} = \frac{\pi\sigma_c^2 a}{E} \rightarrow \sigma_c = \frac{E\, G_{IC}}{\pi a} \qquad 3)$$

$$\sigma = \frac{Po - Pv}{\rho U_o^2/2} \qquad 4)$$

where Po and Uo are the ambient values of pressure intensity and velocity and Pv and are the vapor pressure and the density of the liquid, respectively. For maximum cavitation in the chamber the outlet pressure should be approximately 1% of the inlet pressure. To control these conditions, a specially designed cavitation chamber was used [5].

Two types of nozzles were used. The first series utilized a nozzle that was not point loaded, but rather contains a cylindrical cavity of air in the center of the jet, which causes very high turbulence (Figure 4). For this series the coal was loaded into the cavitation cell and acted by the high pressure water. In the second series a solid water jet nozzle was used combined with a mixing chamber and slurry nozzle.

Using the cavitation nozzle, tests were conducted for jet action time of 5.0 seconds at an inlet pressure of 5,000 psi for a mass of 200 grams. The results showed that an almost linear relationship existed between the initial coal size and the energy consumption. The lowest energy consumption was for the smallest coal particle size of #30 mesh. As the coal size was increased the energy consumption increased. These results can be explained by the fact that for the same coal mass but smaller grain size, the total surface area of coal which comes into contact with the cavitation bubbles is greater. Cavitation is a micro-phenomenon and the area of contact is very important. For this reason, the erosion process observed during the cavitation phenomenon is proportional to the coal grain size.

For the same initial coal size of #30 mesh, as the time of jet action was increased to 10.0 seconds a drastic increase in the energy consumption occurred (13,502 kWh/ton for the 10 second tests as compared to 839 kWh/ton for the 5.0 second test). These results indicate the importance of the slurry concentration. To further emphasize these results, tests were conducted for constant pressures but for different amounts of initial coal of 200, 400 and 600 grams. The results show that as the initial coal mass was increased the energy consumption decreased.

For the next series of experiments the mechanism of coal feeding was identical to that for solid jets (Figure 2). The coal entering the mixing chamber was attacked by the high pressure water jet and exists through the slurry nozzle into the cavitation chamber. Inside the cavitation chamber erosion of the coal particles takes place due to the cavitation phenomenon and high turbulence in the chamber.

The tests were conducted for a nozzle diameter combination of d=0.041" and D=0.120" for pressures of 3,500 and 5,500 psi. The initial coal particle size was #30 mesh. The tests were conducted for different back pressures, as shown in Figure 5.

The lowest energy level achieved for a final product size of -75 microns was 407 kWh/ton for an inlet pressure of p=3,500 psi. Also, the results show that no significant changes in the energy level was observed at higher pressures. Slight changes in the back pressure caused no significant change in the energy consumption.

As conclusions from this series of experiments it could be concluded that the coal should not be surrounded by water. A higher slurry concentration would produce better results. The importance of the initial particle size was brought out again. As the initial particle size was decreased the energy consumption decreased.

Rotating Water Jets:

A specially designed and machined test rig was used in conducting these experiments. The primary system component was the rotating spindle. Three nozzles were attached to the nozzle head. The rotating spindle was supplied with high pressure water through the rotary coupling. The maximum speed of rotation for this rotary coupling was limited to 600 rpm. The system was driven by an electric motor. A schematic view of the assembly can be seen in Figure 6. The coal was filled into both perforated and imperforated container. The container placed on a mechanical lifter made it possible to give vertical movement to the container.

EXPERIMENTAL EQUIPMENT, PROCEDURE AND DISCUSSION OF RESULTS:

No theoretical value of G_{IC} is given for coal in the literature. The heterogeneous structure of coal would account for this.

To gain a better understanding of material disintegration by water jet action, a model study on material discontinuities has been carried out earlier [4]. The pressure distribution inside a receiving pipe, designed to simulate a representative micro-crack in the material was studied. The results show that the pressure within the receiving pipe depends on the ratio of the injecting nozzle and receiving pipe diameters. As the injecting nozzle diameter increased with respect to the receiving pipe the pressure inside the pipe P 2 increased. Also, the pressure P 2 was strongly dependent on the stand off-distance between the injecting nozzle and receiving pipe. In practice it means that for maximum pressurization of the crack, the jet diameter has to be bigger or equal to the micro-crack. Also, the distance between the jet and the coal is important.

As mentioned, three types of jets were tested, i.e., solid, cavitating and rotating jets. In all tests the comminuted particles below 75 microns (200 mesh) was separated by a wet sieve analysis [4] and the specific energy levels calculated. The calculated specific energy consumption was the energy of the water stream alone and does not include the energy consumed by the system as a whole. In this chapter each series of experimental equipment, experimental procedure and the results achieved will be discussed separately for each kind of jet.

Solid Water Jets:

The first series of tests was concerning the use of solid water jets for coal comminution. The apparatus consists of a solid water jet nozzle connected to a mixing chamber and slurry nozzle assembly. The mixing chamber was connected to a long plexi glass tube by a conical shape adaptor. Figure 2 shows a schematic view of the equipment set up. The coal was fed directly into the mixing chamber to be attacked by the jet emerging from the nozzle. The water jet moving through the mixing chamber creates a vacuum inside the chamber which results in a suction at the coal inlet to the mixing chamber. By taking advantage of this suction, it was possible to get an uniform flow of coal into the mixing chamber. The coal after being attacked in the mixing chamber flows through the slurry nozzle and was collected at the end of the tube.

The initial task was to find the dependence of the initial coal particle size. Tests were carried out for #4 and #30 coal. The energy consumption for the #4 coal was almost 7 times as that for the #30 coal (7147 kWh/ton for the #4 coal as compared to 1032 kWh/ton for the #30 coal).

The next series of tests were for different injecting and slurry nozzle combinations. The initial coal particle size was #30 mesh. The results are presented in Figure 3. These test results show that for a pressure increase that no significant change in the energy consumption occurred. This is an important remark from a practical point of view because lower pressures are easier to generate and does not require expensive equipment. Also, as the slurry nozzle diameter was increased a reduction in the energy consumption occurred. This can be explained by the fact that in a bigger nozzle the possibility of the particles hitting the nozzle wall, deflecting and hitting other particles is greater, thereby, increasing the attrition of particles.

As conclusions from this part of the tests it could be stated that as the initial coal particle size was reduced, the energy consumption was reduced. Also, as the slurry nozzles diameter was increased from 0.086" to 0.120" for the same injecting nozzle of 0.041" a reduction in the energy consumption occurred. Increasing the pressure had an adverse effect on the energy consumption.

Cavitating Water Jets:

The second series of experiments were for cavitating jets. The cavitation number which defines the inception and subsequent growth and collapse of cavitation bubbles is given by the equation

The initial coal particle size was 0.742" <S<0.525". The tests were conducted for a pressure of 5,500 psi using three nozzles each of diameter 0.032".

The initial tests were carried out with the nozzles oriented at 3, 8 and 20 degree angles. The first task was to investigate the importance of increasing the volume of water to the comminution process. Tests were carried out for jet action times of 15, 30 and 75 seconds using an imperforated container. It was seen that as the time of jet action increased the energy consumption increased. To explain this, consider the water jet action on the coal and the time over which it acts. Increasing the jet action time increases the volume of water utilized. The coal particles tend to become suspended in the excess water. They are in effect, surrounded by a coating of water whose protective ability increases with the volume of water utilized. The water jets lose energy in penetrating this protective coating in order to come in contact with the coal particles. This energy is not used to create new surfaces during direct collision with coal particles and hence is wasted.

For the same series of tests a perforated coal container was used and water jet action times of 75 seconds and 150 seconds investigated with vertical up and down axial movement (8 cycles/minute) of the coal container. A test with a jet action time of 75 seconds was conducted without container movement. The results show (Figure 7) that the energy consumption with coal container movement to be almost half those of the case with rotation only. These results clearly indicate the importance of the kinematic movement of the high pressure water jets, which gives a better opportunity for the coal particles to come in direct contact with the water jets.

In the next series the orientation of the nozzles were changed. The nozzles were now oriented perpendicular to the spindle axis. The effect of vertical movement of the coal container was investigated for both 3 and 12 full cycles of motion for 2 minute tests. For the purpose of comparison the coal container was also kept stationary. The energy requirements appear almost 20% less for the case when rotating jets were moved up and down 12 times per minutes as compared to other kinematic conditions of the jets for the tests carried out (Figure 8).

As conclusions from this portion of experiments the importance of the slurry concentration was brought out again. The coal particles should not be surrounded by water. Also the kinematics and dynamics of the interaction between the high pressure water jets and the material to be comminuted plays a very important role in the effectiveness of the comminution process.

GENERAL CONCLUSIONS:

Based on the experimental results presented in this paper the following conclusions can be formulated:

The energy consumption taken into consideration as a criterion of the effectiveness of the comminution process shows a very strong dependence on:

- jet diameter and pressure
- initial coal particle size
- solid concentration in slurry
- kinematics of the interaction between the high pressure water jets and coal

The minimum specific energy input of 400 kWh/ton achieved to date represents a significant improvement in the comminution technology. Typical specific energy consumption levels associated with fluid energy mills are in the range of 700-800 kWh/ton [6]. It is envisaged that application of the knowledge gained from the tests carried out to date will enable further improvement of the comminution technology.

ACKNOWLEDGEMENT:

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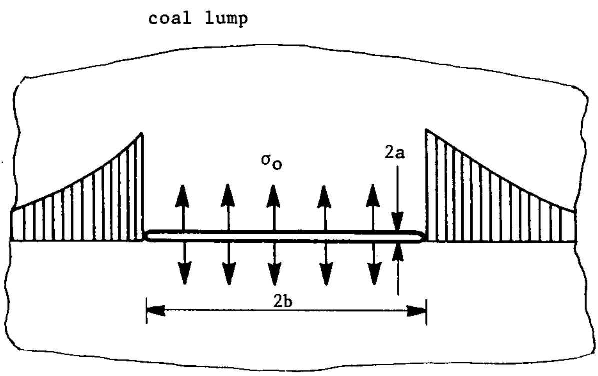
For Illinois Coal:

$\sigma_{\perp}$ = 26.7 MPa
$\sigma_{\parallel}$ = 15.0 MPa
compression

$\sigma_{\perp}$ = 3.3 MPa
$\sigma_{\parallel}$ = 1.9 MPa
tension



σ_o - stagnation pressure developed inside the crack by jet

σ_{max} - tip tension stress

$$\sigma_{max} = \sigma_o \left(1 + \frac{2b}{a}\right)$$

For b/a = 10, $\sigma_{max} = 21\ \sigma_o = 3.3$ MPa

The stagnation pressure to grow a micro-crack is

$$\sigma_o = 15.7 \text{ kPa}$$

Figure 1. Pressure necessary to propagate coal micro-cracks.

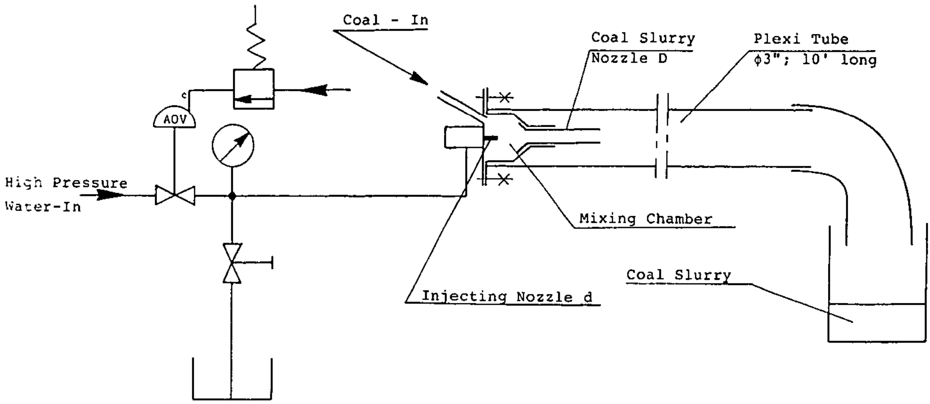


Figure 2. Schematic Drawing of Apparatus for Solid Water Jet Tests with Mixing Chamber.

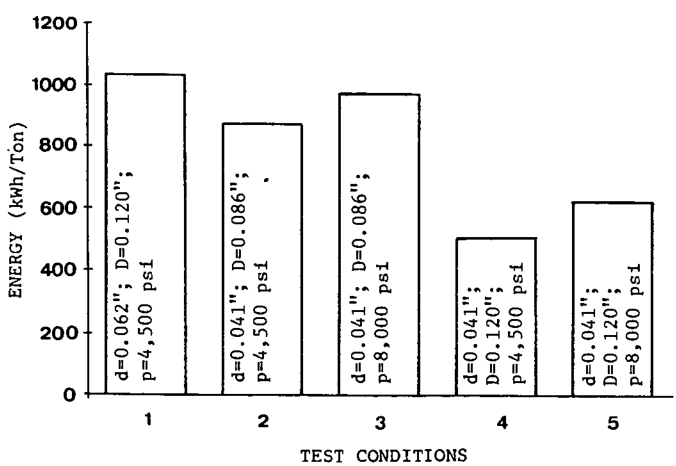


Figure 3. Graph of Energy Versus Different Test Conditions of Pressures and Slurry Nozzle Diameters for Direct Water Jets.

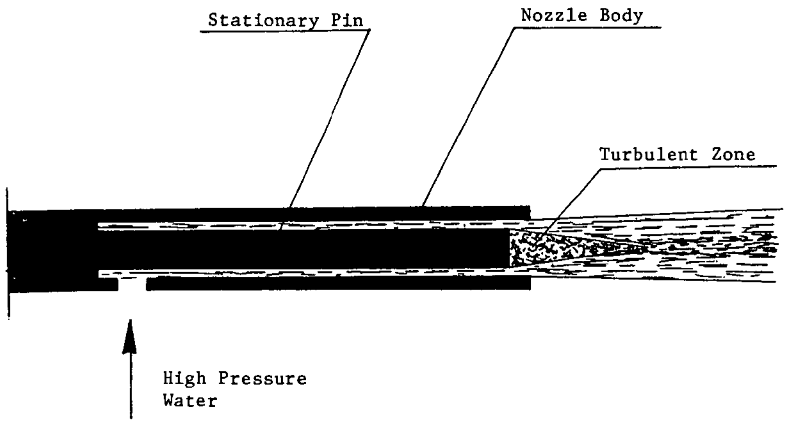


Figure 4. Schematic Drawing of Nozzle with Cylindrical Cavity of Air.

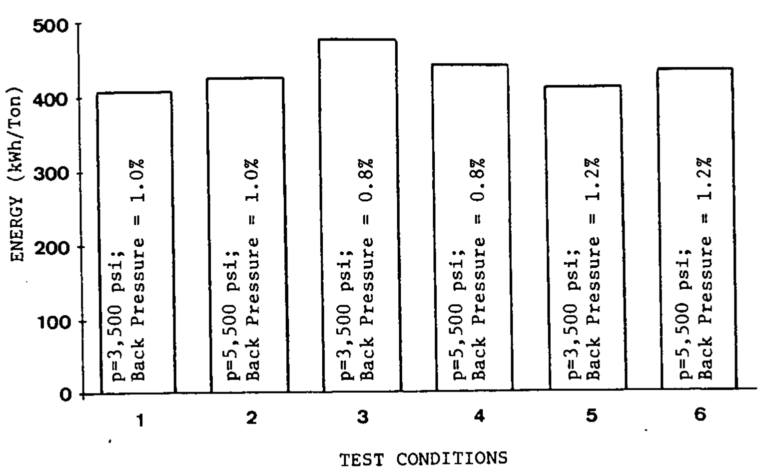


Figure 5. Graph of Energy Versus Different Combinations of Inlet and Back Pressures for Cavitation Tests.

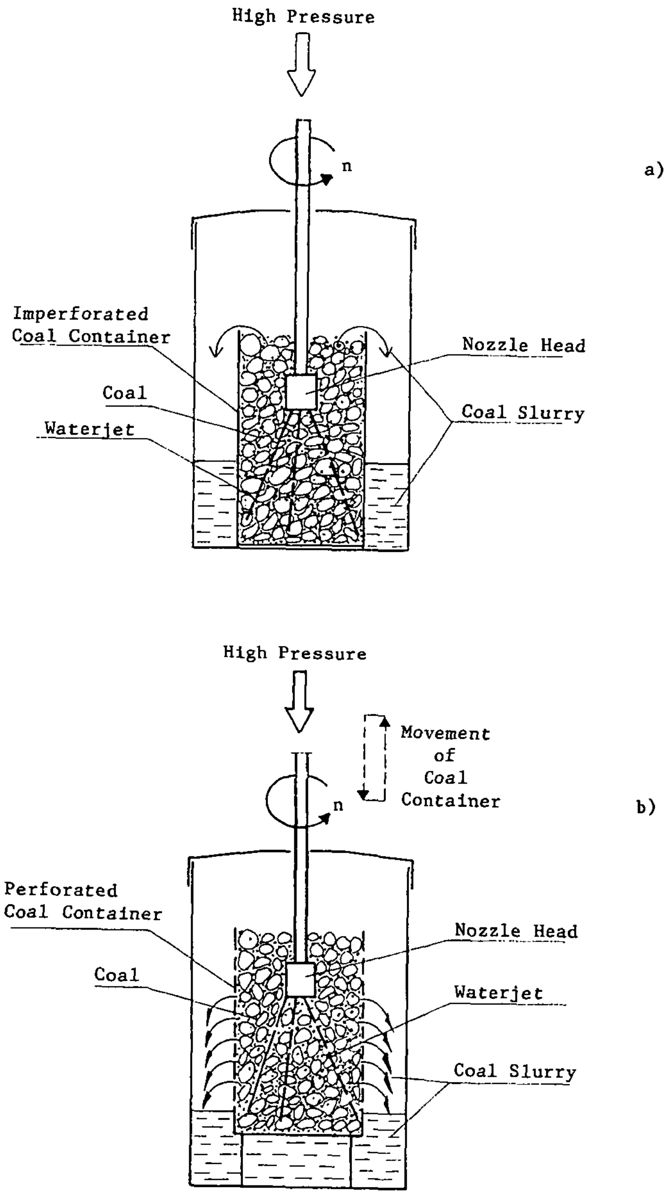


Figure 6. Schematic Drawing of Rotating Water Jet Experimental Equipment.

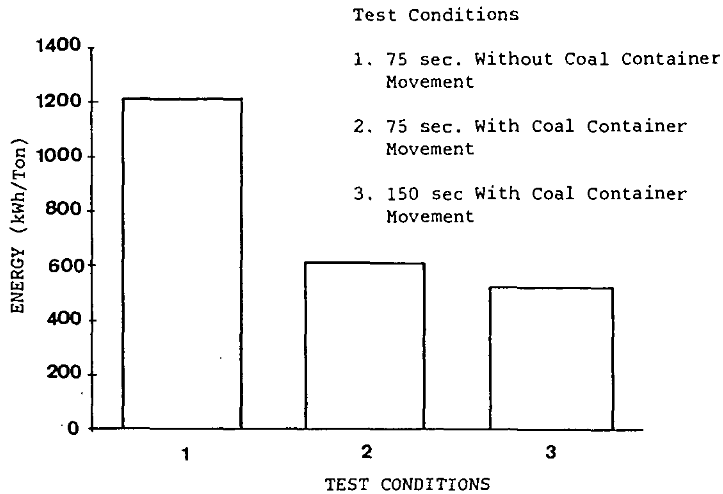


Figure 7. Graph of Energy Versus Different Test Conditions for Nozzles Angled at 3, 8 and 20 Degree Angles.

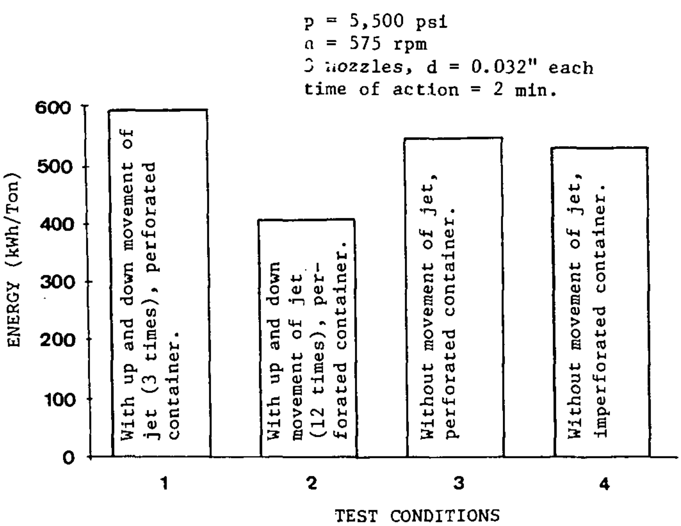


Figure 8. Graph of Energy Versus Different Test Conditions for Nozzles Angled Perpendicular to the Axis of Rotation.