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ENERGY BASED MODELLING OF ABRASIVE SLURRY JET

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ABSTRACT

Over the more than twenty-five years since the benefits of adding abrasive particles to high-pressure waterjet streams were demonstrated, and made commercially available, there have been considerable technical advances in the field. One of these was a change in the way in which the abrasive was introduced into the fluid flow. Introducing the abrasive between the pump and the nozzle creates an abrasive slurry, which is then accelerated through the single nozzle to a final jet velocity. Abrasive slurry jet (ASJ) cutting systems enjoy an advantage of higher cutting efficiency over conventional abrasive waterjet (AWJ) cutting systems as a result of more efficient momentum transfer between the high pressure water and the abrasive.

Although the use of ASJ in industrial applications has occurred many of the applications have focused more on niche applications, such as bomb disposal, rather than on widespread use in manufacturing. Part of the problem in using the tool in more common industrial cutting comes from the need, in that application, to sustain an even flow of abrasive in the water over the length of time needed to complete individual cuts. Abrasive slurry cutting systems can cut very narrow kerfs in the target material, and operate, for equivalent cutting performance, at lower jet pressures. There is a question as to how much more effective the tool can become.

Based on a series of experiments and theoretical modeling, ASJ cutting efficiency is, therefore, discussed in terms of pressure, slurry concentration and nozzle diameter.

1. INTRODUCTION

Abrasive slurry jets in contrast to the more conventional abrasive waterjets, are formed as a two phase jet with the abrasive particles mixed with the water before the fluid is accelerated to form a high velocity jet. Note that this definition also relates to those systems where the fluid and the abrasive are mixed before passing into the high-pressure pump, as well as those more common systems where the abrasive is fed from a pressurized container into the line between the pump and the nozzle. In the conventional AWJ the abrasive is carried into the mixing chamber, located beyond the primary water acceleration nozzle, typically by an air feed that brings with it a gas component, so that the the AWJ stream is a three-phase, rather than two-phase structure. The absence of this gaseous component in the ASJ jet stream results in higher efficiency of energy transfer to the abrasive (since none is expended on accelerating the air [1]) and a more coherent jet structure, since inter alia there is no air expansion to induce disruption of the flow.

The higher efficiency of ASJ as compared to AWJ has been discussed by Hashish [2] theoretically and more recently Jiang [3] explored the cutting capability of the ASJ both theoretically and experimentally. Yazici [4] investigated the cutting of granite with an ASJ and used specific energy and erosion efficiency as metrics of cutting efficiency. More commonly experimental studies of the cutting capability of abrasive slurry jets [3], [4] have largely used depth of cut as the measure of performance, in materials ranging from metals to ceramics and rocks. The effects of the change in abrasive concentration, pressure, nozzle size on depths of cut are good indirect indicators for how these parameters affect the efective use of the abrasive power of the ASJ in removing material.

An important distinction that needs to be made in the application of an ASJ is the range of impact. Short range impact applications include metal cutting, and the cutting of precision parts for the semiconductor industry, where standoff distances are less than tenth of an inch. Oil well drilling in contrast, for example uses directly pumped ASJ's [5, 6] and, because of the need to partially recess the nozzles from the cutting plane, this was more of a long range impact. The distinction is in that the particles need to travel a significant distance in air or through fluid in order to impact and erode the target. The work described in this paper is directed towards understanding the energy contained in, and lost by, the jet in such long range applications

2. THEORETICAL ANALYSIS

High velocity ASJ are formed as a result of a premixed slurry being forced through a nozzle by a high driving pressure. Previous work by Hashish [2], and Jiang [4] have relied on energy based modeling of the abrasive power (P_a) of the ASJ. This can be expressed as

$$P_a = \frac{1}{2} \cdot \dot{M}_a \cdot v^2 \qquad (1)$$

where $\dot{M}_a$ is the mass flow rate of abrasive out of a nozzle and v is the velocity of abrasive particles exiting the nozzle. The velocity of the exiting abrasive particles can be expressed in terms of the pressure P and density ρ_{mix} of the abrasive suspension, where μ_m is a constant that includes a measure of the momentum transfer efficiency.

$$v = \mu_m \cdot \sqrt{\frac{2P}{\rho_{mix}}} \tag{2}$$

The density ρ_{mix} defined in terms of R, the loading ratio in the slurry

$$\rho_{mix} = \frac{\rho_a (1 + R)}{\frac{\rho_a}{\rho_w} + R} \tag{3}$$

The loading ratio R can be expressed in terms of the concentration by weight C as

$$R = \frac{\dot{M}_a}{\dot{M}_w} = \frac{C}{1 - C} \tag{4}$$

where

$$C = \frac{\dot{M}_a}{\dot{M}_a + \dot{M}_w} \tag{5}$$

$$\rho_{mix} = \frac{\rho_a \left(1 + \frac{C}{1 - C}\right)}{\frac{\rho_a}{\rho_w} + \frac{C}{1 - C}} \tag{6}$$

The mass flow rate $\dot{M}_a$ can be expressed as

$$\dot{M}_a = \frac{\pi}{4} \cdot D^2 \cdot \sqrt{2P\rho_{miz}} \cdot \frac{C}{1 + C} \tag{7}$$

where D is the nozzle diameter. Substituting (2) and (6) in (1) we get the abrasive power of the ASJ as

$$P_a = \mu_m \cdot \frac{\pi}{4} \cdot D^2 \cdot P^{1.5} \cdot \sqrt{2} \cdot \sqrt{\frac{\frac{\rho_a}{\rho_w} + \frac{C}{1 - C}}{\rho_a \left(1 + \frac{C}{1 - C}\right)}} \frac{C}{1 + C} \tag{8}$$

Differentiating (8) with respect to concentration C it is possible to find the optimal concentration when the abrasive power of an ASJ is maximum.

$$\frac{\partial P_a}{\partial C}=\frac{\pi\cdot D^2\cdot\mu_m^2\cdot\sqrt{2}\cdot P^{3/2}}{\left(1+C\right)\cdot\sqrt{\dfrac{\rho_a\left(1+\dfrac{C}{1-C}\right)}{\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}}}}\cdot\left[\frac{1}{4}-\frac{C}{4\cdot\left(1-C\right)}-\frac{C}{8}\cdot\left\{\frac{\dfrac{\rho_a\left(\dfrac{1}{1-C}+\dfrac{C}{\left(1-C\right)^2}\right)}{\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}}-\dfrac{\rho_p\cdot\left(1+\dfrac{C}{1-C}\right)\cdot\left(\dfrac{1}{1-C}+\dfrac{C}{\left(1-C\right)^2}\right)}{\left(\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}\right)^2}}{\cdot\left\{\dfrac{\rho_a\left(1+\dfrac{C}{1-C}\right)}{\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}}\right\}}\right\}\right]=0 \qquad (9)$$

The first term in (9) cannot be equal to zero, equating the second to zero we get

$$\left[\frac{1}{4}-\frac{C}{4\cdot\left(1+C\right)}-\frac{C}{8}\cdot\left\{\frac{\dfrac{\rho_a\left(\dfrac{1}{1-C}+\dfrac{C}{\left(1-C\right)^2}\right)}{\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}}-\dfrac{\rho_p\cdot\left(1+\dfrac{C}{1-C}\right)\cdot\left(\dfrac{1}{1-C}+\dfrac{C}{\left(1-C\right)^2}\right)}{\left(\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}\right)^2}}{\cdot\left\{\dfrac{\rho_a\left(1+\dfrac{C}{1-C}\right)}{\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}}\right\}}\right\}\right]=0 \qquad (10)$$

Simplifying further we get

$$\left[\frac{1}{4\cdot\left(1+C\right)}-\frac{C}{8}\cdot\left(\frac{1}{1-C}+\frac{C}{\left(1-C\right)^2}\right)\left\{\frac{\left(\dfrac{\rho_a}{\rho_w}-1\right)}{\left(\dfrac{\rho_a}{\rho_w}+\dfrac{C}{1-C}\right)\cdot\left(1+\dfrac{C}{1-C}\right)}\right\}\right]=0 \qquad (11)$$

At this stage the abrasive used is assumed to be garnet which has a specific gravity of 4. Substituting in (16) we get

$$\left[\frac{1}{4\cdot\left(1+C\right)}-\frac{C}{8}\cdot\left(\frac{1-C+C}{\left(1-C\right)^2}\right)\left\{\frac{\left(4-1\right)}{\left(4+\dfrac{C}{1-C}\right)\cdot\left(1+\dfrac{C}{1-C}\right)}\right\}\right]=0 \qquad (12)$$

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$$\frac{1}{2}\cdot\left\{\frac{C\cdot 3}{4-3C}\right\}=\frac{1}{(1+C)} \tag{13}$$

$$3C^2+9C-8=0 \tag{14}$$

Solving for C we get values of -3.71 and 0.71. Since the value of concentration cannot be greater than 1 nor can it be negative, the optimal concentration from these calculations is 71%. This is quite a high value but important to note that it does not take into consideration particle interaction within the jet stream. A major loss of cutting performance with abrasive jets comes from the interactions of the particles, the water and the mixing chamber/acceleration section of the flow. Because particles are often fractured during this interaction, and because drag decelerates smaller particles faster than larger ones, this interaction is fairly critical to accurate analysis and the effects this has on cutting head efficiency have been studied in [7].

3. TEST SET-UP

The abrasive power of an ASJ is a function of the energy that the abrasive particles have when they exit the nozzle. Ideally all exiting particles should have the same velocity under perfect momentum transfer, steady state uni-directional flow and equal particle size. However, in the less than perfect world flow analysis must also include particle interaction and nozzle design, both of which induce a considerable loss in particulate energy. One method that has been used at UMR as a means of abrasive velocity measurement and distribution is through the collection of the abrasive after it has left the nozzle. This nozzle is mounted horizontally and directs the resulting jet along the centerline of a tube, divided in 30 cm divisions, so that as the particle velocity declines the particles will settle to the bottom of the tube, with insufficient residual energy to cut the tube. This loss in particle kinetic energy changes the particle trajectory so that the velocity distribution as the particles leave the nozzle is reflected in the particle distance distribution along the tube. For this purpose the samples distributed over each 30-cm increment were collected. These samples were dried separately in an oven and weighed with the mass designated as that having reached the center point of that interval along the tube. Using the travel distance and the incremental mass collected, the kinetic energy of the particles was calculated, both by increment and in combination. Figure 1 show the test set up.

The tests were carried out at 35Mpa, 69Mpa, 103Mpa and 138MPa with 0.272 kg/min, 0.453 kg/min and 0.68kg/min abrasive feed rates. Nozzle sizes of 0.5 mm and 0.7 mm were used. Barton garnet of mesh size 80 was used throughout the tests.

4. RESULTS AND DISCUSSIONS

4.1 Effect of Pressure on Kinetic Energy

The velocities of particles are calculated from their respective displacements, i.e. points along the tube where they were collected. The mass of abrasives are plotted against the square of their respective calculated velocities and the area under the curve is proportional to the energy of the jet. Figures 2, 3 and 4 show the distribution of the particle velocities for the 0.5 mm nozzle, at 0.272, 0.453 and 0.68 kg/min feed rates. It can be seen that as the pressure increases a greater percentage of the abrasive particles reaches the higher velocities.

The energy of the particles was also calculated for 0.7 mm nozzle at the same feed rates. The total energy has been plotted for different pressures for both nozzles where Figure 5 shows the 0.5 mm and Figure 6 the 0.7 mm nozzle. It is clear from both graphs that an increased abrasive flow rate results in the energy curve shifting upwards for the same range of pressures.

4.2 Efficiency as a function of Pressure for different Abrasive Flow rates

Once the combined energy contained in the particles has been computed, the relative efficiencies of energy transfer, with respect to the input energy from the pump were calculated. The equation for input energy is given by

$$E_i = P \cdot Q \tag{15}$$

where P is the pumping pressure and Q is the total flow rate which sum of the mass flow rate of abrasive and water.

$$Q = \frac{\dot{M}_a}{\rho_a} + \frac{\dot{M}_w}{\rho_w} \tag{16}$$

Figure 7 and Figure 8 show the variation of efficiency with increase in pressure for different abrasive flow rates with a 0.5 and 0.7 mm nozzle. It can be seen that the higher the abrasive feed rate higher the efficiencies. The efficiencies seem to level out once a certain pressure is reached at a level that differs for the two nozzles.

5. CONCLUSIONS

A theoretical examination of the optimal concentration by weight of abrasive that can be used in abrasive slurry jet systems in order to achieve maximum cutting power for the ASJ suggests that the concentration be at a surprisingly high value. (Some three times the level found for an AWJ in recent tests [8].) One important assumption in these calculations was that the momentum transfer efficiency was independent of the abrasive concentration, a detail that has to be looked into further.

Initial experimental investigations reveal that the particles show an increase in kinetic energy with both an increase in pressure and an increase in abrasive flow rate. However an increase in jet pressure has a negative effect on the efficiency of the jet, although this seems to reach a plateau after reaching a threshold pressure which is a function of nozzle diameter.

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NOMENCLATURE

a_3 - Constant

C - Mass concentration of abrasive

D - Nozzle diameter

E_i - Input energy

$\dot{M}_a$ - Abrasive mass flow rate

$\dot{M}_w$ - Water mass flow rate

P - Pressure

Q - Total flow rate

R - Loading ratio

v - Abrasive slurry velocity

η_t -Momentum transfer coefficient

μ_m - Momentum transfer parameter

ρ_a - Density of abrasive

ρ_w - Density of water

Figure 1: Tube tests for measurement of energy of ASJ.

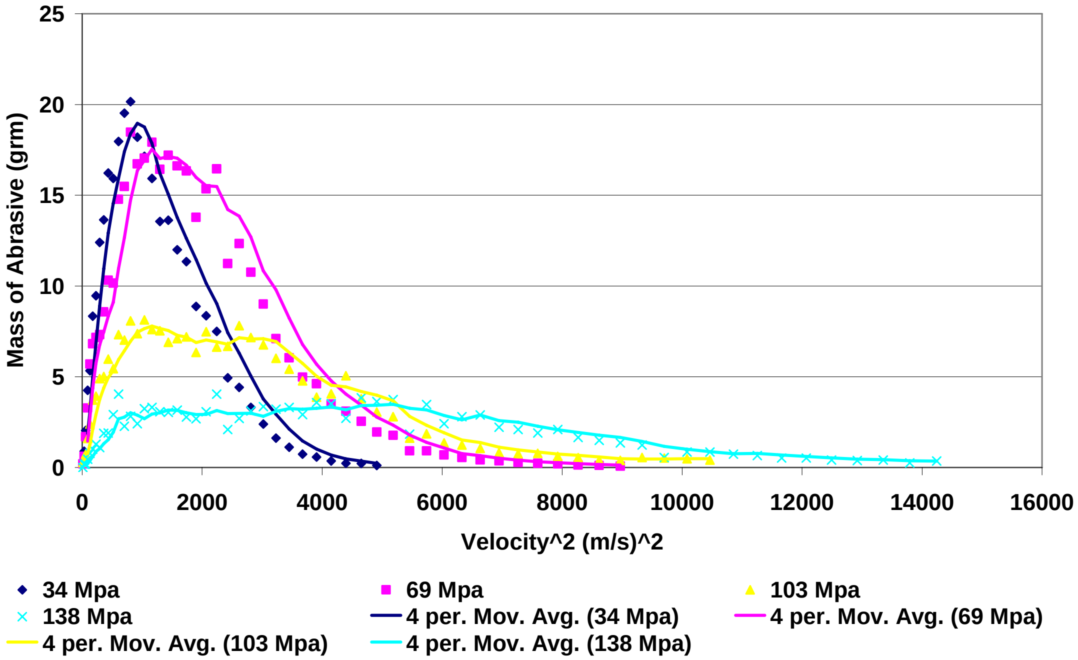

Figure 2: 0.5 mm nozzle at 0.272 kg/min feed rate.

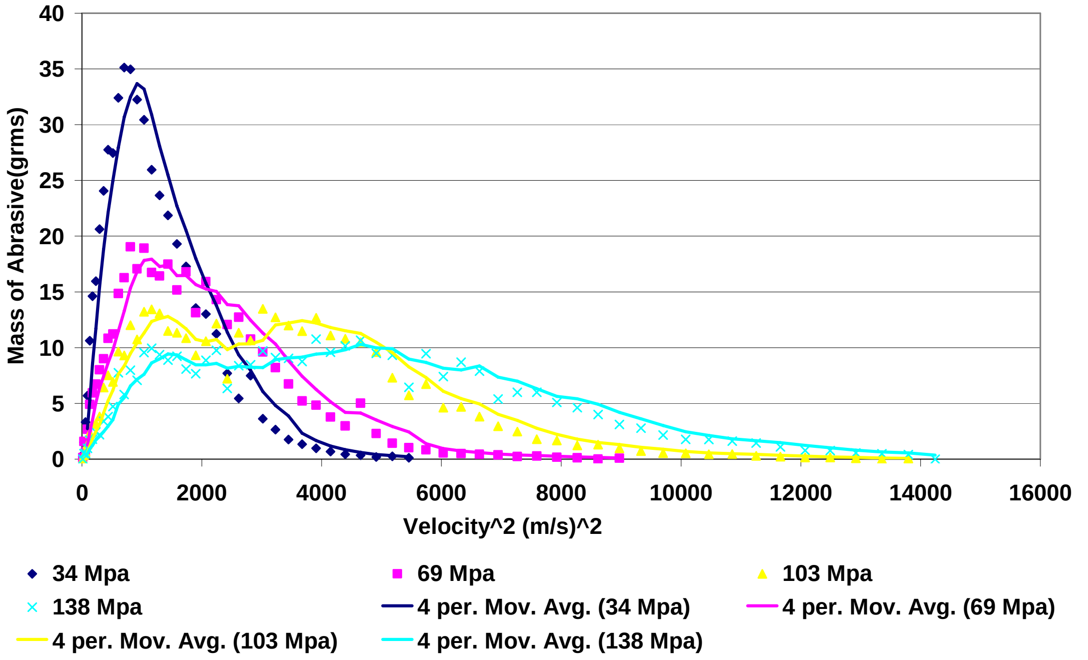

Figure 3: 0.5 mm nozzle at 0.453 kg/min feed rate.

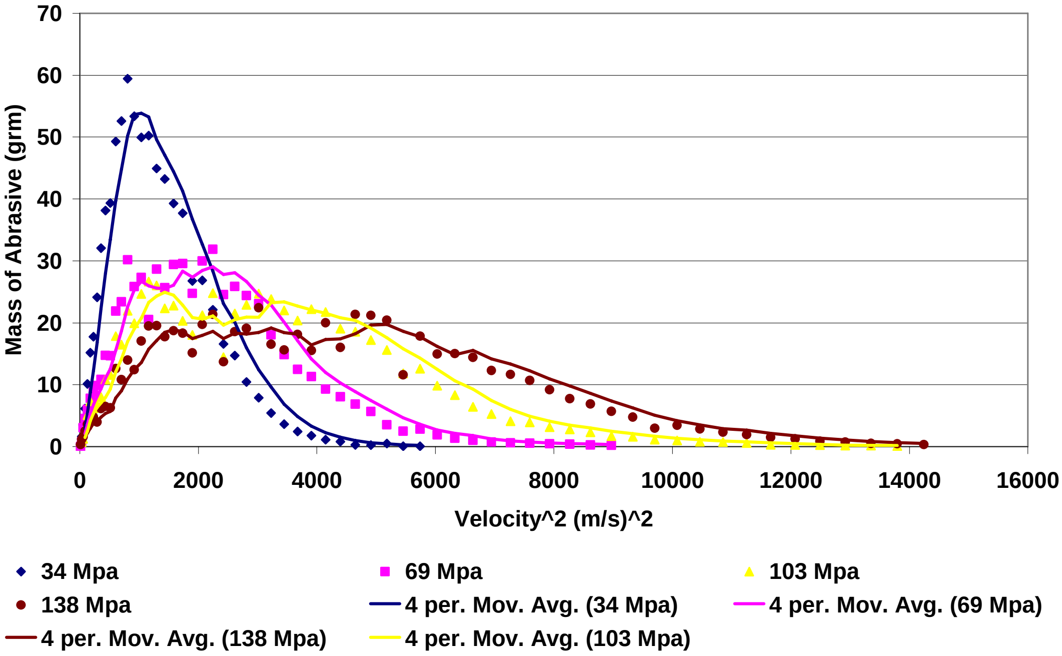

Figure 4: 0.5 mm nozzle at 0.68 kg/min feed rate.

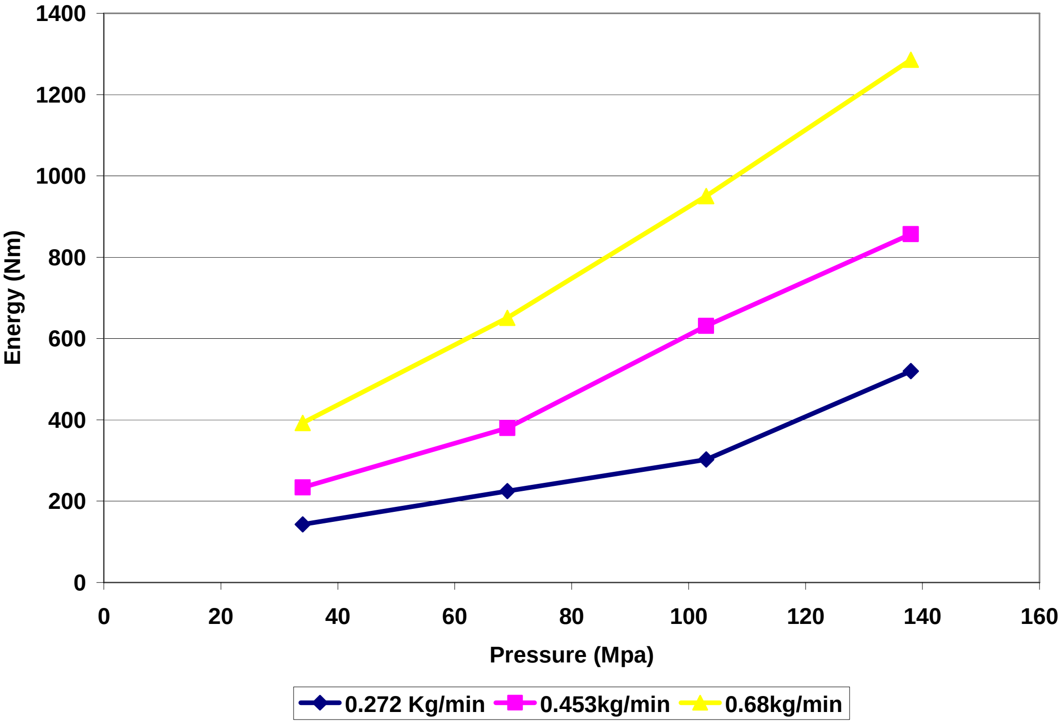

Figure 5: Total energy for 0.5 mm nozzle at different feed rates.

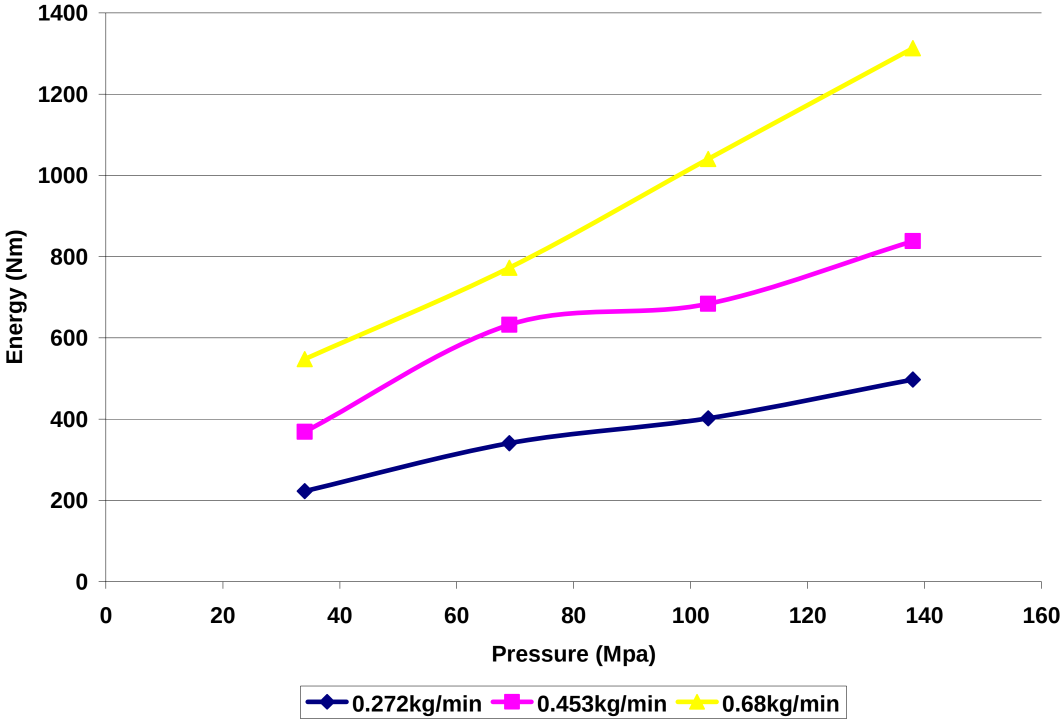

Figure 6: Total energy for 0.7 mm nozzle at different feed rates.

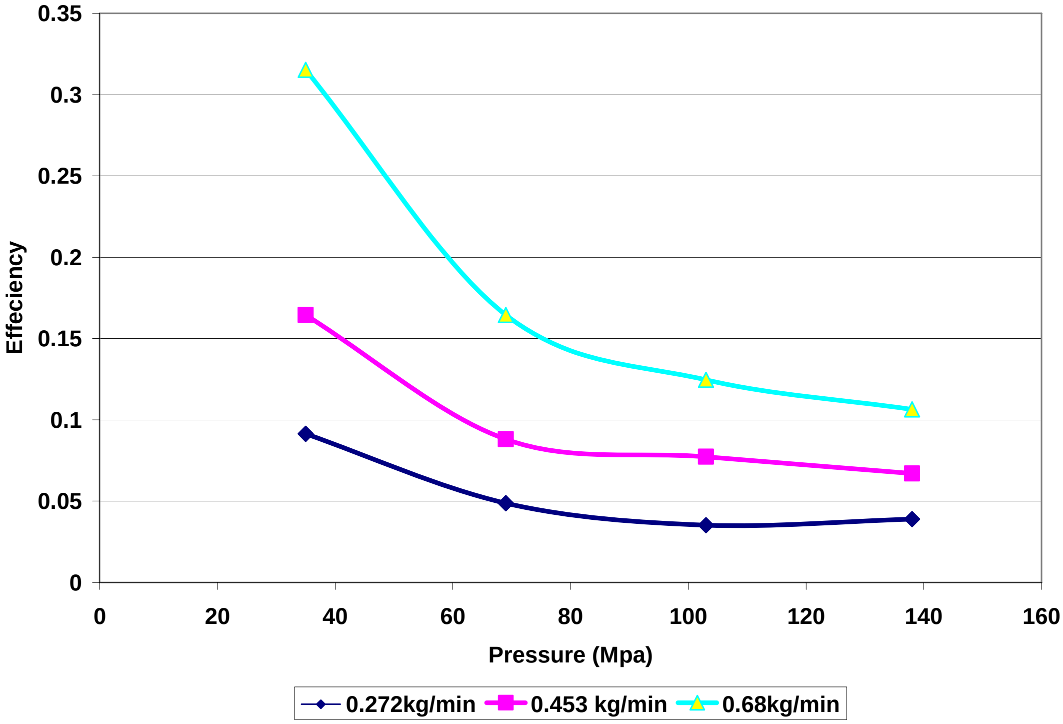

Figure 7: Efficiency for 0.5 mm nozzle at different feed rates.

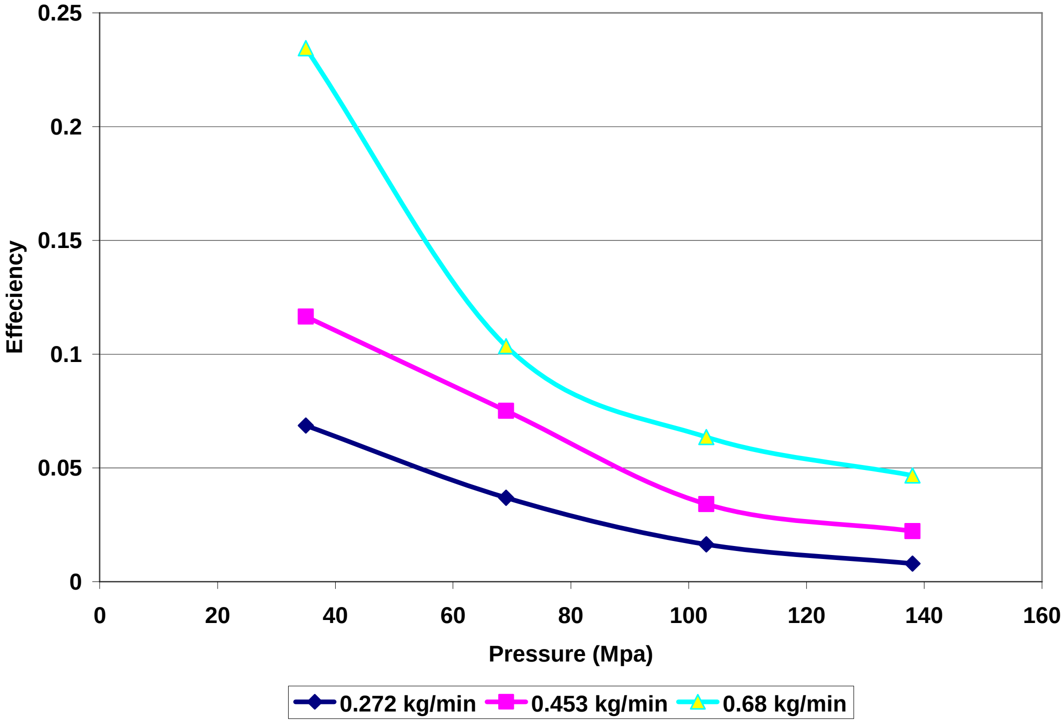

Figure 8: Efficiency for 0.7 mm nozzle at different feed rates.