Labor Maschinenkonstruktion

Application of high pressure waterjet

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1 Introduction

Nowadays, high pressure water jets (HPWJ) are used widely in various mechanical works such as cutting, cleaning, surface treatment and others. The major problem using mechanical conventional cutting tool is their excessive tool wear due to the direct contact of the tool with workpiece which resulted in quick rise of cutting temperature. Worn out tools produce high cutting forces, poor surface finish and eventually results in large processing costs. This major problem can be eliminated with the use of HPWJ technology since it does not have thermal related problems like recast layer and thermal distortion also it exerts minimal force on the work material. This technology is achieved by producing high velocity stream of water with or without abrasives which removes material mainly by erosion mechanism. The erosive effect of HPWJ had been used since early 30's in the tunnel and mining industry. By then, it had been possible to produce pump pressures of about 10 MPa. The regular use of water jet technology began around 1975 with the cutting of baby diapers with pure water. The crucial extension of the potential application took place from about 1980 through the addition of abrasives such as sand (garnet) or corundum (aluminium oxide), whereby cutting performance has been significantly improved with addition of these hard abrasive materials. Due to its development in recent years, HPWJ technology can be applied in almost every manufacturing process with a wide range of materials.
2 Principles of high pressure water jet technology

2.1 Background

In contrast to mechanical cutting methods, in HPWJ the tool is not a rigid body but a stream of fluid flow. During course of action, its geometric dimensions and physical characteristics of the fluid flow are not constant. When viewed as a whole, the system includes the complexity of jet formation, the generation of pressure in the pump, the flow of fluid in pipe as well as nozzle and the transformation of the fluid stream in free air space to the workpiece. Within this flow system boundary, there is a mass and energy flow. Figure 1 shows the black-box model for the process of water jet formation.

Figure 1: Black box "formation water"

In Figure 1 above, "1" is referred as the input side and "2" is the output side that hit the workpiece.

2.2 Definition of the water jet and the jet speed

Water escapes from a combined opening and moves within the beam stream. It is analogous to a river in which the stream remains the same but the flowing water exhibits a spatially and temporally variable flow rate. Also at the opening of water originating from a jet nozzle, the beam diameter and length may not be constant and can be changed from time to time.
2.2.1 Nozzle flow

Assuming the fluid jet exiting the nozzle as in the ideal case, there is a rotationally symmetric flow with a constant speed over the cross sectional of pipe. This simplification will neglect the pipe and nozzle friction for an incompressible flow. Therefore the exit velocity \( v_2 \) can be estimated. According to the Bernoulli equation, the equilibrium equation (the inlet is indexed as 1, and the outlet side is 2) can be established as in Equation (1):

\[
p_1 + \rho_1 gh_1 + \frac{1}{2} \rho_1 v_1^2 = p_2 + \rho_2 gh_2 + \frac{1}{2} \rho_2 v_2^2 + \Delta P_{\text{verlast}}
\]

\( \Delta P_{\text{verlast}} \) means a pressure loss in the nozzle (energy that is lost because of friction in the nozzle). In order to calculate the theoretical maximum possible energy conversion in the nozzle, the pressure drop is neglected as in ideal case, i.e. \( \Delta P_{\text{verlast}} \approx 0 \). The height difference between inlet and outlet is negligible especially in horizontal arrangement, i.e. \( h_1 = h_2 \). Let \( P_2 \rightarrow 0 \) and \( v_1 \rightarrow 0 \), then simplification of Equation (1) becomes Equation (2) below:

\[
p_1 = \frac{1}{2} \rho v_2^2.
\]

After rearranging the Equation (2), it will give the exit velocity, \( v_2 \) as in Equation (3).

\[
v_{2,\text{th,ink}} = \sqrt{\frac{2p_1}{\rho}}.
\]

As indicated by the index "th", this is the theoretical maximum possible velocity. In actual case due to friction, the rate may be lower. The index of "ink" indicates that in this calculation, the compressibility of water was neglected. The water is assumed to be incompressible. If the pipe and the nozzle are a continuous flow channel with variable cross section, then there corresponding flow conditions can be characterized by Reynolds number. The Reynolds number for the nozzle is determined using Equation (4).

\[
\text{Re}_D = \frac{d_D v_2}{\nu}
\]

Meanwhile, the Reynolds number for the pipe is determined using Equation (5).

\[
\text{Re}_R = \text{Re}_D \frac{d_D}{d_R}
\]
This $d_D$ and $d_R$ denote the nozzle and pipe diameter respectively and $\nu$ is the kinematic Viscosity, at room temperature (20 °C), $\nu = 1.01 \times 10^{-6}$ m$^2$/s.

2.2.2 Pressure profile in the jet

The cutting force of the water jet is based on the dynamic pressure of the water flow hitting the workpiece to be cut. After the end of the nozzle, the water flows freely in the ambient air. This dynamic pressure profile is the profile of the dynamic pressure of the water shortly after leaving the nozzle. It is the velocity distribution of turbulent nozzle flow. The frictional interaction with the surrounding air results in the outermost layers of the water jet to slow down and at the same time the ambient air is entrained and accelerated. This is characterized by turbulence flow which leads to variation of pressure and velocity of water flow. The pressure profile loses its rectangular shape and becomes a bell-shaped as shown in Figure 2.

![Figure 2: Pressure profile on the beam length](image)

In the figure above $\bar{x}$ denotes the distance traveled relative to the nozzle tip. The measurement was made using a pitot tube, where the nozzle diameter $D_0$ was 2 mm, and the pressure $P_1$ after nozzle inlet was 10.13 MN/m$^2$. $P_M$ is the measured dynamic pressure. With the progressive deceleration of the flow over the distance traveled, the maximum velocity decreases in jet core, so does the cutting effect when it strikes.

Due to the friction with the surrounding air, this pressure profile will be transformed, where the air is accelerated in the boundary area for water flow. Since the streamlines in the beam is only curved slightly, the entire beam cross section prevails as static pressure around ambient pressure. If the static pressure in the jet core much larger than the margin, the flow would be directed more to the outside edge.
For cutting application, it is done at the starting zone and the beginning of the main zone in which the beam is coherent as shown in Figure 3. The length of the area in which the beam is consistent is called the coherence length which by virtue of boundary layer characteristics is difficult to define and measure. Figure 3 shows the structure of a very coherent beam.

![Coherent beam]

**Figure 3: Coherent beam**

The beam coherence is an important quality measure for the nozzle, particularly when high cutting precision is required. Some researchers refer the coherence length arbitrarily as the length which the beam diameter relative to the beam exit has doubled. As mentioned above, a provision in distance with an air boundary layer interposed with the surrounding water droplets is difficult to determine.

### 2.2.3 Nozzles figures

**Contraction number:** The contraction number \( \mu \) describes the jet contraction. It is according to Equation (6) defined as the ratio between the minimum beam cross-sectional area after leaving the nozzle to the nozzle cross-sectional area itself.

\[
\mu = \frac{A_{\text{min}}}{A_0}
\]  

(6)

For the present application, there is a low number of contraction, i.e. a high jet contraction tends to be regarded as positive, and a small beam diameter is desired. For the current nozzle, the contraction number is 0.9.

**Speed point:** The speed at point, \( \phi \) is defined as the ratio of actual to theoretical jet velocity as in Equation (7). Thus, \( \phi \) also describes the friction losses. The values for \( \phi \) are given in the literature from 0.95 to 0.99.
\[ \varphi = \frac{v_2}{v_{2,th}}. \]  

(7)

The speed point should be high because a high kinetic energy is desired.

2.2.4 Coefficient of discharge and nozzle efficiency

The contraction number, \( \mu \) and speed, \( \varphi \) are often used together to calculate discharge point, \( \alpha \) as in Equation (8). It is used to identify and check the nozzle jets for possible signs of wear.

\[ \alpha = \varphi \mu. \]  

(8)

The discharge point reaches values from 0.65 to 0.7. Steady jet form shows significantly higher discharge numbers than discontinuous jet form as illustrated in Figure 4.

![Figure 4: Discontinuous jets form (left) and continuous nozzle shape (right).](image)

The discharge point represents a value that is on the measurement of mass flow which can easily be determined - if this is constant. Usually, the discharge point is determined by measuring the mass flow rate from Equation (3) which is identified as theoretical mass flow rate as in Equation (9).

\[ \alpha = \frac{\dot{m}_2}{\dot{m}_{2,th}}. \]  

(9)

It contains the jet contraction and the influence of friction, both of which are the energy input of the water jet impact. However, as in the present application, a low number of jet contraction and speed point, which provides high friction means is viewed negatively. It is recommended instead that these characteristic nozzle numbers for the present application are collected and evaluated separately. The same applies to the characterization of the energy
conversion process concept commonly known as jet efficiency, by including the exiting kinetic beam energy ($E_{\text{kin}}$) and the potential (pressure) energy ($E_{\text{pot}}$) as in Equation (10).

$$\eta = \frac{E_{\text{kin}}}{E_{\text{pot}}} = \frac{\dot{m}v_{2}^{2}}{2p_{1}Q}.$$  \hspace{1cm} (10)

Rearranging Equation (10) using already introduced variables $\alpha$ and $\phi$, Equation (10) can be formulated as in Equation (11):

$$\eta = K\alpha\phi^{2}.$$  \hspace{1cm} (11)

The additionally introduced constant $K$ can be regarded as characteristic of the fluid jet.

### 2.2.5 Jet shock forces

The exiting impulse from the nozzle jet under the fluid mechanics laws of momentum is shown in Equation (12):

$$\dot{J} = \dot{m}_{2}v_{2}.$$  \hspace{1cm} (12)

The impulse is constant throughout the free jet region. Due to the mixing of water and the ambient air, certain impulse is lost but it is only a momentum exchange between the two phases instead. As specified in Equation (12), momentum flux has the dimension of a force and is in absolute value equal to the recoil i.e. a water jet impinging on a flat plate with squeezed rectangular flow deflection exercise. The mass flow results in the impulse flow, which will be referred to by jet force as in Equation (13).

$$\dot{m} = \int_{A} \rho (\vec{v} \cdot \hat{n}) dA.$$  \hspace{1cm} (13)

If we perform the integral over the impingement surface, we obtain the balance of forces with a force transducer beam measurable force $F$ as in Equation (14).

$$F = \int_{A} \rho (\vec{v} \cdot \hat{n})^{2} dA.$$  \hspace{1cm} (14)

Assuming a constant velocity over the beam cross section (given in measurement for short nozzle exit) and in the event that no impulse flow away from the plate takes place, we get the simplified formula for the radiance of the vertical impinging on a flat baffle plate at which flows along the jet and the plate as in Equation (15):

$$F = \rho Av_{2}^{2}.$$  \hspace{1cm} (15)
By neglecting the compressibility of water and combining the Equation (3) and Equation (15) for the theoretical jet force, \( F_{th} \) from a given pump pressure results in Equation (16).

\[
F_{th} = 2 \rho_1 v.
\]  

(16)

In Equation (16), the radiance of the moving jet of water on the wall is twice as to cause the pressure of the fluid at rest. It is the theoretical effective force that friction losses in the nozzle can be ignored. In the measurement of this force, the radiance sensor on the vector is the difference between the incoming and outgoing momentum flux. If the beam that is deflected or reflected and leaves the wall with a significant velocity, it increases to the plate acting force. This principle is used in the design of turbine blades (Pelton) and also in the design of an impingement surface force transducer. From the ratio of the theoretically calculated value and the measured force, \( F_{eff} \), the so-called impulse efficiency, \( \varepsilon_{eff} \) is determined based on Equation (17).

\[
\varepsilon_{eff} = \frac{F_{eff}}{F_{th}}.
\]  

(17)

### 2.3 Detailed revision

The effect of high pressure fluid jet on a solid and the resulting material contribution based on the complex interaction of various damage mechanisms. Specifically, the followings are various mechanisms of damage for the material.

- Fluid impact (Shock pressure),
- Dynamic pressure of the fluid,
- Erosion,
- Abrasion,
- Cavitation

Fluid shock and dynamic pressure of the fluid are the main damage mechanisms and are discussed in more detail.
2.3.1 Fluid Impact (Shock pressure)

Water passes over the workpiece where it creates a shock-load, which causes a significant short-term spike. This primary load or the first contact of the fluid jet is called fluid shock. Equation (18) shows how to calculate the load as a so-called shock pressure, \( P_{\text{Stoß}} \):

\[
P_{\text{Stoß}} = v_2 c_2 \rho_2 \left( 1 + \frac{\rho_2 c_2}{\rho_s c_s} \right)
\]  

The pressure shock affects only within a few thousandths of seconds then the shock wave is eliminated. But it attributes an essential crushing effect.

2.3.2 Dynamic pressure of the fluid

The stationary beam by a resulting pressure is called dynamic pressure as shown in Equation (19).

\[
P_{\text{Sta}} = \frac{1}{2} \rho_2 v_2^2
\]  

The resulting exposure of the workpiece to this pressure is a lot less than the shock pressure.

2.3.3 Mode of action in the cutting mechanism

Since the cutting process is so far largely beyond the direct observation, the interaction between the fluid jet and the material is poorly investigated. The mechanism of water jet cutting offers basically two possible variants of the separating mechanisms:

- Separation through material removal
- Separation through crack

Table 1 lists various cutting materials with respect to their properties and separation processes.
**Table 1: Cutting materials and their properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Separation process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>Homogeneous, isotropic, crystalline</td>
<td>splitting and removal, e.g. about outbreaks, preferably along grain boundaries</td>
</tr>
<tr>
<td>Concrete, earth</td>
<td>Inhomogeneous, anisotropic</td>
<td>separation, preferably by removing along the less solid parts</td>
</tr>
<tr>
<td>Fiber composites, Wood</td>
<td>Homogeneous, anisotropic</td>
<td>separating the matrix and the less solid materials, possibly tearing of fibers</td>
</tr>
</tbody>
</table>

Whether as an effective mechanism for cutting or cracking, it essentially depends on the material properties in conjunction with the diameter and pressure of the water jet. Cracking takes place when the front of the jet acts as a water cushion such as a wedge pushing forward and slicing the materials. If the slice is soft enough and the material strength is low enough, the wedge produces enough tensile forces which consequently tear the material. Material removal takes place when the material is rather hard and brittle and upon impact causes outbreaks which are removed by the water.

**2.3.4 Influence of nozzle diameter on the cut**

Principle must be observed that larger diameter nozzles at the same pressure can expend more energy to separate, because a large volume flow and thus the momentum flux is larger. Due to the friction at the interface between the jet and cutting material, a high water pressure is recommended so that the dynamic pressure of jet core is still high enough to penetrate over the entire depth of cut. Correspondingly, a smaller diameter nozzle requires a higher pressure for better cutting depth. However, increasing the pressure decreases the coherence length of the beam due to increased interference in jet stream. Therefore, for small nozzle diameter, the pressure must be optimized to a specific value, at which the best surface quality results for the required depth of cut can be achieved.
3 Experiment

3.1 Description of the high pressure systems

3.1.1 UHDE 6000 bar high pressure water jet

There are two water jet systems at the chair. The first one is high pressure water jet system with a maximum pressure of 6000 bar. It is used for cutting applications with small nozzle diameters and achieves a flow rate of 2 l/min. The pressure is generated by a high pressure water pump. An adjustable axial piston pump of a flanged motor drives a constant speed which is produced in an open oil circuit of the pressure oil. The oil pressure is supplied through a reversing valve where the two sides of the cylinder work alternately. The piston of the working cylinder is moving in the direction where it drives the plunger of the high-pressure pump heads. The ratio of the plunger area to working cylinder surface area for the high-pressure head is 30:1. The method of setting the operating pressure is by adjusting and changing the flow of pressure oil.

3.1.2 WOMA double-pump system 750 bar and 2000 bar.

The second water system has a lower pressure between 750 bar to 2000 bar. With that pressure, it is suitable to be used for cleaning and coat removal application. It has a larger diameter nozzle with a dual pump system provided by WOMA company. It is available in either pumps with a maximum of 750 bar with a flow rate of 42 l/min or a 2000 bar pump, which has a maximum flow rate of 10 l/min. The pump design in both cases is a 3-piston plunger pump.

3.2 Safety instructions

During the execution of the test, the following safety rules have to be observed:

- The instructions of the instructor (supervisor) are obliged to heed and any infringement may result in exclusion from the experiment.
- The operation of the control is carried out by the instructor.
- When opening the cutting valve, a safety distance of 1 meter to the cutting nozzle is to be observed.
- The emission of noise can be up to the level of 115 dB. Therefore, before opening the cutting valve the individual hearing protector has to be arranged.
- Remove all unnecessary items before switching on the pump and close the door of the cabin.
3.3 Experiment implementation

The purpose of the laboratory work is to carry out some experiments to illustrate the capability of HPWJ system. There are two tests to be conducted using the HPWJ system available at chair. The results are to be evaluated by the students.

3.3.1 Cutting depth measurement

A. Different pressures

Date:
Material:
Nozzle diameter:
Distance between nozzle and workpiece:
Feedrate:

<table>
<thead>
<tr>
<th>No.</th>
<th>Pressure [MPa]</th>
<th>Cutting depth [mm]</th>
<th>Cutting rate $[\text{mm}^2/\text{s}]$</th>
<th>Water velocity (m/s)</th>
<th>Water flowrate [l/min]</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>50</td>
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<td></td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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</tr>
<tr>
<td>6</td>
<td>300</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Notes:
B. Different feedrates

Date: 
Material: 
Nozzle diameter: 
Distance between nozzle and workpiece: 
Pressure:

<table>
<thead>
<tr>
<th>No.</th>
<th>V [mm / min]</th>
<th>Cutting depth [mm]</th>
<th>Cutting rate [mm^2 / s]</th>
<th>Water velocity (m/s)</th>
<th>Water flowrate [l / min]</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<tr>
<td>6</td>
<td>1200</td>
<td></td>
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</tr>
</tbody>
</table>

Notes:

C. Different standoff distances

Date: 
Material: 
Nozzle diameter: 
Feedrate: 
Pressure:

<table>
<thead>
<tr>
<th>No.</th>
<th>Distance [mm]</th>
<th>Cutting depth [mm]</th>
<th>Cutting rate [mm^2 / s]</th>
<th>Water velocity (m/s)</th>
<th>Water flowrate [l / min]</th>
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<td>6</td>
<td>60</td>
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</tbody>
</table>

Notes:
3.3.2 Surface roughness measurement
Measurement of the roughness is based on the visual inspection for every specimen tested as in 3.3.1.

Notes:

3.4 Evaluation of test results
Evaluate the results from the studies conducted on the basis of the following criteria (LESS than 5 A4 pages):

3.4.1 Methodology
A. Brief description of the experiment
B. Tabular listing of the test results, calculation of the missing variables from the experimental procedures

3.4.2 Cutting depth measurement
- Compare the advantages and disadvantages of high-pressure waterjet technology with other manufacturing processes.
- Graphical representation of the experimental results
  - cutting depth vs. pressure
  - cutting depth vs. feed rate
  - cutting depth vs. standoff distance
- Explain the effect of cutting depth with respect to the pressure, feedrate and standoff distance

3.4.3 Surface roughness measurement
- Visual analysis of surface roughness measurement depending on pressure, feedrate and standoff distance and their possible causes.

The laboratory report is to be submitted individually and within 14 days after the experiment takes place. Submit the laboratory reports to your lab instructor.