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# Modelling of abrasive particle energy in water jet machining

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ABSTRACT

A phenomenological model of the three-phase flow inside an abrasive water jet machining cutting head has been developed. Several improvements over previously presented models such as taking into account the abrasive particle size distribution, and the effect of breakage of particles on the energy flux have been made. The model has been validated using an extensive set of experimental data with wide variations in cutting-head geometry, operating pressure, and abrasive mass flow rates. The cross-sectional averaged abrasive particle velocity at the exit of the focussing tube has been predicted with good accuracy over the whole range of experiments. In particular, the Pearson correlation between the model and the experimental results is found to be more than 95%, implying the utility of this model in design.



## 1. Introduction

Erosion of material by solid particles accelerated by a high-speed water jet is the basic process of abrasive water jet (AWJ) machining. A typical commercial AWJ system consists of a pump, a mixing and acceleration section, a positioning system, and a catcher. Depending on the method of dosage of abrasive particles into the water jet, AWJs can be classified as injection jets or suspension jets. For practical cutting applications, injection jets are more commonly used, wherein an AWJ is formed by accelerating small solid particles (typically Garnet) through contact with a high-speed water jet (see Fig. 1). The high-speed water jet, in turn, is formed in an orifice placed on top of the mixing and acceleration head. The solid particles are dragged into the mixing chamber through a separate inlet by the low pressure created by the water jet in the mixing chamber. Mixing between the solid particles, water jet and air takes place in the mixing chamber, and the acceleration process occurs in the focusing tube. After the mixing and acceleration process, a high speed three-phase mixture leaves the tube at velocities of several hundred meters per second.

Abrasive water jet machining is considered to be a rapidly growing technology capable of processing a variety of materials. Since AWJ machining relies on erosion by fine abrasive particles, mechanical loads exerted on the workpiece are small, and the flow of water leads to very low thermal stress on the workpiece. For the application of the abrasive jet as a milling tool, the capability of the AWJ technology for accurate depth cutting is still a challenge. Since there are several parameters that affect the material removal rate and profile, such as pump pressure, jet feed rate, abrasive mass flow rate, stand-off distance, and abrasive breakage inside the cutting head, it becomes difficult to obtain the desired local material removal. The process is also subject to fluctuations in pressure and abrasive mass flow rate. Therefore, one of the main factors of the success of this process is an accurate understanding of the jet properties at the exit of the cutting head.

Several methods have been used to characterise the mixing and acceleration process experimentally. However, most of the experiments were unable to accurately measure the velocities of abrasive particles as they leave the focussing tube, due the complex topology of the three-phase mixture. Recently, a novel set of experiments has been performed by Balz et al., where two different non-intrusive optical measurement techniques have been used. Balz et al. (2013) performed ultra-fast X-ray velocimetry experiments to measure velocities and spatial positions of abrasive particles within the solid–liquid–gaseous three-phase flow. Balz and Heiniger (2011) used a method based on stereo particle image velocimetry to obtain full spatial resolution of fluorescent dyed abrasive particles. New results and understanding have been obtained from these experiments, such as the fact that more particles leave the focussing tube near the centre as compared to the edges. A large set of experimental data is available for the validation of phenomenological models as well as for validating advanced computational fluid dynamics (CFD) based models.

Knowledge of the particle velocity and the energy distribution across the abrasive jet is of great importance because the material

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**Fig. 1.** Abrasive water jet (AWJ) cutting head: (A) high pressurised water, (B) orifice, (C) abrasive particles and air inlet, (D) mixing chamber, and (E) focusing tube.

is cut or eroded due to wear, which depends on the kinetic energy of each particle. Several modelling attempts are based on a momentum equilibrium assumption that is only true for very long tubes. These models introduce a modelling parameter that takes into account the acceleration efficiency. Such models are meaningful because these studies attempted to model the whole process including the erosion of the cut material. There have been only few attempts to develop a detailed phenomenological model of the cutting head. Tazibt et al. (1996) developed a three-phase model where they first considered the case of only water and particles (without air) and then extended it to include the presence of air. The model assumed the water and air to be a two-phase mixture in contrast to the current model where several topological assumptions regarding the air–water interaction are made. Also, they did not consider the effect of particle size distribution. The validation of their model was limited due to restricted availability of experimental data. Momber (2001) presented a lumped model that attempts to predict the abrasive exit velocity based on impact force measurements on the work piece. Advanced three-dimensional CFD-based modelling has also been attempted by Prisco and D'Onofrio (2008). However they simulate only the two-phase water and air flow inside the cutting head. CFD modelling of the three-phase flow in the cutting head is complicated by the fact that the abrasive particles are not small in comparison to the focussing tube diameter. A full moving object model coupled with multiphase flow modelling of the air, water mixture would be required, which is beyond the state-of-the-art of CFD simulations. Ahmed et al. (2001) presented a CFD model where all the three phases are modelled as Eulerian phases. However, very limited validation was carried out.

## 2. Scope of paper

The goal of this study is the development and validation of a phenomenological model of the abrasive water jet cutting head with the capability to predict the energy of the abrasive particles as they leave the focussing tube. The study distinguishes itself from previous attempts by analysing several hitherto unaddressed issues:

- It presents a complete model for the cutting head which only requires inputs that are easily available to an engineer.
- It takes into account the size distribution of the abrasive particles, which is shown to be indispensable in predicting the correct energy flux, based on new experimental evidence.
- It analyses the effect of abrasive particle breakage inside the cutting head and shows that the breakage has a significant impact on the energy transfer process.
- It attempts a comprehensive validation of the model using several experimental data sets covering different geometries, and operating parameters; primarily the ones by Balz and Heiniger (2011) and Balz et al. (2013).

## 3. Modelling

A consolidated numerical model is proposed in this document for predicting/estimating the energy flux of abrasive particles on a workpiece. Each part of the process is addressed separately. The water jet cutting apparatus/process is split into the following parts for modelling purposes:

1. Creation of the water jet from high-pressure conditions, based on the diameter of the orifice and the operating pressure.
2. Modelling of entrainment of air and abrasive particles based on the jet-pump effect of the water jet.
3. One-dimensional (cross-section averaged) modelling of the three-phase mass and momentum balance in the focussing tube.

The various parts of the cutting head are shown in Fig. 1. The model takes into account the following parameters (both geometric and operating),

1. Geometry of cutting head, viz. nozzle diameter, mixing chamber diameter, mixing chamber length, focussing tube diameter, and length of focussing tube.
2. Operating pressure.
3. Entrainment of air and particles; therefore, diameter and length of air delivery tube.
4. Size distribution and density of abrasive particles.
5. Abrasive mass flow rate.

The model delivers as output the water and abrasive particle velocities at the exit of the focussing tube for given input parameters.

### 3.1. Post-nozzle conditions

For a specified nozzle diameter and operating pressure ($P$), the jet diameter can be calculated as in Hashish (2003). We assume that a discharge coefficient ($C_d$) is available.

$$d_{jet} \approx d\sqrt{C_d} \tag{1}$$

where $d$ is the diameter of the orifice and $d_{jet}$ is the diameter of the resulting water jet. If the discharge coefficient is not available for a given cutting head, it is calculated using the correlation given by Hashish (2003),

$$C_d = 0.785 - 0.00014P - 0.197d \tag{2}$$

where in the above equation, $P$ is pump pressure given in MPa and $d$ is given in mm. The jet velocity ($v_{jet}^{is}$) on exiting the nozzle can be calculated using the Bernoulli equation adjusted by using a compressibility coefficient $\Psi$ as,

$$v_{jet}^{is} = \Psi\sqrt{2\frac{(P - p_2)}{\rho_2}} \tag{3}$$

where $\rho_2$ is the density of water at the ambient pressure, $p_2$ is the mixing chamber pressure, and the compressibility coefficient is given as (Hashish, 2003),

$$\Psi = \sqrt{\frac{L}{P(1-n)}\left[\left(1+\frac{P}{L}\right)^{(1-n)} - 1\right]} \tag{4}$$

where the model constants $L = 300$ MPa, and $n = 0.1368$ at 25 °C.

### 3.2. Mixing chamber pressure

An estimate of the pressure inside the mixing chamber ($p_2$) is essential for the entrainment model to calculate the mass flow rate of air being entrained into the focussing tube. Due to the jet-pump action of the water jet, $p_2$ will be lower than ambient pressure $p_\infty$. Also, the mixing chamber pressure is found to be a strong function of the geometric parameters, viz. mixing chamber dimensions and focussing tube diameter and shape.