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# Orifice Coefficients Evaluation for Water Jet Applications

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***Abstract* -** The topic of water jet orifices efficiency and effectiveness evaluation has been considered in this paper. The performed analysis is based on the evaluation of the discharge, velocity and contraction coefficients for different water orifices. In order to overcome the difficulty to measure the water velocity at the orifice exit, which can reach 900 m/s in case of pure water jet applications (without abrasive additives), a suitable laser Doppler measurement system has been applied. An analysis of orifice performances is presented in the present paper, also considering the case of broken orifices, very important for industrial applications.

## I. Introduction

Water Jet/Abrasive Water Jet (WJ/AWJ) technology can be considered a suitable technology to cut a great spectrum of materials (e.g. special steel, titanium alloys, aluminium alloys, marble, wood, plastic, composites, etc.). These materials can also be turned, milled or treated on their surface by means of the water jet technology. The great variety of possible operations makes this technology one of the most flexible among the non conventional machining processes.
Water jet cuts, thanks to a water beam, producing no thermal effects on the workpiece (the metallic material structure is not damaged). For this reason this technology is often preferred to other beam technologies such as laser and plasma.
A very important part of the water jet plant is the final component, the water orifice. Defining the overall efficiency $\eta$ as the ratio between the available fluid-dynamic power and the electric active power from the network, it is well known and proved [1,2] that it strongly depends on the orifice. In particular, orifices with the same nominal diameter but produced by different manufacturers could result very different in terms of fluid-dynamic behaviour [2].
Starting from thermodynamic considerations, efficiency and effectiveness indexes are defined for characterising orifices: an analysis of such indexes will be proposed in this paper.

## II. Thermodynamic considerations

In order to evaluate the orifices' performance, it is useful to introduce the efficiency index:

$$\eta_{\mathrm{N}} = \frac{\frac{1}{2}V_1^2}{\frac{1}{2}V_{1s}^2} = \frac{h_0 - h_1}{h_0 - h_{1s}} \tag{1}$$

where $\eta_{\mathrm{N}}$ is the orifice efficiency, $V$ is the jet stream mean velocity and $h$ is the enthalpy; the subscripts in the equation (1) have the following meaning: 0 indicates the orifice entry section, 1 the orifice exit section and $s$ the isentropic transformation. The efficiency index $\eta_{\mathrm{N}}$ is the ratio between the kinetic energy produced at the section 1 and the enthalpy available for the expansion through the orifice.
The orifice efficiency can be usefully determined also by means of the *velocity coefficient* $C_v$, strictly related to $\eta_{\mathrm{N}}$:

$$C_v = \frac{V_1}{V_{1s}} \tag{2}$$

Considering that water, at the operating pressures of water jet systems, can be considered compressible and all the available enthalpy is used to produce the jet velocity $V_{1s}$, it is possible to write [1]:

$$V_{1s} = \sqrt{\frac{2L}{\rho_1(1-C)}\left[\left(1+\frac{p_0}{L}\right)^{1-C}-1\right]} \quad (3)$$

where $C$ = 0.1368 and $L$ = 300 MPa.

Starting from the definitions in equations (2) and (3), it is possible to introduce the orifice coefficients. The first step is the definition of the *theoretical velocity* coming from the Bernoulli equation:

$$V_{\mathrm{th}} = \sqrt{\frac{2p_0}{\rho_1}} \quad (4)$$

The *compressibility coefficient* allows defining a relationship between $V_{1s}$ and $V_{\mathrm{th}}$:

$$\psi = \frac{V_{1s}}{V_{\mathrm{th}}} \quad (5)$$

At this point, the actual velocity at the section 1 can be calculated as:

$$V_1 = C_{\mathrm{v}}\psi V_{\mathrm{th}} \quad (6)$$

In order to calculate the volume flow rate, $V_1$ has to be multiplied by the area of the *vena contracta* $A_{\mathrm{c}}$, but $A_{\mathrm{c}}$ can be related to $A$, the nominal area of the orifice bore, by means of the *contraction coefficient* $C_{\mathrm{c}}$:

$$C_{\mathrm{c}} = \frac{A_{\mathrm{c}}}{A} \quad (7)$$

So, the water flow rate at the section 1 can be calculated as:

$$Q_1 = C_{\mathrm{v}}C_{\mathrm{c}}\psi V_{\mathrm{th}}A \quad (8)$$

The so called *coefficient of discharge* can be defined as:

$$C_{\mathrm{d}} = C_{\mathrm{v}}C_{\mathrm{c}}\psi \quad (9)$$

The coefficient of discharge $C_{\mathrm{d}}$ is than composed by the mentioned coefficients $C_{\mathrm{v}}$, $C_{\mathrm{c}}$ and $\psi$; it takes into account the geometrical effect of the internal shape of the orifice on the flow by means of $C_{\mathrm{c}}$, the compressibility of water by means of $\psi$ and the dissipations across the orifice by means of $C_{\mathrm{v}}$; generally speaking, $C_{\mathrm{d}}$ gives a direct indication of the effectiveness of the orifice, which can be thought as its capability to provide flow rate: in effects, $C_{\mathrm{d}}$ can be obtained, as in the present study, from water flow rate measurements from the equation (10):

$$C_{\mathrm{d}} = \frac{Q_{acq}}{Q_{th}} \quad (10)$$

where $Q_{\mathrm{acq}}$ is the acquired mean value of the water flow rate at the section 1 ($Q_1$) and $Q_{\mathrm{th}}$ is defined by the equation (11):

$$Q_{\mathrm{th}} = \pi\cdot\left(\frac{d_{\mathrm{or}}}{2}\right)^2\cdot V_{\mathrm{th}} \quad (11)$$

where $V_{\mathrm{th}}$ is calculated by means of the equation (4) basing on $p_{\mathrm{acq}}$, the acquired mean value of the water pressure at the orifice entrance ($p_0$). $Q_{\mathrm{th}}$ is obtained considering a jet cross section area $A$ corresponding to the nominal diameter of the orifice ($d_{\mathrm{or}}$).

Together with $C_{\mathrm{d}}$, also the water velocity at the orifice exit $V_1$ itself defines its effectiveness, in fact it determines the kinetic energy on which the jet can count for the material removal [1].

$C_{\mathrm{v}}$ is calculated, in the present study, from the equation (2), basing on $V_{\mathrm{acq}}$, the acquired value of the water velocity at the orifice exit $V_1$, and $V_{1s}$, calculated by means of the equation (3) in which $p_{\mathrm{acq}}$ is employed as $p_0$. $C_{\mathrm{v}}$ is the only orifice coefficient taking into account energy losses, i.e. its efficiency.

The compressibility coefficient $\psi$ is calculated in the following from the equation (5), applying the values of $V_{1s}$ and $V_{\mathrm{th}}$ obtained as stated before. The compressibility coefficient $\psi$ represents a lower production of kinetic energy due to the compressibility of water, but this is not related to the orifice efficiency.

The last coefficient $C_{\mathrm{c}}$ is determined from the equation (9) where the values of the other terms are known. The coefficient of contraction $C_{\mathrm{c}}$ explains how the actual minimum section of the flow is smaller than the geometrical one: it does not represent energy losses but it indicates that the orifice is 'requiring' less energy than it could be foreseen by its nominal diameter. $C_{\mathrm{c}}$ also gives an indication on the actual jet diameter, important in case of fine cuts performed on soft materials employing pure water jets.

The aim of this work is to experimentally determine the orifice coefficients $C_{\mathrm{d}}$, $C_{\mathrm{v}}$ and $C_{\mathrm{c}}$ in order to compare orifices performance on the base of their efficiency and effectiveness. Not only new orifices are compared, but, defined the standard performance on reference orifices, other orifices coming from a different producer and broken orifices are tested in order to point out possible differences in terms of orifice coefficients. This fact allows a deeper knowledge about wrong operating conditions and their characterisation.

Previous studies by the authors were addressed to the determination of the orifice coefficients [2, 3, 4, 5, 6, 7], but some important differences and improvements can be outlined in order to point out the relevance of the present study:

- the first version of the laser Doppler velocimeter applied to acquire the water jet velocity was described in [3], but only few measurements were carried out without performance comparisons among orifices;
- a new approach on the water jet plant diagnostics based on the analysis of the power signal at the electrical motor was presented in [2], where also the coefficient of discharge was estimated for some orifices; the other orifice coefficients were not taken into account;
- a first comparison among orifices performance in terms of jet dispersion was presented in [4], but no calculations regarding orifice coefficients were performed;
- the study presented in [5] compared the orifice coefficients for diamond orifices characterised by a particular internal shape in order to evidence how the orifice geometry can affect the cutting capability on soft materials; different orifice diameters (0.15 and 0.25 mm) and a different orifice material were tested comparing to the present study, where 0.20 and 0.30 mm synthetic sapphire orifices are applied. Moreover, broken orifices and different brands orifices are tested in the present study in order to evidence their different behaviour;
- only 0.30 mm orifices were tested in [6]; different orifices brands were compared basing in the orifice coefficient and cutting tests with abrasive on aluminium; broken orifices were not considered;
- a new set-up procedure for the applied laser Doppler measuring system, characterised by a better repeatability, is presented in [7]: the improvement allowed by this procedure allows carrying out fine orifice performance comparisons as the one proposed in the present paper.

## III. Experimental set-up

The experimental set-up (Figure 1) was determined in order to acquire the quantities of interest for the orifice coefficients calculation:

- water pressure at the cutting head ($p_{acq}$);
- water volume flow rate at the entrance of the high pressure pump ($Q_{acq}$);
- water velocity at the exit of the orifice ($V_{acq}$).

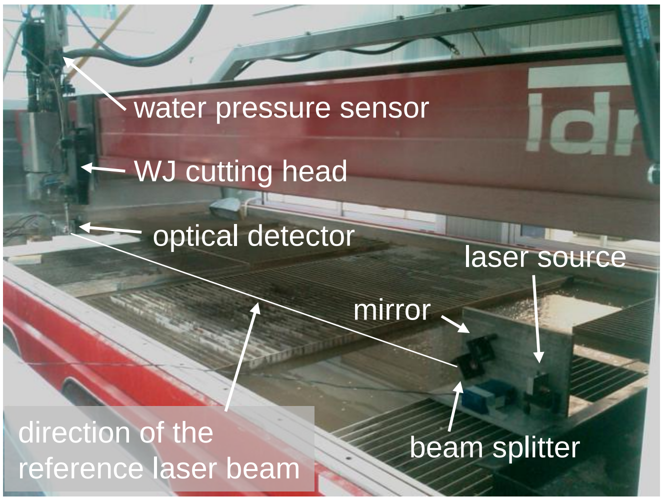


Figure 1 – Water jet working table with the employed experimental set-up

These quantities are acquired thanks to the sensors indicated in the Table 1; in the case of the present study, only the mean values of pressure, flow rate and velocity is important to calculate the orifice coefficients.

Table 1: Signals acquired on the water jet plant of the Non Conventional Production Technologies Laboratory of the Politecnico di Milano with the employed sensors

| Signal | Sensors |
|---|---|
| water pressure | Intersonde; HP-48 (500 MPa; 0-10 V) |
| water volume flow rate | Kobold; DPM 1550 G2 L343 (0.05-5 l/min; 4-20 mA) |
| water velocity | Self produced LDV system [3,7] |

According to the procedure explained in the previous paragraph, $C_d$ is calculated by equations (4), (10) and

(11), $C_v$ is calculated by equations (2) and (3), $\psi$ is calculated by equations (4) and (5) and $C_c$ is calculated by equation (9) knowing the value of the other coefficients.
The measuring activity has been performed by a DSP-based system that acquires the output of sensors and the conditioned signals. An Analog-to-Digital Converter (ADC), 8 differential input channels or 16 single-ended input channel, with simultaneous sampling up to 200 kHz sampling rate on a single channel, ±10 V range, 16-bit resolution and offset, gain and non-linearity error in the range ±½ LSB, is employed.
Among the employed sensors, the Laser Doppler Velocimeter (LDV) is worth further explanations since it has been targeted by the authors to this specific application by means of non standard characteristics [3,7].
The LDV employs a non-invasive technique that consists in creating a pattern of light fringes by means of the interference between two laser beams (Figure 2), at the same wavelength $\lambda$, colliding at an angle $\alpha$ [8]. The period of the fringe pattern is $\delta=\lambda/[2\sin(\alpha/2)]$. When small particles suspended in fluid or water droplets pass through the pattern, they provide a diffused light which exhibits an amplitude modulation at a frequency $f$, simply depending on the speed $V$ of the particles and fringe spacing $\delta$ : $f=V/\delta$. In order to optimize the optical detector, an aspherical lens (condenser) with diameter 4 cm and focal length 2.2 cm is used to collect the diffused light. This lens focuses the image of the water jet illuminated by the laser to the large-area photodiode (5 $mm^2$). In order to better optimize the system alignment, maximising the received signal, the photodetector is mounted on a 3-axis micrometric translator stage, as depicted in Figure 3.

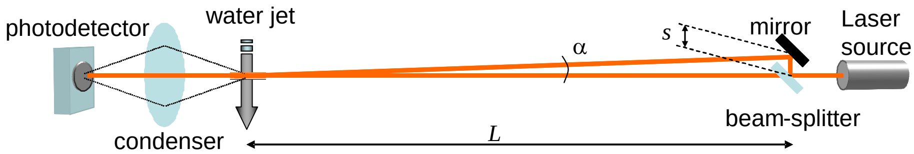

Figure 2 – Scheme of the LDV system

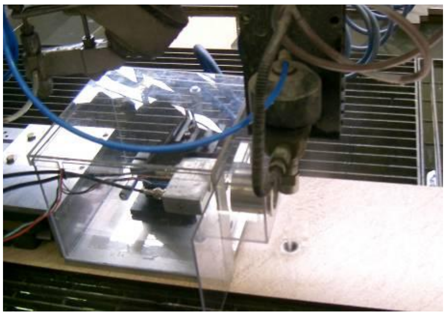
Figure 3 - Photography of the optical detector for the LDV system

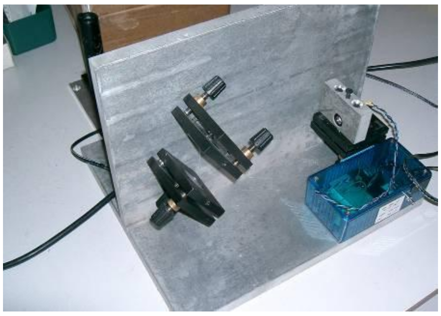
Figure 4 - Photography of the optical source for the LDV system

For protecting the photodetector and the lens from the water jet and especially from the abrasive, the whole system is enclosed in a transparent box under pressure, with air flows in front of the lens, acting as a shield from splashes (Figure 3). The bandwidth of the transimpedance amplifier is 35 MHz.
In order to obtain an optical signal with frequencies below 20 MHz, we decided to implement a very-low angle $\alpha < 1°$, by means of a long distance $L$ = 286 cm between the twin-beam laser source and the water jet. The two laser beams are obtained with a 50 % beam splitter and a mirror, placed at an optical-path distance $s$ = 3.5 cm. The laser source is a low-cost collimated semiconductor laser diode, emitting 70 mW optical power at a wavelength $\lambda$ = 787 nm. The Figure 4 shows the implementation of the mounting for the laser source and the beam-splitter. The period of the resulting fringe pattern is $\delta=\lambda/[2\sin(\alpha/2)] \cong \lambda L/s \cong 64$ µm, therefore the sensitivity of this measurement setup, defined as the ratio between the output frequency $f$ and the water speed $V$, is given by $S = f/V = 1/\delta \cong 15.6$ kHz/(m/s). The signal of the photodetector is acquired by a digital oscilloscope, and the measured data are transmitted via GPIB to a PC by means of a custom LabVIEW program, also taking the FFT of the signal, and plotting the fluid speed distribution after an averaging process applied to 10 time windows. The Figure 5 shows two measurements, at different pressures (200 MPa and 365 MPa), made with a standard diamond orifice (diameter: 0.15 mm).
The employed LDV system has been recently improved with a new set-up procedure able to improve its repeatability by means of the acquisition, thanks to a CCD camera, of the fringe pattern produced in the measurement volume [7]: the direct knowledge of the fringe distance allows to reduce the variability of the set-up operations and so the variability of the velocity measurements; this fact allows to carry out more accurate comparisons between different velocity acquisitions, as in the case of the present paper.

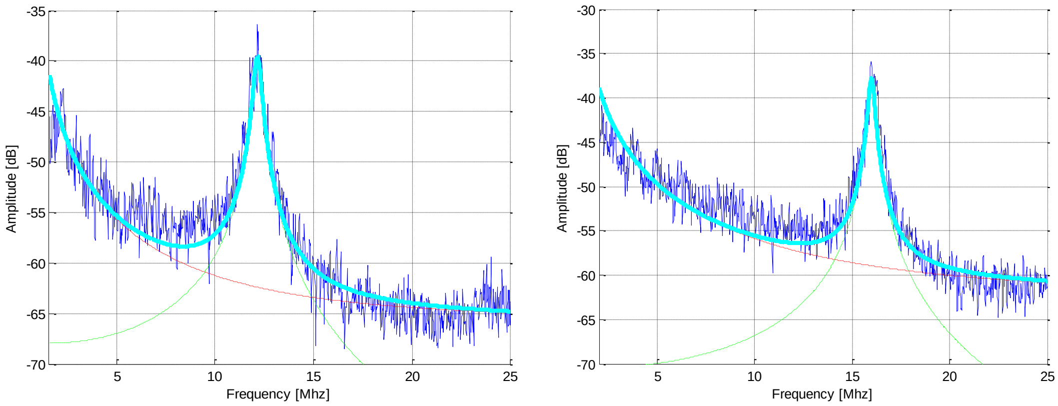


Figure 5 – Spectra of the acquired LDV signals, for 200 MPa and 365 MPa, with peak velocity equal to 610 m/s and 825 m/s. The figures also show the background noise fitting and the lorentzian-shape velocity distribution.

## IV. Experimental Results

An experimental plan has been performed in order to evaluate the orifice coefficients for two different orifice diameters, 0.20 and 0.30 mm, at two different water pressure values (200 MPa and 300 MPa); a representative manufacturer (called “A” in the following) has been selected as provider of all the orifices tested according to this plan. Each experimental condition has been repeated three times in a random order mounting a new orifice at each run (a total of 12 orifices have been tested).

A time window of five minutes has been acquired for the water pressure and water volume flow rate signals at each run; during each this acquisition, three water velocities have been carried out by means of the LDV system. The mean values of water pressure and water volume flow rate over the acquired time window have been calculated for the determination of the orifice coefficients at each run; the mean value of the acquired water velocities has been considered for the same purpose.

The mean values and standard deviations of the indexes $C_d$, $C_v$, $C_c$ and $\psi$ calculated on the three replications of each experimental condition of the carried out plan are reported in the Table 2.

Table 2: Coefficients for manufacturer A orifices

| **Experimental conditions (A orifices)** | $C_d$ | | $\psi$ | $C_v$ | | $C_c$ | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **St. Dev.** | | **Mean** | **St. Dev.** | **Mean** | **St. Dev.** |
| 0.20 mm @ 200 MPa | 0.74 | 0.02 | 0.98 | 0.99 | 0.01 | 0.76 | 0.02 |
| 0.20 mm @ 300 MPa | 0.72 | 0.01 | 0.97 | 0.99 | < 0.01 | 0.75 | 0.01 |
| 0.30 mm @ 200 MPa | 0.74 | < 0.01 | 0.98 | 0.97 | 0.01 | 0.78 | < 0.01 |
| 0.30 mm @ 300 MPa | 0.72 | < 0.01 | 0.97 | 0.97 | < 0.01 | 0.77 | < 0.01 |

The sensitivity of the orifice coefficients to different working conditions has been tested comparing the results obtained for A orifices to the performance of different orifices:

- orifices with the same nominal diameter of A orifices but provided by a different manufacturer (called “B” in the following)
- B broken orifices

The analysis about type B orifices is reported in the Table 3 and 4.

Table 3: Coefficients for manufacturer B orifices

| **Experimental conditions (B orifices)** | $C_d$ | | $\psi$ | $C_v$ | | $C_c$ | |
|---|---|---|---|---|---|---|---|
| | **Mean** | **St. Dev.** | | **Mean** | **St. Dev.** | **Mean** | **St. Dev.** |
| 0.20 mm @ 200 MPa | 0.73 | - | 0.98 | 0.99 | - | 0.75 | - |
| 0.20 mm @ 300 MPa | 0.72 | - | 0.97 | 0.99 | - | 0.75 | - |
| 0.30 mm @ 200 MPa | 0.67 | < 0.01 | 0.98 | 0.98 | < 0.01 | 0.70 | < 0.01 |
| 0.30 mm @ 300 MPa | 0.68 | < 0.01 | 0.97 | 0.97 | < 0.01 | 0.72 | < 0.01 |

Table 4: Coefficients for manufacturer B broken orifices

| **Experimental conditions (B broken orifices)** | **Mean $C_d$** | $\psi$ | **Mean $C_v$** | **Mean $C_c$** |
|---|---|---|---|---|
| 0.30 mm @ 200 MPa | 0.72 | 0.98 | 0.89 | 0.82 |
| 0.30 mm @ 300 MPa | 0.70 | 0.97 | 0.93 | 0.78 |

The experimental conditions regarding B orifices where standard deviation is not indicated were repeated only one time; other conditions were repeated two times.

## IV. Discussion

Results are compared basing on the orifice coefficients mean values, considering the standard deviation as a parameter to evaluate the magnitude of differences. Comparing the results obtained by A and B orifices at a diameter of 0.30 mm, it is possible to notice that the efficiency, evaluated in terms of the $C_v$ coefficient both at 200 MPa and 300 MPa, is similar. The differences in terms of the $C_d$ coefficient, i.e. in terms of effectiveness, can be related to different $C_c$ values. B orifices at 0.30 mm could be considered less effective at both pressures because they discharge less water flow rate and the flow rate is directly related to the mass removal rate on the workpiece; this fact is due to their $C_c$, indicating how their *vena contracta* is smaller than in case of A orifices. The low values of Cc also indicate how the jet could be more focused in case of B orifices: this characteristic can be useful in case of fine cuts without abrasive, even if they are usually carried out with smaller orifices. Results obtained for 0.20 mm orifices indicate how performances are very similar for A and B orifices. Comparing the results for B orifices in normal (Table 3) and broken (Table 4) conditions, we can observe that the capability to discharge water flow rate increases (the $C_d$ coefficient improve its value from 0.67 to 0.72 @ 200 MPa and from 0.68 to 0.70 @ 300 MPa) due to the strong loss of coherence (the $C_c$ coefficient increases from 0.70 to 0.82 @ 200 MPa and from 0.72 to 0.78 @ 300 MPa). The efficiency sensibly reduces for broken orifices, probably due to more turbulence: the $C_v$ coefficient reduces from 0.98 to 0.89 @ 200 MPa and from 0.97 to 0.93 @ 300 MPa.

## V. Conclusions

A complete characterization of orifices behaviour in terms of efficiency and effectiveness has been carried out in this paper thanks to the identification of the orifice coefficients.
The improved capability of the laser Doppler velocimeter employed in this study reduces the measurement variability and allows an accurate comparison of performances among different orifices.
Orifices provided by different manufactures have been tested pointing out how the presented procedure is able to quantitatively determine their different performance. Also in case of broken orifices, measurements seem to be sensible to the different behaviour comparing to unbroken orifices.

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