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Analytical and experimental investigations of the pulsed air–water jet

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ABSTRACT

This paper describes a new way of generating pulsed air–water jet by entraining and mixing air into the cavity of a pulsed water jet nozzle. Based on the theory of hydro-acoustics and fluid dynamics, a theoretical model which describes the frequency characteristic of the pulsed air–water jet is outlined aimed at gaining a better understanding of this nozzle for generating pulses. The calculated result indicates that as the air hold-up increases, the jet oscillation frequency has an abrupt decrease firstly, and then reaches a minimum gradually at α (air hold-up)=0.5, finally it gets increased slightly. Furthermore, a vibration test was conducted to validate the present theoretical result. By this way, the jet oscillation frequency can be obtained by analyzing the vibration acceleration of the equal strength beam affected by the jet impinging. Thereby, it is found that the experimental result shows similar trend with the prediction of the present model. Also, the relationship between vibration acceleration and cavity length for the pulsed water jet follows a similar tendency in accord with the pulsed air–water jet, i.e. there exists a maximum for each curve and the maximum occurs at the ratio of L/d_1 (the ratio of cavity length and upstream nozzle diameter) =2.5 and 2.2, respectively. In addition, experimental results on specimens impinged by the pulsed water jet and pulsed air–water jet show that the erosion depth increases slightly with air addition within a certain range of cavity length. Further, this behavior is very close to the vibration test results. As for erosion volume, the air entrained into the cavity significantly affects the material removal rate.

1. Introduction

The increased erosivity afforded by causing a continuous jet to break up into a series of pulses has long been recognized. At one extreme were the mechanical methods for producing high-energy water pulses repeatedly such as rotating, reciprocating or wobbling mechanisms (Glenn, 1975; Grinspan and Gnanamoorthy, 2010; Dehkhoda and Hood, 2013). Although these devices could drive large scale oscillations of the water flow and improve erosion effect, they required high

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levels of mechanical maintenance and limited durability in harsh industrial environments such as well drilling, tank cleaning, rock-cutting and mud discharge. Also, the complexity and short life-times associated with these mechanical methods has prevented the development of a high-pressure pulsed water jet system. At the other extreme were the high-frequency low-energy pulsed jets formed using an ultrasonic upstream of the nozzle introduced by Vijay et al. (1993). Similar approach was adopted by Foldyna et al. (2004). Between these extremes was the so-called "self-resonating jet" which could be generated by the instability of shearing flow field. Morel (1979) described an experimental study of a Helmholtz resonator driven by a round air jet passing through it. In their research, jet instabilities coupled with the Helmholtz resonance to produce strong oscillation of the air jet. The amplitude of dynamic pressure oscillations reached values of up to 5.6 times the jet dynamic pressure. Simultaneously, the exiting flow pulsated at the same frequency with an amplitude of up to 60 percent of the exit jet velocity. Another oscillating-jet nozzle consisting of a cylindrical chamber, a triangular inlet orifice and an outlet lip was proposed by Lee et al. (2003), it was concluded that the initial spreading angle of the jet flow was much larger than that of a basic turbulent jet flow and favorable for the flame of fuel nozzle. A similar study was done by Mi et al. (2006). Unfortunately, their devices were unsuitable for use as a rock-breaking and rock-cutting. To this end, a nozzle producing self-sustaining oscillations was developed by Schreck and Schaefer (2000) for addressing the above problems, they investigated a geometrically simple but physically still complicated two-dimensional flow that was known for flow asymmetry and self-sustained oscillations. Since it has been thoroughly only investigated experimentally, the further detailed numerical investigations have been performed by Kolsek et al. (2007). Especially the long time behavior of impinging jets has been investigated both in laboratory and in numerical investigations. We (Chuanlin et al., 2011, 2013) have also conducted a study of the effects of structure parameter on the frequency characteristics of a round jet whose precession was generated by a Helmholtz oscillator, there was an optimum cavity length corresponding to the jet dynamic pressure. Such pulsed water jets offered significant advantages, relative to steady-flowing jets, for either cleaning a substance from a substrate or cutting into a bulk material such as a rock.

A new type of pulsed air–water jet, which uses principles of self-resonance to create pressure fluctuations, is now being developed by entraining air into the cavity of the pulsed water jet nozzle. As the work continued, it is noted that there is particular interest in devices which produce oscillating air–water jet generate low pressure loss and have no moving parts, lower cost, non-polluting, simple structure and high reliability.

An early study of air–water jet was performed by Eddingfield and Albrecht (1979), further development of a similar research was done by Momber (2000) focused on its erosion characteristics using concrete as specimen (Its compressive strength is 39 MPa.) Their results showed that the depth of cut was not significantly influenced by the air addition, but the material removal rate became sensitive to the amount of air supplied and came up to a maximum value corresponding to an optimum air flow-rate. Meanwhile, the cracks on concrete surface also extended to a large scale as air was added into the water jet. The air–water jet technology was also applied in oil drilling proposed by Kolle (2002) in American Tempress Company and helped to increase the rate of penetration (ROP) obviously. The extensive experimental work have been done and a new PDC bit was developed by combining the air–water jet nozzle, the associated equipment such as underground supercharger, gas separator and rotor were also developed, but detailed information were not included in his research report as related to the technology secret. Another series of experiments has been conducted by Yahiro and Yoshida (1977) who studied the fluid characteristic of an air–water jet under submerged condition. Moreover, they conducted extensive research work and applied it to a high-pressure chemical churning process, then proposed double and multiple high-pressure chemical churning processes. Currently, these technologies have been widely applied in mine reinforcement, anti-seepage, pier design, ground reinforcement and so on.

The Scientific Research Institute of Former Soviet Union developed a new pulsed air–water jet nozzle comprising two orifice plates and a cavity, the air–water jet through one orifice plate exhibited periodic characteristic because of a continuously reciprocating piston movement in the cavity. In such device, the erosion effect has increased by 27% over the continuous water jet. However, such device may be unsuitable for use in special conditions such as cesspools, corrosive and radio-active liquids because the piston was limited to a relatively narrow range of movement. We also extended their study for high pump pressure where the compressibility of air was taken into consideration and performed a new pulsed air–water jet nozzle which was used to impact the white sand brick. As a result, all of the nozzles, together with entrained air interrupted periodically by a closed-loop control of fluid, have been more erosion performance to be used in engineering applications. Compared with pulsed water jet and continuous jet, the maximal material removal rate of the new nozzle increased 1.5-times and 2.7-times respectively. Also, Dehkhoda et al. (2012) extended the study of the Scientific Research Institute of Former Soviet Union by designing a new driving system of piston. This study has illustrated the mechanism by which high velocity water pulses could be generated using an impacting technique. Although the discharge velocity was significantly affected by the relative sizes of the hammer and piston as well as the height of the water column, the moving parts in this device led to low reliability. Again, Seto et al. (2011) designed an actuator-driven pulsed water jet generator. Results of their experiments, by applying piezo actuator drive the piston, showed that the dissection characteristics of pulsed jet were superior to those of continuous water flows, but the penetration depths were not increased. This phenomenon was of great importance and benefited to damage soft tissues in a controlled fashion for clinical treatments.

The early study shows that the pulsed air–water jet, which has advantages of both pulsed water jet and air–water jet, gives a great potential in cleaning, rust removal and rock-breaking. From the practical point of view, even though the pulsed air–water jet technology are known to be much efficient, less information is available on its velocity profile as well as the structure of this nozzle. Moreover, up to now, only cutting or material removal experiments have been carried out to prove