On the application of gas detonation-driven water jet for material surface treatment process

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Abstract

The recent advances in pulsed waterjet technology create new opportunities for developing green manufacturing process. New methods of generating pulsed water jets in a simple, controlled fashion are sought after to improve the efficiency of current techniques. This paper examines an unconventional concept for producing high-speed liquid jets, created by detonation phenomenon. The technique relies on harnessing the pressure gain from a detonative combustion to drive a piston that in turn propels a liquid jet at high speed. The proof-of-concept, together with recent pulsed detonation engine development, holds promising potential for detonation-driven pulsed water jet generation applied to manufacturing process.

Keywords: Pulsed water jet; detonation; coatings removal; aerospace

1. Introduction

Water jet machining is a well-established manufacturing process for cutting soft or hard materials like metals or stone by adding abrasives to a high speed liquid jet [1]. In recent years, advanced pulsed water jet technology, i.e., using unconventional means of creating water jets in the form of a series of discrete pulses, have been developed as a new green manufacturing process, particularly in the aerospace industry for surface preparation, hard coating removal or peening without damaging the substrate. For instance, demonstration of its potential and tested samples can be found in [2-7]. These pulsed water jets are generated from a continuous water stream through a high pressure pump modulated by ultrasonic vibrations [8, 9] or self-excited oscillations past a cavity [10, 11]. In fact, recent techniques suggest using pulse modulation through pulse multiplication, which relies on hydraulic shocks in order to create a high speed jet [12]. New methods of generating pulsed water jets in a simple and controlled fashion are continuously sought after in order to improve the efficiency and precision of current techniques as well as providing a greener manufacturing platform.

This paper explores an alternative approach using gaseous detonation as the power source for pulsed liquid jet generation. Detonative combustion has been used for some aspects of manufacturing, such as thermal sprayed coatings [13]. In order to create a high-speed liquid jet through detonative combustion, the ignited gas mixture generates a high pressure shock and discrete hammer-like impact action on a plunger, which pressurizes fluid placed within a chamber, expelling it at high velocity through a nozzle. This study examines the feasibility of the proposed gas detonation-driven, pulsed liquid jet generation concept for surface preparation using a simplified modelling approach and assesses the resulting pulsed water jet performance. The analysis describes a simple detonation-driven liquid jet injector and reviews the basic detonation physics and modelling approach. The results of discrete water jet generation and the potential of this proposed technique are also discussed.

2. Modelling and Methods

The proposed detonation-driven water jet device is described schematically in Fig. 1. Initiation of a detonation can be achieved either directly by a high voltage discharge or through the deflagration-to-detonation transition (DDT) from a weak spark [14]. The detonation wave together with a trailing expansion wave propagate into the unburned reactant at a velocity D_{CJ} and eventually impinge upon the piston surface. The impact results in a reflected shock into the combustion product and the high reflected pressure $P_R(t)$ drives the injection piston and pressurizes the water column, which is subsequently ejected through the micro-orifice nozzle as a high-speed jet.

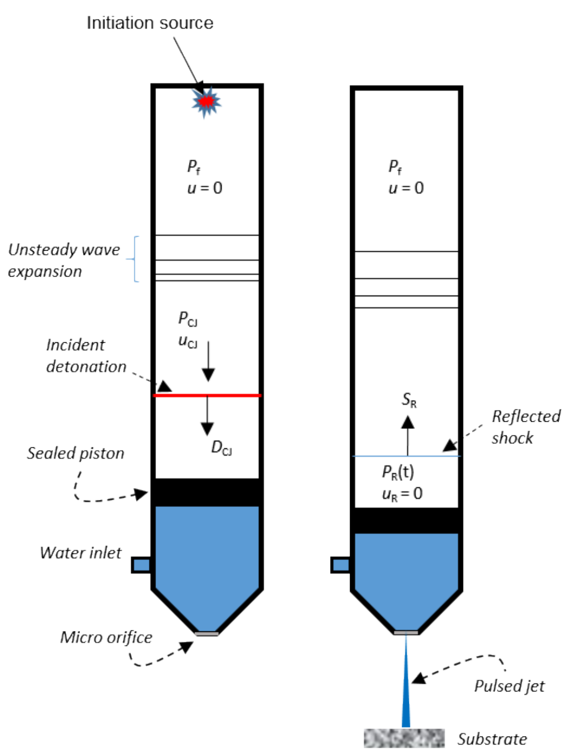


Figure 1. A schematic of the detonation-driven pulsed water jet device

For a given combustible mixture, the detonation propagating speed D_{CJ} and thermodynamic equilibrium states (pressure, sound speed, temperature, etc.) can be analytically obtained. Equilibrium codes such as CEA [15] or CHEMKIN [16] are available for such computations. For the purposes of this study, the commonly used stoichiometric acetylene-oxygen mixture in HVOF and welding initially at standard conditions (P_o = 101 kPa and T_o = 298 K) is considered. The computed average specific heat ratio, detonation velocity, sound speed and pressure behind the detonation wave result in: $\gamma = 1.27$, D_{CJ} = 2,425 m/s, c_{CJ} = 1316.5 m/s and P_{CJ} = 3.432 MPa, respectively. The pressure behind the trailing unsteady expansion wave (or referred to as Taylor wave expansion), can be obtained based on gas dynamics by the isentropic relationships:

$$P_f = P_{CJ}\left(\frac{c_f}{c_{CJ}}\right)^{2\gamma/(\gamma-1)}$$

where the sound speed c_f after the expansion can be determined from the Riemann invariant Γ_- along the C^- characteristics for the detonation:

$$\Gamma_- = u_{CJ} - \frac{2c_{CJ}}{\gamma-1} = -\frac{2c_f}{\gamma-1}$$

where u_{CJ} is the flow velocity immediately behind the detonation. For a steady Chapman-Jouguet (CJ) detonation, i.e., sonic outflow criterion at the equilibrium plane in the wave fixed frame or tangency solution between the Rayleigh line and product Hugoniot) [14], u_{CJ} is equal to the detonation velocity D_{CJ} minus the sound speed at the CJ state, c_{CJ}. Hence:

$$c_f = \frac{\gamma+1}{2}c_{CJ} - \frac{\gamma-1}{2}D_{CJ}$$

When the detonation impinges upon the piston, the reflected shock pressure in the initially stagnated flow (assuming a solid non-moving piston) can be obtained based on the following analytical expression derived from Rankine-Hugoniot equations [17]:

$$\frac{P_{R0}}{P_{CJ}} = \frac{5\gamma + 1 + \sqrt{17\gamma^2 + 2\gamma + 1}}{4\gamma}$$

where P_{CJ} is the CJ detonation pressure, P_{R0} the immediate reflected-detonation shock pressure, γ the ratio of specific heats. Using the simple pressure decay proposed and validated experimentally in [18, 19], the reflected pressure variation driving the injector's piston is given by:

$$P_R(t) = (P_{R0} - P_f)exp\left[-\frac{t}{\tau}\right] + P_f$$

where τ is a time constant fit to experimental data for this exponential decay in pressure. For this study, a value of $\tau \approx 300$ μs is considered [18]. The pressure evolution $P_R(t)$ is plotted in Fig. 2 (a).

A simplified one-dimensional model developed by Baker & Sanders [20] is used to describe the jet formation and performance from the detonation-driven release. Assuming the water is incompressible and performing a mass balance and force analysis on the injector's driver, the jet characteristics as a function of time, i.e., jet stagnation pressure and velocity, can be described by:

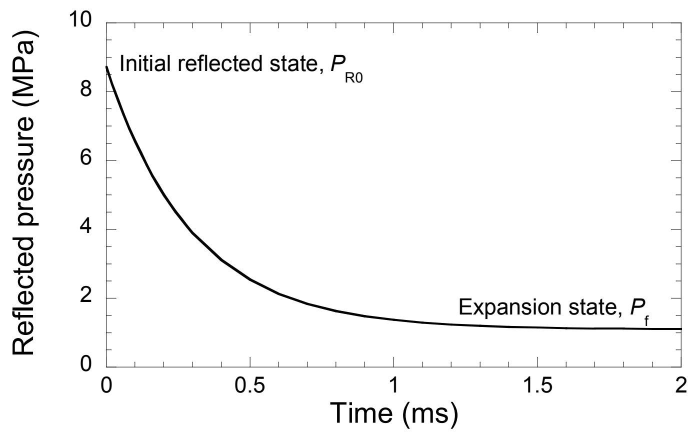
$$\frac{dP_{jet}}{dt} = \frac{(B + P_{jet})\frac{dx_p}{dt} - \frac{BA_o}{A_p}\sqrt{\frac{2P_{jet}}{\rho_o}}}{L - x_p}$$

$$\frac{d^2x_p}{dt^2} = \frac{A_d P_R(t)}{M_p} - \frac{A_p P_{jet}(t)}{M_p} - \frac{F_{O-rings}(t)}{M_p\left|\frac{dx_p}{dt}\right|}\frac{dx_p}{dt}$$

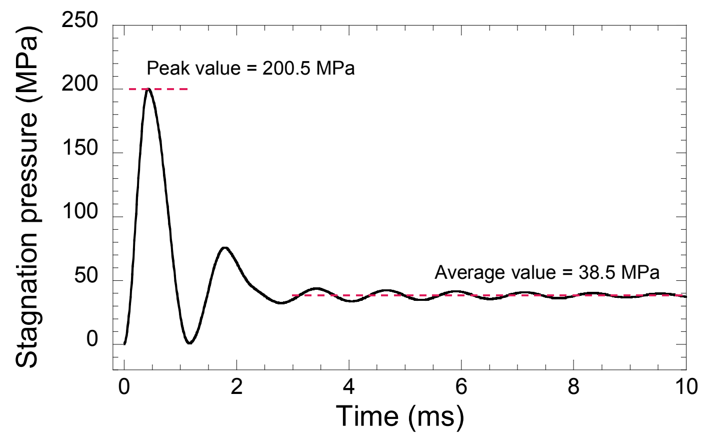
The equation of motion for the piston displacement x_p pressurizing and expelling the water considers the driving force generated by the reflected shock pressure, the fluid pressurization, as well as frictional losses due to the O-ring sealing in the plunger, $F_{O\text{-}rings}(t)$. It must be emphasized that the frictional forces due to O-ring sealing is a complex phenomenon as there are many factors in play that have reciprocal influence and are difficult to model. Although it is possible to replace this term by a detailed description [21], at extreme initial high pressure loading condition, $P_R(t)$, such as what is experienced in the present detonation-driven water injector, it is difficult to establish an exact expression for the level of friction $F_{O\text{-}rings}(t)$ which represents the damping term of the system. In this model $F_{O\text{-}rings}(t)$ is obtained through the following phenomenological approach:

$$F_{O-rings}(t) = F_s \cdot H(t_R - t) + \beta \cdot P_R(t) \cdot (1 - H(t_R - t))$$

where $H(t_R\text{-}t)$ is the Heaviside function and t_R is a time constant chosen to equal 0.44 ms. The frictional force takes on this simple expression with the first term modeling the separation friction F_s which is an initial force that is overcome under the initial high load in order to break static friction and generate piston movement. The second term is required for diminishing friction after the piston reaches the sliding value once static friction is overcome. In the present simulation, values of $F_s = 4{,}400$ and $\beta = 3 \times 10^{-4}$ are used to obtain a realistic trace (e.g., without negative pressure) and qualitatively agree with previous water jet evolution results [22, 23].



(a)

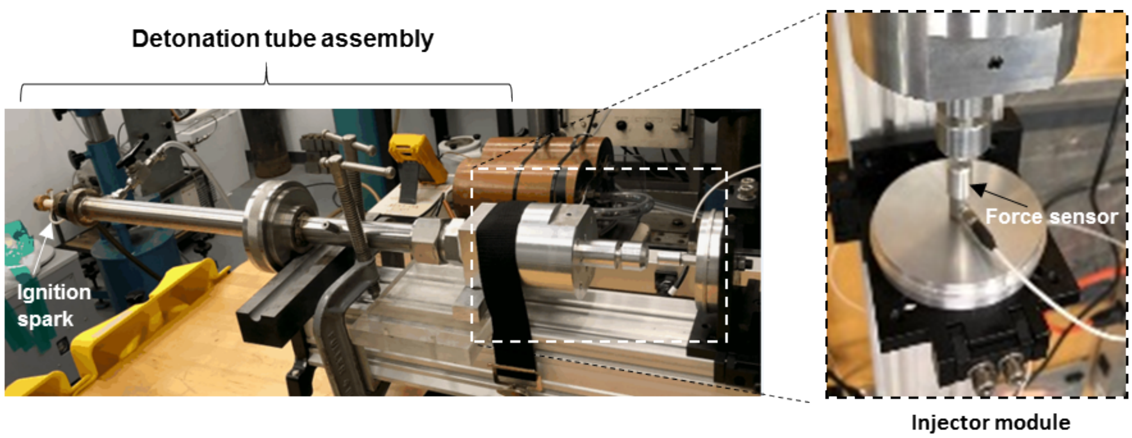


(b)

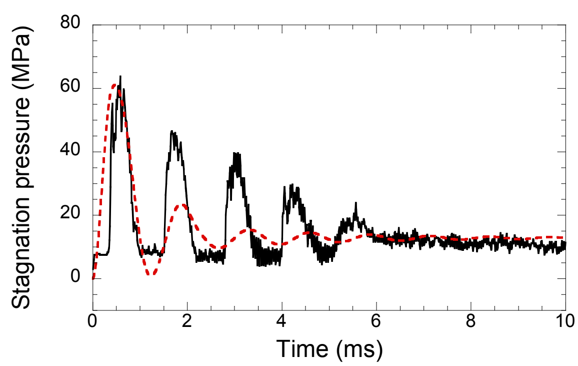
Figure 2. a) The reflected shock pressure evolution for driving the piston; and **b)** the water jet stagnation pressure evolution obtained from the model.

A sample pressure profile obtained from the simplified fluid model is given in Fig. 2 (b). This result is obtained using equivalent properties and physical parameters considered in previous studies [21-23] with a custom-built air-powered and a detonation-driven liquid jet injector prototypes, i.e., water density ρ_o = 1,000 kg/m^3, fluid bulk modulus B = 2.18 x 10^9 N/m^2, piston mass M_p = 150 g, liquid column L = 20 mm, orifice nozzle diameter D_o = 200 μm, piston diameter D_p = 6.35 mm and driver diameter D_d = 44.4 mm. It is important to note that upon the detonation reflection, a peak stagnation pressure can be observed, which subsequently decays and stabilizes around an average value. For a manufacturing process such as surface preparation, coating removal or peening, the resulting peak pressure is advantageous and provides the ability to create a hammer effect resulting in coating breakdown. The average jet pressure, which follows the peak, plays a role in deburring or cleaning the material surface. Current pulsed water jet technologies

(Pratt & Whitney PurePulseTM Waterjet technology [6], automated pulsed waterjet stripping system (APWSS) by VLN Advanced Technologies Inc. [7]) have demonstrated that surface coatings like thermal barrier or hydrophobic coatings can be effectively removed at pulse pressures on the order of 69 MPa. The peak pressure obtained using the proposed detonation-driven injector is of comparable magnitude. It is also worth noting the oscillatory behavior of the pressure evolution depends significantly on the friction damping term. Future work, will focus on fitting experimental pressure traces with their theoretical counterparts in order to provide a more accurate portrayal of the O-ring sealing effect. Secondly, with the high pressure loading due to the detonation reflection at the early stages of the injection process, the fluid can approach the local speed of sound and possibly reach a state of choked flow. In practice, this can affect the piston movement, limit the pressurization and the peak stagnation pressure of the jet. Consequently, future models will need to consider flow compressibility in order to give an accurate description of both peak and average stagnation pressure.



(a)



(b)

Figure 3. a) Pictures showing the current detonation-driven injector setup for low pressure application [23, 24]; and **b)** a comparison between the experimental and modelling results with an initial pressure of 40 kPa.

The current prototype detonation-driven liquid jet injector as shown in Fig. 3 (a) is for low-pressure, biomedical applications, using an acetylene-oxygen mixture with initial pressure up to 60 kPa [23, 24]. It consists of a detonation tube assembly made of a 590-mm long, circular, steel tube with an inner diameter of 26.4 mm. A gaseous detonation wave is initiated at the closed end of the tube via a high-voltage capacitor spark discharge. It continues to propagate throughout the tube until it hits a piston inside the injector module, which has the same dimension described in the model. The resulting impact moves the piston forward and generates a high-speed liquid jet through the orifice/nozzle. The jet pressure is recorded and determined using a PCB Model 209C11 miniature force sensor. The output of the transducer is amplified and gathered using a RIGOL DS1102E oscilloscope with 1G sample/second. A sample experimental output for an initial pressure of 40 kPa is compared with the modeled result, a good agreement can be observed in Fig. 3 (b), particularly, the two critical jet properties, namely, the peak and average stagnation pressure values. As previously noted, due to the simplification of the O-ring seal modelling, there exists a difference in the amount of damping between the experimental measurement and theoretical prediction as it is related to the global system dynamics. The modification and testing of the current setup are on-going, with further add-ons for safety purposes planned in order to increase the viability of the application proposed in this Letter.

For comparison, the peak stagnation pressure obtained from the immediate detonation wave impact P_{R0} and the average stagnation pressure by the final expansion pressure P_f are plotted and correlated (the regression line is forced through zero). The results using a compressed air-powered injector [21] are also plotted and both datasets are in good agreement. Extrapolating the linear fit of all these data points shown by the dashed lines, illustrates that the experimental results at low pressure initial conditions correlate well with the prediction using the present simplified model at the atmospheric condition, i.e., 231 MPa (extrapolated from experiment data) when compared to 200.5 MPa (present modelling shown by the black point) for peak stagnation pressure, see Fig. 4 (a); and 33.8 MPa (extrapolated from experiment data) when compared to 38.5 MPa (present modelling also shown by the black point) for average stagnation pressure, see Fig. 4 (b). The absolute percentage differences are 14% and 13% for peak and average stagnation pressure, respectively. Considering the simplicity of the model and experimental discrepancies, the difference between the extrapolated experimental data and the analytical results are acceptable. Consequently this modeling approach can be used to estimate and optimize the jet performance by changing the combustible mixture conditions, e.g., mixture composition, initial pressure, and physical length scale of the apparatus controlling the reflected pressure decay time constant, τ, for ultrahigh pressure pulsed water jet for manufacturing applications.

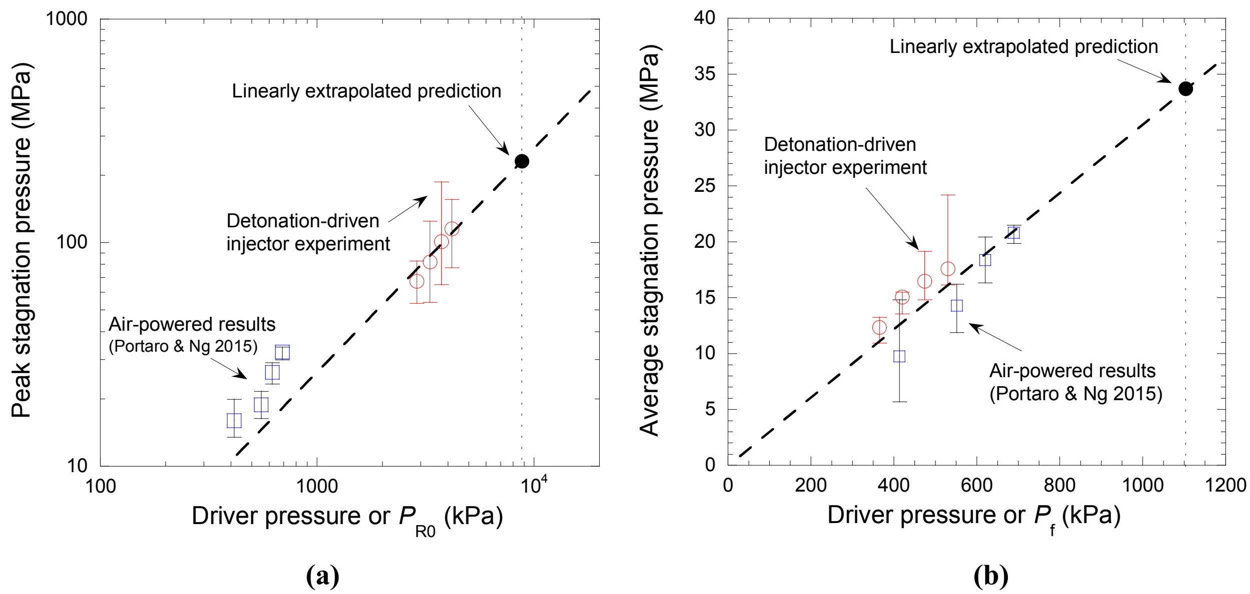


Figure 4. Experimental results of **a)** peak; and **b)** average stagnation jet pressure for low driving pressure experiments from both the air-powered injector [21] and the detonation-driven injector with low initial combustible mixture pressure.

3. Concluding Remarks

Pulsed water jet technology has recently attracted increasing interest as a green manufacturing process which utilizes fluid alone, without abrasives, for coating removal without damaging substrate material. This study utilizes a simplified model in conjunction with available experimental data, to illustrate the application of gas detonation as means of providing a simple and efficient way to generate a high-speed water jet in a controlled manner. The resulting water jet can achieve the same performance and pressure threshold required in current waterjet surface preparation process. It is also worth noting that the present study only examines the water jet formation from one detonation wave interaction. In order to produce a continuous pulsed jet, future studies will focus on integrating current state-of-the-art pulsed detonation wave engine technology, used in aerospace propulsion, whereby pulsed detonation waves can be stably repeated up to 10 Hz [25, 26]. This advanced application can be easily translated to industrial manufacturing. With this power generation concept for forced pulsed waterjet, the next step is to analyze sample substrates resulting from the pulsed water treatment. Apart from the power source, the surface finish quality will also depend on many factors, including the nozzle size, pulse interval and duration, etc.

Acknowledgement

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Figure captions

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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