Experimental investigation and modelling of the gas jet in liquid cross flow

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Abstract. In the present study, the development of a submerged gas jet subjected to liquid cross flow is experimentally and theoretically investigated to evaluate the effects of the cross flow. Experimentally, a submerged gas jet is injected into the liquid flow with different cross velocities (0.35 m/s, 0.7 m/s, 1.0 m/s, 1.5 m/s, 2.0 m/s) created by the newly designed experimental facility. The jet morphologies are captured by shadow photography and the images are processed to extract the parameters of the gas/liquid interface. An integral model including the jet entrainment is proposed to predict the jet evolution. It turns out that the integral model is able to predict the jet development accurately, and an overall good agreement was obtained between the theoretical and experimental results over a range of cross flow velocities.

Key words: submerged gas jet, cross flow, integral model.

1. Introduction
The jet subjected to cross flow has received considerable attention and becomes increasingly significant in many areas of scientific and engineering research, such as air-breathing engine where understanding the break-up of the liquid fuel jet is crucial to improving the engine performance[1-3], and nuclear industry where the postulated core disruptive accident involving the penetration of nuclear fuel vapor jet into cold liquid sodium has potentially disastrous results for the reactor[4], and rocket engine where the thrust vector is controlled by the interaction of the jet plume with the cross flow[5,6]. In recent years, several comprehensive reviews related to the interaction of the jets and cross flow have been presented by Karagozian [7], Getsinger et al. [8], and Broumand and Birouk [9].

In this paper, we focus on a particular flow that has attracted considerably less attention: a gas jet submerged in liquid cross flow. The discrepancy in the density and compressibility between the gas and the liquid makes the interaction process and flow structure between the gas jet and liquid cross flow radically different from the flow with same or similar density and compressibility. There is a large quantity of study on a gas or liquid jet injected into gaseous cross flow, while few researches on the multiphase flow consisting of a gas jet and liquid cross flow have been presented [10-12]. A gas jet submerged in liquid cross flow is complicated by the effects of unsteadies of the pulsatile behavior at the nozzle exit and the impact from the cross flow. In an experimental study Weiland et al.[10] adopted high speed photography and pressure transducers to analyze the effects of the nozzle geometry and the
injection pressure on the gas jet development. They found that the frequency of pressure pulsation reduced with the increase of the injection pressure. Experimental research performed by Dai et al. [11] revealed the flow pattern and hydrodynamic effect of the horizontal gas jets submerged in still water from subsonic and supersonic nozzles. Their results showed that high-speed gaseous jets in still water can induce large pressure pulsations in the upstream of the nozzle exit, which is termed as back-attack, and that the strong hydrodynamic pressure formed by the shock-cell structures in the over- and under-expanded jets was also analyzed. Harby et al. [12] performed experiments on the horizontal gas jets submerged in the liquid, and the results processed by two different methods showed that the penetration length followed a power relationship in the momentum region and approximately a polynomial relationship in the buoyant region. The effects of the Froude number and the nozzle diameter on the unsteadiness of the gas liquid interface and the expansion angle of the gas jet were also studied. A typical development of a gas jet in liquid cross flow is depicted in Figure 1. In the region near the nozzle exit, the gas jet is affected less by the cross flow, and with the evolution of the gas jet the effects from the liquid cross flow become significant.

![Figure 1. Definition sketch and details of a gas jet in liquid cross flow.](image1)

2. Experimental set-up
The experiments were performed in the physical model basin of the marine laboratory in the 713 Research institute of CSIC. The whole experimental system is depicted in Figure 2 consisting of three subsystems: the experimental basin, the movable injector system and the imaging system.

![Figure 2. Schematic diagram of the experimental set-up.](image2)
2.1. Experimental system
The gas-injection system plays the most important role in the present research to perform the experiments. As the subsystem should move stably along the tracks to provide accurate initial gas jet and incoming flow condition. A movable injector system is elaborately designed to meet the experimental requirements. The details of the movable injector system is depicted in Fig. 2 (b). The gas source combined with a gas pressure regulator that is insensitive to back pressure changes in the gas source was adopted to deliver a constant mass flow to the injector. A gas tank in conjunction with an air compressor was designed to supply a 6 m³ reservoir maintaining at the fixed demanded pressure. The pressure and temperature of the gas source were monitored to calculate the mass flow rate delivered to the injector according to the ideal gas equation. In the present experiments, dried air was used as the gas source and the tap water was used as the ambient incoming liquid. An automatic carriage transports instruments beneath the bottom of the basin at speeds ranging from 0.1 m/s to 5 m/s. The injector system is located beneath the bottom of the basin, and the injector penetrates into the basin through a device which can move stably along the bottom centerline of the basin. The details can be found in Figure 2 A Photron FASTCAM APS-RX in conjunction with a Canon lens (EF 24-30 mm, f/ 28L II USM) was installed on the injection system to digitally record images of the test section. The system should move synchronously with the injector system to record the morphology of the gas jet. The height of the camera and the distance from the experimental section can be adjusted according to the experimental situations. The illumination system consisted of a series of 100 W light emitting diode (LED) lights. High-speed videos were recorded with 1024×860 pixel resolution at 200 Hz frame rate and 5 ms exposure time, and all the experiments were recorded for 4 s.

2.2. Experimental test conditions
The ranges of the experimental parameters are listed in Table 1. The independent parameters of the experimental consisted of the free-stream flow speed (i.e. the movable injector system speed), \( U_\infty \), diameters of the gas injection orifice, \( d_N = 12 \) mm, mass flow rate of the jet, \( m_j = 0.165 \) kg/s, static pressure, \( P_s = 1.01 \times 10^5 \) Pa, and the depth of the water, \( h = 10 \) m. The density of the air \( \rho_j \) was equal to 1.2 kg/m³ at the ambient pressure and temperature, and the density of the liquid water \( \rho_w \), was assumed to be constant throughout the experiment and equal to 998 kg/m³. The Mach number was defined in the gas phase only at the exit plane of the nozzle. The pressure before the nozzle is sustained at about 1.26 \( \times 10^6 \) Pa, and the pressure at the nozzle exit was 2.25 \( \times 10^5 \) Pa. The Mach number was about 1.78 with a uncertain of \( \pm 0.02 \) for all the cases. The temperature of the water was sustained at 293 K during the experiments.

3. Experimental results and mathematical model
A series of experiments were performed using the equipment and photographic technique as detailed in section 2 to achieve the morphology and evolution of the gas jet injected into cross flow. The parameters including jet trajectory of each case were extracted from the experimental result processed by a MATLAB program to analyze the characteristic structures of the gas jet. The main steps to process the experimental results can be divided into three steps as shown in Figure 3.

3.1. Experimental results
The experimental results with cross flow velocities ranging from 0.35 m/s to 2 m/s are illustrated in Figure 4. It should be noted that only three sequences (\( U_\infty = 0.35 \) m/s, 1.0 m/s and 2.0 m/s) are shown for the results of \( U_\infty = 0.7 \) m/s and 1.5 m/s are similar to those of 0.35 m/s and 1.0 m/s, respectively, and are omitted here. As the gas jet is injected into a liquid cross flow, the flow structures and the process are essentially unsteady and turbulent. The gas jet evolves accompanied by appreciable fluctuations of the static pressure in the flow passage and the jet boundaries. In the near nozzle exit region, the gas jet is mainly dominated by the gas jet momentum and obvious spreading process occurs. As the gas jet penetrates further, the jet momentum decreases rapidly and the gas jet is dominated by the cross flow and the buoyancy force. For the case with 0.35 m/s cross flow velocity, the gas jet evolves with little
effect from the cross flow for the small magnitude of the velocity, and correspondingly the boundary of the gas jet bends slightly. With the increase of the cross flow velocity, the boundary of the gas jet becomes more curved and more fluctuations appears at the gas liquid interface.

The time and space averaging experimental results from the Matlab program are showed in Figure 5 (only two typical cases of $U_{\infty} = 0.35$ m/s and 2.0 m/s are presented for lack of space). According to Figure 5, the edges of the gas jet become more unstable with the increase of the cross flow velocity. It indicates that the increasing cross flow velocity make the entrainment zone broader in the region dominated by the buoyancy and cross flow, while in the momentum dominant region, the difference is much slighter, and it can be conclude that the effects of the cross flow on the entrainment becomes more important beyond the momentum region.

Figure 3. Steps to process the experimental results, and the case shown is 1.5 m/s.

Figure 4. Experimental results of case submerged gas jet with liquid cross flow velocity (a) 0.35 m/s, (b) 1.0 m/s, (c) 2.0 m/s.
3.2. Mathematical model

The mathematical models to predict the gas jet evolution can be classified mainly into three different categories: integral models, length-scale models, and models that use a combination of both lengthscales and integral techniques. Integral models which are based on the conservation equations of mass, momentum and buoyancy fluxes are the most common ones, and they are widely used in engineering practice for the prediction of characteristics for the buoyant jet discharges. However, few experimental data and calculations on the gas jet with liquid cross flow are presented. In the present study an integral model considering the entrainment and effects from liquid cross flow is proposed to predict the jet development.

As the jet is created by a gas jet mixing with ambient liquid, the gas volume fraction at the beginning of the jet (nozzle exit) is 100%, which then decreases progressively along its trajectory. The jet mass flow rate remain constant for a non-condensable gas, and taking some assumption, the continuity equation for the gas jet in liquid cross flow can be expressed as follows,

\[ 2\pi b \rho_g u_s l_2 \frac{db}{ds} + \pi b^2 \rho_g l_3 \frac{du_s}{ds} = 0 \]  

(1)

In the equation, \( b \), \( \rho_g \) and \( u_s \) are the radius, density and central velocity of the gas jet respectively, and \( l_3 \) is a constant and equals to \((1-e^{-1})\).

A shear layer appears at the gas jet interface when there is large velocity difference between the gas jet and the ambient liquid. The interfacial shear stress (\( \tau_{it} \)) acting at the gas/liquid interface is crucial to determine the gas jet development. Considering the shear stress and the effects from the liquid cross flow, the basic momentum expression of a gas jet element in liquid cross flow in the x-direction can be expressed as:

\[ 2\pi \rho_g u_s b^2 l_2 \cos \theta \frac{du_s}{ds} + 2\pi \rho_g u_s^2 b l_2 \cos \theta \frac{d\theta}{ds} - \pi \rho_g u_s^2 b^2 l_2 \sin \theta \frac{d\theta}{ds} = F_d - \tau_{itx} - M_{dx} \]  

(2)

where \( s \) and \( r \) are the natural system, and \( \theta \) is the angle of the s-axis with the horizontal direction. The parameter \( s \) stands for the distance along the jet center from the nozzle exit. The shear stress in the x-direction \( \tau_{itx} \) can be calculated form the shear stress at the gas/liquid interface \( \tau_{it} \) which can be given by...
\[ \tau_{it} = c_1 \pi \rho_g (u_s b) I_2^{2}(1 + 360 \frac{\delta}{D}) [R_{em}]^{-c_2} \]

where \( c_1 \) is constant and \( R_{em} \) is the jet Reynolds number. According to the work by Wallis[13], the ratio of the shear layer thickness (\( \delta \)) and jet diameter (\( D \)) can be calculated by empirical equation. The effect of the liquid cross flow on the gas jet reflects as flow drag (\( F_d \)), and the flow drag of a gas jet element can be calculated by an empirical relationship. Thus the shear stress in the x-direction is calculated as: \( \tau_{itx} = \tau_{it} \cdot \cos \theta \). For the momentum of the entrainment droplet (\( M_{dt} \)), it is calculated by the empirical equation which is acquired from a large quantity of former experimental research, and the momentum of the entrainment droplet in the x-direction \( M_{dx} = M_{dt} \cdot \cos \theta \).

In the y-direction, the momentum flux increases due to the action of the buoyancy force. Thus the change rate of the y-direction momentum is equal to the buoyancy (\( \pi g b^2 (\rho_a - \rho_g) \)), y-direction shear force (\( \tau_{ity} = \tau_{it} \cdot \sin \theta \)) and entrainment droplet momentum in the y-direction (\( M_{dy} = M_{dt} \cdot \cos \theta \)). The final equation for the change of the vertical momentum gas flux is expressed as:

\[
2\pi \rho_g u_s b^2 I_2 \sin \theta \frac{du_s}{ds} + 2\pi \rho_g u_s^2 b I_2 \sin \theta \frac{d\theta}{ds} + \pi \rho_g u_s b^2 I_2 \cos \theta \frac{d\theta}{ds} = \pi g b^2 (\rho_a - \rho_g) - \tau_{ity} - M_{dy}
\]

Combined with the geometric relationship as follows:

\[
\frac{dx}{ds} = \cos \theta \quad \frac{dy}{ds} = \sin \theta
\]

The system of ODEs consisting of equation (1), (2), (4) and (5) were solved by the 4th order Runge-Kutta method. The comparison between the experimental results and result from the theory model is depicted in Figure 6. From Figure 6, an good agreement is acquired between the experimental result and theory model, it turns out that the integral model predicts the evolution of a gas jet in liquid cross flow well.

![Figure 6. Jet trajectory comparison between the experimental data with the theory model.](image)

4. Conclusion

Appropriate condition was generated by a newly designed experimental method for the study on the submerged gas jet with different cross flow velocities. The interfacial morphology of gas jet were direct measured depended on the results from high speed digital photography. The former researchers mainly focused on the pure buoyant submerged gas jets or the vertical submerged gas jet without liquid cross flow, this work focus on the study of submerged gas jet with liquid cross flow. The comparison results
showed that the integral model can predict the developing of the gas jet rather well in a variety of liquid cross flow velocities. While the effects from the large density variation and high Mach number should be exploit in the future work.

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