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An experimental investigation on the characteristics of submerged horizontal gas jets in liquid ambient

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ABSTRACT

Gas injections into liquid are prevalent in the natural environment and are essential in industrial applications, they can lead to complex flow. The flow structure and processes are essentially unsteady and turbulent. In this study, a set of experiments were carried out to investigate the behavior of horizontal round noncondensing gas jets that discharge in a stagnant water ambient, considering subsonic and sonic jet exit conditions. A flow visualization technique using a CCD camera, which allowed simultaneous measurements, was used to investigate such flows. This technique provided a direct measurement of the interfacial behavior between the gas jet and the liquid ambient. Two different methods, the summation and the statistical one were used to obtain and analyze the experimental results, and we have found that both methods yield almost identical results.

The results showed that the injector diameter and the Froude number play an important role in dictating both the jet pinch-off and the jet interface unsteadiness. The maximum location before the jet pinch-off is shown to have a logarithmic relation with the Froude number for all the jet diameters. The jet penetration length was measured in the momentum and buoyant regimes respectively and it was found to be strongly influenced by the nozzle diameter and the Froude number as well as by the mass and momentum flow rates of the injected jet. Jet spreading which is indicative of liquid entrainment is also shown to increase with the Froude number and the injector diameters. Also it was found that the Froude number plays an important role in dictating the expansion jet angle and the jet half-width. These magnitudes were obtained from recorded time-averaged images and finally empirical correlations have been developed to predict these parameters.

1. Introduction

A buoyant jet can be defined as the fluid motion caused by the sustained injection of a low-density fluid with large momentum through an orifice into a fluid ambient of bigger density. Because of its inherent instability, the jet breaks up into a train of bubbles, either immediately at the nozzle exit or at some distance downstream depending on its initial momentum and the density difference between the two fluids. As the jet penetrates into the liquid ambient, it gradually evolves along a trajectory within it.

The whole gas injection consists of several regions as shown in Fig. 1, a jet region, a transition region, a plume region, a two-phase turbulent zone of gas dispersed in liquid, a liquid recirculating zone, and sloshing waves formed on the surface of the bath when the gas flow rate is high enough. Previous past experimental studies (e.g. [1,2]) suggested that a buoyant jet flow can be divided into three main flow regions, which characterize the development of the gas flow after leaving the nozzle. These flow regions are: (i) the jet like, (ii) the plume like, and (iii) the transition region. In each of these regions the flow is dominated by a group of independent flow parameters, and the overall flow behavior can therefore be described by a sequence of these distinct flow regimes.

In the jet regime region, the discharged flow is mainly governed by the jet momentum force and the self-generated turbulence plays a dominated role in the path of the jet; the gas jet does not disintegrate until it reaches some distance from the nozzle, where the jet breaks up into a column of rising bubbles. In the plume regime region, the flow is chiefly controlled by the buoyancy force and characterized by the production of bubbles that break and rise independently in the direction dictated by gravitational or buoyancy effects. Between the jet and plume regimes, there exists an intermediate regime called transition stage [3]. In the transition stage, the effluent flow is governed by both momentum and buoyancy force and will cause the jet to curve from horizontal to upward direction.

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Nomenclature

b	Jet half width (m)
d_N	Nozzle diameter (m)
Fr_0	Initial Froude number at nozzle exit (–)
L_b	Buoyant jet penetration length (m)
L_m	Momentum jet penetration length (m)
L_Q	Geometric length, $\sqrt{A_N}$ (m)
M_0	Jet momentum flow rate at the injector exit (N)
u_0	Initial jet velocity at the nozzle exit (m/s)
x_p	Maximum axial distance before pinch-off (m)

The study of high speed fluid flowing from an orifice into quiescent fluid, defined as a jet, is a classic subject in fluid mechanics. Helmholtz [4], Kelvin [5], and Rayleigh [6] were among the first who studied this problem. Although the literature contains a large body of works on single phase jets ([7,8]) such as a water jet in a water environment, there is relatively little work on the behavior of submerged gas jets injected horizontally in water ambient. One important difference between injection of a gas jet into a liquid and the baseline case of a gas jet into a gas is the characteristic unsteadiness associated with gas injection into liquids. When the gas jets enter the liquid, initially, the pressure of the gas is not high enough to overcome the inertia effect of the water due to the large density ratio of both fluids. Therefore large pressure pulsations in the surrounding liquid upstream of the nozzle exit will form behind the nozzle exit. This pressure will accumulate and keep increasing, and once it is high enough to overcome the pressure of the water, the gas can expand freely to complete the expansion process.

While the structure and stability of single phase jets have been studied for quite some time, multiphase systems formed by a gas jet submerged in liquid are infrequently studied [9]. Also, gas jets submerged into liquids are complicated by effects of unsteadiness at low flow rates, similar to the pulsatile behavior of highly-buoyant single-phase flows. This involves oscillatory release of gas which can cause liquid to slug into the jet passage. In an experimental study on the gas jets, Hoefele and Brimacombe [10] carried out high speed photography and pressure measurement of gas discharging into liquids. Both straight and convergent-divergent nozzles were used. They found that as the gas injection pressure increased; the rate of pressure pulsation was reduced, which had undergone a flow transition from bubbling to jetting.

Lin [11] showed that increasing density ratios (ρ/ρ_a) also yielded a less stable discharge. Another feature of multiphase jets involves the highly nonlinear variation of the two-phase acoustic velocity (noted by Semanov and Kosterin [12] and Wallis [13]) which probably affects the gas dynamic processes for air injection into water. However, the unsteadiness and turbulence together with the large density ratio across the interfaces lead to difficulties in the experimental measurements and numerical approaches, and hence it remains challenging to measure and investigate the flow structures with numerical methods.

Dai et al. [14] performed experiments to display the flow pattern and hydrodynamic effect of underwater gaseous jets from sonic and supersonic nozzles experimentally. Their results show that high-speed gaseous jets in stagnant water can induce large pressure pulsations in the upstream of the nozzle exit, and that the shock-cell structures in the over- and under-expanded jets can lead to a strong hydrodynamic pressure. Wang et al. [15] observed the back-attack phenomenon of the jet process experimentally under supersonic conditions. These experimental findings indicated that the distortion of the gaseous jet could induce a strong pressure pulse behind the nozzle exit. Shi et al. [16,17] noticed that the process of supersonic air jets into water causes large flow oscillation, which can be related to shock waves reflecting in the gas phase.

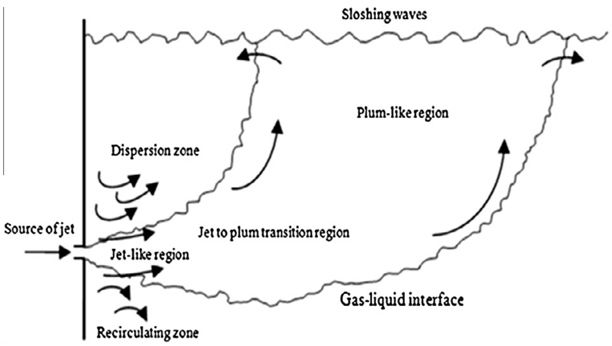

Fig. 1. Submerged gas jet into a liquid ambient.

The jet penetration distance is defined as the maximum length along the jet centerline, and it is governed by several parameters, such as the diameter of the nozzle, the water depth, and the jet mass flow rate. The jet penetration length in the water ambient is pulsated and the penetration distance varies in time along the jet axis. Several previous works have measured the penetration distance of submerged round gas jets using electro resistive or optical probes lowered into the water and traversed through space [18–20]. They used this method to determine what they called gas holdup, which is a statistical mapping of how far gas penetrates into the surrounding water. If water was present at the measurement point an electrical circuit was completed and registered a value of 1 and if gas was present a value of 0 was recorded. By summing up all of these values in time for a given point the time fraction of gas penetration at that point was calculated. Other researchers measured the jet penetration distance by means of a simple rule fixed on the tank wall. The most widely used technique is the direct visualization technique. Their use usually involves the utilization of a camera which resort to Charge-Coupled Device (CCD) and lighting systems based on solid-state and stroboscopic light sources. Helmholtz [4] have investigated the dynamics of a gas jet discharging horizontally into liquids over a wide range of gas flow rates. They have found that flow regimes and penetration distance depend both on the Froude number and the density ratio ρ_g/ρ_a.

Due to its momentum, the jet entrains ambient fluid from outside of the jet boundary into the main turbulent stream thus increasing the volume flux of the jet. The mixing results in a change in both the jet velocity and its width.

Christopher [21] investigated experimentally the submerged high speed gas jets in water ambient, ranging from subsonic to supersonic Mach numbers, using the photographic technique with a CCD camera. The experimental results showed that the jet penetration distance increases linearly when the Mach number increases, and the jet spreading rate is a function of both: the Mach number and the injector diameter. Increasing injector aspect ratio and Mach number increases the spreading rate in a nonlinear form. Also he studied experimentally the phenomenon of the gas jet pinch-off produced by rectangular submerged nozzles in a water and he showed that the number of pinch-off events de-