An entrained Droplet by an underexpanded gas jet into water

Satoshi Someya¹, Yanrong Li², Koji Okamoto³

¹: Graduate School of Frontier Science, The University of Tokyo, Kashiwa & Energy Technology Research Institutes of AIST, Tsukuba, Japan, some@k.u-tokyo.ac.jp
²: Graduate School of Frontier Science, The University of Tokyo, Kashiwa, Japan, yanrong@vis.k.u-tokyo.ac.jp
³: Graduate School of Frontier Science, The University of Tokyo, Kashiwa, Japan, okamoto@k.u-tokyo.ac.jp

Abstract

When a heat exchanger in a Fast Breeder Reactor cracks, highly pressurized water or steam escapes into the surrounding liquid sodium. A sodium-water reaction then occurs, forming disodium oxide (and hydrogen gas). It can cause secondary damages to the heat exchangers by the reaction heat and erosion corrosion. The released flow of steam from the cracks of the heat exchanger is an underexpanded jet because the ambient pressure outside the tubes is lower than the critical pressure. When the pressure of a jet released at high pressure cannot be reduced to the low pressure of the ambient fluid, the flow is said to be underexpanded. Because this expansion causes a reduction of pressure and the pressure is lower than the critical pressure, the velocity of the flow can reach supersonic speed. Several studies have examined the underexpansion of the gas-gas phase. However, there have been few studies on the underexpansion of gas-liquid two-phase flows. The flow characteristics of the gas-liquid two-phase flow differ from the gas-gas flow because breakups of the bubbles appear in the gas-liquid two-phase flow. Therefore, in this study qualitative measurement was carried out for the purpose of revealing the flow with the underexpanded gas jet injected into water.

The gas jet distance L and the expansion angle $\theta$ were then obtained from averaged image of a high-speed camera. L and $\theta$ increased approximately linearly with increasing pressure. The entrainment velocity and the velocity of entrained water droplets into the gas jet were obtained by PIV. Images of unstable expansion near the jet nozzle were captured for the first time.

1. Introduction

It is important to understand the reaction between sodium and water in order to achieve safe steam-generator designs for Fast Breeder Reactors (FBRs). If cracks occur in the heat exchanger in such a FBR, highly pressurized water or steam can escape into the surrounding liquid sodium. An explosive reaction between sodium and water can then occur, generating a large amount of heat, and forming sodium hydroxide and hydrogen gas [1-3]. This sodium hydroxide may corrode the surfaces of metal tubes, and the hydrogen gas can cause an increase in pressure in surrounding systems. In addition, the reaction heat can cause an increase in the temperature of the metal tubes and a decrease in their strength. The mixed gas-solid jet can also cause damage to surrounding tubes through erosion and corrosion, a phenomenon known as wastage. Another phenomenon referred to as overheating rupture can lead to the deterioration of materials due to the reaction heat. All of these effects can lead to secondary failures of the heat exchangers.

The released flow of steam from the cracks of the heat exchanger is an underexpanded jet because the ambient pressure outside the tubes is lower than the critical pressure. When the high pressure of the jet cannot be reduced to the lower pressure of the ambient fluid, the flow is said to be underexpanded and it can attain supersonic velocities. Thus, in order to understand the sodium-water reaction, it is important to investigate the gas jet expansion into the liquid medium. In addition, with respect to erosion-corrosion effects, it should be clarified whether or not small liquid droplets and reaction product can be entrained into an underexpanded gas jet. It is also important to estimate the velocity of such entrained droplets.

Many numerical and experimental studies have examined the underexpansion of a gas jet into a gas phase. The Schlieren measurement technique has been widely applied in experiments [4, 5]. Nouri
et al. [6] also investigated gas-gas underexpanded jets using a shadowgraph and a laser Doppler velocimeter. They mentioned that entrained droplets were observed but did not study them in detail. Kitade et al. [7] performed a detailed study of steady free and impinged jets of highly pressurized vapor. They investigated the underexpansions of free gas jets for stagnation pressures in the range 0.98–3.92 MPa, and observed typical underexpanded gas jet behavior with mach disks. Kihm et al. [8] focused on droplets in an air blast atomizer, which were entrained by an underexpanded gas jet flowing into atmosphere. They performed experiments at stagnation pressures of 0.168–0.372 MPa, some of which were carried out under underexpansion conditions. By using a Rayleigh scattering technique, Kihm et al. [8] observed that clustered vapor molecules in the Rayleigh range were entrained by a gas jet with a condensation during isentropic gas expansion. They also took photographs of relatively large spray droplets and, although they did not mention the droplet velocity, these images showed that underexpansion reduced the likelihood of droplet coalescence compared to overexpansion.

There have been several numerical studies on the underexpansion of gas-liquid two-phase flows under high pressure conditions. The flow characteristics of gas-liquid two-phase flow differ from those of gas-gas flow because bubble breakup occurs in the former case. Epstein et al. [2] and Takata et al. [3] carried out numerical studies on the underexpansion of gas-liquid two-phase flows. However, Epstein et al. [2] did not take the effects of entrained droplets into consideration. They also did not deal with the entrainment of the surrounding fluid, flow fluctuations or chemical reactions occurring during the underexpansion. Takata et al. [3] also failed to consider entrained droplets.

On the other hand, there have been few experimental studies. Chun et al. [9] and Loth et al. [10] performed experiments on underexpanded free gas jet flow into water. Chun et al. [9] focused on the condensation of a steam jet into water at different temperatures. Loth et al. [10] reported the structure and mixing properties of underexpanded round turbulent air jets submerged in quiescent water at relatively low pressures. They measured the static pressure distributions along the jet axis, void fraction distributions and entrainment rates.

However, there have been few studies dealing with the flow of underexpanded gas jets into water at high pressures, in relation to the failure of a steam generator in a FBR. There is still very little experimental data that could be used to verify the results of numerical studies. In addition, there are no reports concerning the velocity of entrained droplets. Therefore, in the present study, as a preliminary step towards clarifying the flow of an underexpanded gas jet injected into water, flow visualization was performed using a high-speed camera, and the behavior of the underexpanded jet was investigated at different high-pressure conditions. In these experiments, the gas-jet expansion angle and maximum length, the entrainment velocity of the surrounding water and the entrained droplet velocity were measured.

![Fig. 1 Experimental apparatus](image-url)
2. Experiments

2.1 Experimental apparatus

Figure 1 shows a schematic of the experimental apparatus. A jet nozzle was attached to the surface of the front observation wall of an acrylic water tank filled with water. The width and the height of the tank were 700 and 400 mm, respectively. The depth of water was fixed at 300 mm. The jet nozzle had an inner diameter of 1.0 mm and an outer diameter of 1.6 mm. Nitrogen gas was injected into the water from the jet nozzle through a solenoid valve. The gas jet imitates the steam released into the liquid sodium coolant in a FBR, and it was injected along the surface of the front wall for purposes of visualization. The behavior of the gas jet was visualized using a high-speed camera (Photron, FASTCAM SA1.1). The pressure and temperature in the tube near the nozzle exit were measured by a pressure gauge and a T-type thermocouple, respectively, which were placed upstream at a location 125 mm from the jet nozzle exit. The accuracies of the pressure gauge and the thermocouple were higher than ±0.01 MPa and ±0.1°C, respectively. A buffer tank (SUS304, 50 cm³) was placed in front of the solenoid valve in order to reduce pressure loss and fluctuation. The length of the tube from the solenoid valve to the position of the thermocouple was 500 mm. A temperature decrease was expected to occur due to expansion in the tube. However, the temperature change of the gas in the tube was found to be negligibly small. This is attributed to the fact that the inner diameter of the tube and the volume of consumed gas were too small to cause any appreciable change in temperature.

The depth of the water was 150 mm from the jet nozzle to the water surface, and the water temperature was 27.6°C during the experiment. Experiments were carried out at stagnation pressures \( p_0 \) of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, and 8.0 MPa. The stagnation pressure was determined by a pressure gauge mounted to the buffer tank. Images were taken at each stagnation pressure.

The camera began to record images at the moment the solenoid valve was opened, synchronized by a TTL pulse trigger. The width of the trigger also controlled the open time of the solenoid valve, which was fixed to 500 ms. The solenoid valve had a certain time delay, opening about 1.5~2.1 ms after receiving the trigger signal. Thus, the camera started to record images just before the valve opened.

Two kinds of experiment were performed, the first to determine the shape of the gas jet, and the second to measure the entrainment velocity of the ambient fluid and the velocity of the entrained droplets, using particle image velocimetry (PIV) on fluorescent particles added to the fluid.

2.2 Experiment 1

The configuration (shape) of the underexpanded gas jet at high pressure was measured in this experiment. The gas jet length and the expansion angle were analyzed from temporally-averaged images of the gas jet. Lighting was supplied by three metal halide lamps placed laterally from the upstream side of the gas jet in order to reduce reflections. Wide-area images were first captured, with a frame rate of 500 frames per second (fps) and a spatial resolution of 1024×1024 pixel² (394×394 mm²). These images of the complete gas jet were temporally averaged and were used to determine the gas jet length. In addition, images focusing on an area near the nozzle were captured in order to obtain the expansion angle of the gas jet. For these measurements, the frame rate of the high-speed camera was set at 40,000 fps, and the resolution was 512×256 pixel² (17.0×8.5 mm²). Images were processed in the manner described above and the expansion angle of the gas jet was determined from the processed images.

2.3 Experiment 2

This experiment was carried out to investigate the entrainment effects of the gas jet. As shown in Fig. 1, a sheet of laser light was injected from the bottom of the tank, across the center of the jet exit nozzle, and tracer fluorescent particles were mixed into the water for PIV measurements. The light source was a Nd:YLF double-pulsed laser (Pegasus-PIV, New Wave Research Inc.). The output power of each laser head was about 8 W. An optical high-pass filter was placed in front of the
camera lens in order to cut out reflected and scattered excitation light at 527 nm, so that images of the fluorescent particles alone appeared. In this way, the flow patterns in the liquid phase in and around the gas jet could be visualized. The frame rate of the camera was 4,000 fps, and the spatial resolution was 1024×1024 pixel² (36.6×36.6 mm²). The frame straddling technique was performed with an excitation time interval, $\Delta t = 50 \mu$s. Thus, image groups were obtained for $\Delta t = 50 \mu$s and $\Delta t = 450 \mu$s. The entrainment velocity of the surrounding water was determined by PIV using image pairs from the $\Delta t = 450 \mu$s group alone. This was because the displacement of the particles in the surrounding water was too small to analyze the entrainment velocity for the $\Delta t = 50 \mu$s group. However, this image group was used to determine the velocity of the entrained water droplets.

2.4 Critical Pressure
In the present study, the stagnation pressure was varied as a parameter in the experiments. However, the critical pressure is the actual delivery pressure at the jet nozzle exit because the ambient pressure is lower than the critical pressure. The critical pressure is a function of the stagnation pressure and the specific heat ratio, when a steady isentropic flow is assumed in the region from the stagnation point to the jet nozzle. The critical pressure ($p_c$) is represented in the following equation:

$$p_c = p_0 \left( \frac{2}{\gamma + 1} \right) \sqrt{\frac{\gamma}{\gamma - 1}}$$  \hspace{1cm} (1)

where $p_0$ is the stagnation pressure and $\gamma (=1.398)$ is the specific heat ratio.

$$v_g = \left( \frac{2 \gamma}{(1+\gamma)} \right)^{1/2} \left( \frac{p_0}{\rho_0} \right)^{1/2}$$  \hspace{1cm} (2)

The velocity of the gas jet at the exit ($v_g$) is represented by Eq. (2), where $\rho_0$ is the density of the gas at the stagnant pressure.

According to Eq. (1), the critical pressure is reduced to 52.9% of the stagnation pressure. The delivery pressure measured 125 mm upstream from the jet nozzle exit and the estimated critical pressure for each stagnation pressure are shown in Fig. 2. As can be seen, the estimated critical pressure and the measured pressure are strongly correlated. The measured delivery pressure was around 56.8% of the stagnant pressure, and was higher than the estimated critical pressure. This was thought to be caused by the distance between the pressure gauge and the nozzle exit and by the presence of higher-density liquid.

![Fig. 2 Critical pressure and delivery pressure](chart.png)

3. Results and Discussion
3.1 Gas jet length
Knowledge of the gas jet length is important when considering a sodium-water reaction and for verifying numerical results. In the present study, the gas jet was ejected horizontally and the resulting gas bubbles rose up due to buoyancy. The gas jet length was defined as the distance along the nozzle centerline from the exit to the point where the sharpest gradient occurred in the intensity
of the temporally-averaged image, and was calculated as follows.

**Step 1** A total of 1000 images of the entire gas jet were recorded at 500 fps, i.e., over a 2 second period, and were temporally averaged. An example of such an averaged image is shown in Fig. 3 for a stagnation pressure of 8.0 MPa.

**Step 2** The position with the largest image-intensity gradient was identified along the nozzle centerline, using the intensities of 5 contiguous pixels.

**Step 3** The gas jet length was calculated as the distance from the nozzle exit to the point found in step 2.

**Step 4** Experiments were performed five times and the obtained values of the gas jet length were averaged. The repeatability error was less than ±2%.

Figure 4 shows the gas jet length as a function of the stagnant pressure. It can be seen that the increase of the gas jet length was approximately linear with the increase in the stagnation pressure.

![Fig. 3 Temporally averaged image of the entire gas jet at 8.0 MPa](image)

![Fig. 4 Gas jet lengths at different pressures](image)

### 3.2 Expansion angle of the gas jet

In a general jet, there is a potential core where the velocity along the centerline of the jet is uniform at the jet exit. Downstream from this potential core, i.e., in the developed region, fully developed turbulent diffusion enhances mixing of the jet. The expansion angle of the jet in the developed region becomes larger than that in the potential core due to this mixing. In the case of underexpanded gas jet flow into air, the jet expands rapidly and widely immediately after ejection, and subsequently undergoes linear expansion. Thus, similar to the potential core and the developed regions in a general jet, underexpanded gas jet flow into the air can be classified [2] into two regions.

Similar behavior was found for underexpanded gas jet flow into water in the present study. We focused on the expansion angle below the centerline of the nozzle for different stagnant pressure conditions. Wide expansion was observed in the region from the jet exit to a position 3 mm downstream. Further downstream, the jet expanded with a narrower angle. Finally, the jet moved upwards due to buoyancy.

Therefore, we define the first wide expansion region as the expansion area and the second region as...
the developed area, as shown in Fig. 5. For all the pressure conditions used in the present study, the expansion area extended about 3 mm from the nozzle exit.

To determine the effect of the stagnation pressure on the expansion angles, images obtained during Experiment 1 (focusing on the area near the nozzle) were analyzed as follows.

**Step 1)** 4000 images recorded at 40000 fps were temporally averaged.

**Step 2)** The gas jet width at each stagnation pressure was obtained in the same manner described in Section 3.1 for the gas jet length. The image-intensity gradient in the region above the centerline was strongly affected not only by jet expansion and development but also by the rising bubbles. Therefore, the expansion angle below the centerline was calculated. Although the jet could still be affected by the buoyancy even in that region, its velocity was quite large and the effect of the buoyancy on the expansion angle seemed small, at least in the upstream region shown in Fig. 5.

**Step 3)** Points with the largest intensity gradient were identified at several horizontal pixel positions, and the expansion angle was determined by linear regression on these points using the least squares method.

![Fig. 5 Expansion area and developed area of the underexpanded gas jet at 8.0 MPa](image)

The relationship between the obtained expansion angle and the pressure is shown in Fig. 6. The expansion angle in the expansion area increased with increasing pressure; however, in the developed area it was fairly constant at around 7°. The expansion angle in the expansion area at 0.5 MPa was similar to that at 1.0 MPa. The angle at 0.5 MPa was thought to be affected by the unstable expansion discussed later in Section 3.3. The fact that the expansion angle of the developed area is independent of pressure agrees well with previously reported results for free jets or wall jets [7, 10, 11]. In Fig. 6, it is compared to reported values for underexpanded gas jet flow into water [10] and symmetrical wall jet flow [11]. Loth et al. [10] estimated this expansion angle by using the void fraction, and their results are also shown in Fig. 6 for void fractions of 0 and 0.5.

If the boundary between the liquid and gas is taken as the region with a void fraction of 0.5, the
results by Loth et al [10] agree well with the present results. Therefore, the use of the gradient of the image intensity seems to be a valid method for evaluating the expansion angle. The expansion angle or the jet width has often been evaluated from the half-width of the velocity distribution in the case of jet flow into gas. In our case, the velocity distribution in the gas jet could not be measured, and so this technique was impractical. However, for reference, the half-width of the velocity distribution for a symmetry wall jet [11] is also shown in Fig. 6.

3.3 Unstable expansion near the nozzle

Unstable expansion was observed near the nozzle exit for a stagnation pressure of 0.5 MPa, but was not obvious for higher stagnation pressures. The instantaneous images shown in Fig. 7 recorded at intervals of 250 µs show this intermittent expansion behavior. At 0.5 MPa, non-periodic expansion occurred at irregular time intervals of 2–5 ms.

Such unstable expansion may have also occurred for other pressures, but no such clear images of this behavior were captured in the experiment. Under high pressure conditions, unstable expansion is believed to occur downstream, where the pressure of the gas jet balances the ambient pressure. The reason why no clear images of this unstable expansion could be captured is thought to be that the expansion was obscured by the upstream flow.

In order to reveal the relationship between the unstable expansion and pressure, the velocity fluctuation near the boundary between the liquid and gas was examined by PIV using the images obtained in Experiment 2 and the turbulence intensity was calculated from the velocity fluctuations. A typical distribution map of turbulence intensity is shown in Fig. 8. The vectors represent the temporally-averaged velocity distribution at a stagnant pressure of 8.0 MPa and the color map shows the turbulence intensity in the horizontal direction. Bright areas correspond to higher turbulence intensity.

When the unstable expansion occurs, the turbulence intensity may become larger. Thus, regions of large turbulence intensity are considered to be undergoing unstable expansion. Therefore, regions undergoing unstable expansion were roughly identified by where the turbulence intensity became larger than a certain threshold value. The threshold value was assumed to be 0.05 m/s in the present
study. The average velocity near the boundary between the jet and the ambient flow was about 0.03 m/s at 0.5 MPa and about 0.15 m/s at 8.0 MPa. The threshold turbulence intensity of 0.05 m/s corresponded to large velocity fluctuations. The distance from the nozzle to where the turbulence intensity became larger than the threshold value is plotted in Fig. 9. The region where the turbulence intensity was studied is from 1 to 4 mm below the centerline, which is below the boundary between the gas jet and the surrounding water, i.e., below the region studied in Section 3.2. The turbulence became large near the nozzle for a pressure of 0.5 MPa.

The unstable fluctuation may affect the upstream flow too, in which case the position shown in Fig. 9 does not represent the position where the unstable expansion actually occurred. However, this may yield important information. Figure 9 indicates that the region where the turbulence intensity became large shifted toward the downstream side. The higher the stagnant pressure was, the farther the region was from the exit. When the stagnant pressure was low, the velocity was small and the boundary between the gas jet and the surrounding water was close to the nozzle (|y| < ±1). However, as shown in Fig. 9, the turbulence intensity became larger upstream at lower pressure. Thus, the results shown in Fig. 9 may be affected by the unstable expansion. This result suggests that the unstable expansion also occurred at other pressures. Under high pressure, the unstable expansion occurred downstream, where the pressure of the gas jet balances the ambient pressure. A phenomenon similar to this unstable expansion has been reported for an underexpanded gas jet by

![Fig. 8 Distribution of the average velocity and the turbulence intensity at 8.0MPa](image)

![Fig. 9 Distance from the nozzle to the point where turbulence intensity became large at different y-positions and at various pressures](image)
Loth et al. [10], although they did not discuss it in detail. They mentioned that large-scale unsteadiness was observed at comparatively low pressure, 10~20 times per second. They also remarked that it might involve random fluctuations of gas release producing mushroom-like gas structures near the exit and the sudden appearance of gas below the passage exit. In the present study, images of this phenomenon were captured and revealed that the unstable expansion occurred even under high-pressure conditions, although the mechanism involved is still unknown.

3.4 Entrainment velocity
The entrainment velocity \( v_e \) is the inflow velocity from the liquid phase to the gas jet. It indicates how much the surrounding water is entrained by the gas jet. In order to determine the amount of water entrained by the gas jet, the entrainment velocity was calculated as follows, using the temporally averaged velocity distribution obtained by PIV (see Fig. 8).

**Step 1)** For all horizontal pixel positions, the maximum vertical velocity components were found. Close to the boundary between the gas jet and the surrounding water, the vertical velocity components became large due to entrainment. After the particles were entrained, the velocity increased drastically and it was impossible to track their movement from image pairs with \( \Delta t = 450 \mu s \). The vertical position where the vertical velocity became largest indicates the boundary position. The extracted vertical positions for each horizontal position coincided with the boundary calculated using the gradient of the image intensity in Section 3.2, for all pressure conditions except 0.5 MPa. Thus, the entrainment angle and the position of the boundary were obtained.

**Step 2)** Then, from the velocity at those positions, the entrainment velocity was calculated as the velocity component perpendicular to the boundary. The calculated velocities in the developed area were almost independent of the distance from the nozzle. As shown in Fig. 5, the developed area relatively close to the nozzle was considered in the present study. The effect of the buoyancy was small due to the large velocity in this area. The entrainment velocity in the expansion area was slightly larger at the point closer to the nozzle. The entrainment velocity in the expansion area and in the developed area were calculated individually as averages of the extracted velocities in each area.

The entrainment velocity averaged in each area for each pressure is summarized in Fig. 10. The higher the pressure was, the larger the entrainment velocity was. Under high-pressure conditions, the entrainment velocity in the expansion area was larger than that in the developed area.

![Fig. 10 Entrainment velocity in the expansion and developed areas](image)
3.5 Velocity of entrained water droplets in the gas jet

When a sodium-water reaction occurs in a steam generator, erosion-corrosion caused by flying caustic reaction products becomes a problem. It is important to know the behavior of such flying reaction products because they can cause secondary damage. The reaction product is generated at the boundary between the liquid (sodium) and the gas (steam), and it is entrained into the gas jet. Therefore, it is important to evaluate the behavior of the droplets entrained by the gas jet. In the present study, a flying water droplet in the gas could be visualized since the droplet includes a fluorescent tracer particle, while there were not so many droplets visualized in the gas. An image of the water droplet entrained by the gas jet is shown in Fig. 11.

The water droplet velocity was estimated from the displacement of the particle in the image pairs ($\Delta t = 50 \mu s$) obtained in Experiment 2. For each pressure condition, the water droplet velocity was obtained as the averaged velocity of 10 droplets. As shown in Fig. 12, the water droplet velocity was around a hundred times as large as the entrainment velocity and was $1/60$ to $1/30$ of the injected velocity of the gas at the exit, and increased with increasing pressure.

![Sample image of an entrained water droplet](image1)

![Averaged velocity of the entrained water droplet](image2)

(left)Fig. 11 Sample image of an entrained water droplet

(right)Fig. 12 Averaged velocity of the entrained water droplet

4. Conclusion

Flow visualization was carried out using a high-speed camera, and the behavior of an underexpanded gas jet flowing into water was investigated. The following results were obtained.

1) The gas jet length and the expansion angle were calculated from the gradient of the image intensity. The gas jet length increased approximately linearly as the stagnation pressure increased. The expansion angle of the expansion area also increased linearly with increasing stagnation pressure. However, the expansion angle of the developed area was almost independent of the stagnation pressure.

2) An unstable expansion was observed near the nozzle exit at a stagnation pressure of 0.5 MPa. Evaluation of the turbulence intensity indicated that this expansion occurred also at other stagnation pressures, though it might have been obscured by the upstream flow.

3) The entrainment velocity was calculated by PIV, and was found to increase with stagnation pressure. The entrainment velocity in the developed area was independent of the distance from the exit. In the expansion area, it was larger than in the developed area, especially under high-pressure conditions.

4) The water droplet velocity was estimated from the particle displacement, which was obtained from the image pairs of $\Delta t = 50 \mu s$ in Experiment 2. It increased with increasing pressure, and was about a hundred times as large as entrainment velocity.
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References


