Experimental Study on Ice Forming Process of Cryogenic Liquid Releasing underwater

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Abstract. Cryogenic liquid releasing into water would be a process combines hyperactive boiling with ice forming. There are still few researches on the experimental study on the environmental conditions for deciding ice forming speed and liquid surviving state. In this paper, to advance our understanding of ice forming deciding factors in the process of LN$_2$ releasing underwater, a visualization experimental system is built. The results show that the pressure difference significantly influences the ice forming speed and liquid surviving distance, which is observed by the experiment and theoretically analysed by Kelvin-Helmholtz instability. Adding nucleating agent is helpful to provide ice nucleus which can accelerate the ice forming speed. Water flowing has some effect on changing pressure difference, which can affect the ice forming speed and liquid surviving distance.

1. Introduction
With the development of energy storage and usage technology, many kinds of cryogenic liquids are seen as clean energy and attract more attention. The Liquefied Natural Gas (LNG) and Liquefied Nitrogen (LN$_2$) are the most representative. As a result of that, how to ensure safety in transportation, storage and usage becomes an essential issue. Most energy transportation is through marine transportation. If the container is damaged, the cryogenic liquid would be released into water. Because of its low temperature property, the water around the leakage hole will become ice in some special conditions.

Shu et al. conducted a series test of draining the near-atmospheric liquid nitrogen directly into near-atmospheric pressure water [1-3]. They found that temperature of water close-by orifice decrease, water froze and the ice layer continually gain in by a period of continued drain time. Some factors of the draining vent conditions that influence the icing state are analysed. But this series test does not analyse the water condition that influences the icing. There are also some experimental studies on explosive boiling of discharging cryogenic liquid into water have been reported [4-8]. The bubble behaviours were analysed and found some characteristics to explain the extremely rapid heat transferring rate of explosive boiling which is beneficial to analyse heat and mass transfer of cryogenic liquid with water.

Although previous studies have provided some experimental and numerical study on cryogenic liquid releasing into water, the water conditions that influence icing speed and liquid surviving distance have not been analysed in detail.

2. Experimental apparatus
As some kinds of cryogenic liquid could be flammable, noxious or mixture, the experimental system should use intrinsically safe protection technology and include some apparatus which can be used to change the cryogenic liquid phase state. As Figure 1 shown, this experimental system consists of heat
exchanger, visualized pressure tank, plugging device, picture acquisition system, vapour recovery tank and water velocity controlling device et al.

![Figure 1. Cryogenic liquid releasing setup and apparatus](image)

1. hazardous liquid storage tank, 2-LN2 storage tank, 3- hazardous liquid outlet valve, 4-self-pressurization regulating valve A, 5- hazardous vapor outlet valve, 6-N2 outlet valve/scavenging valve, 7,12-LN2 outlet valve, 8-self-pressurization regulating valve B, 9-liquid-vapor conversion three-way valve A, 10-precooling three-way valve, 11-heat exchanger, 13-precooling check valve, 14-hazardous liquid/vapor outlet check valve, 15-main liquid/vapor inlet valve, 16-liquid-vapor conversion three-way valve B, 17-liquid flow meter, 18-liquid magnetic inlet valve, 19-one-way cock A, 20-liquid receiving tank, 21-liquid inlet check valve, 22-heating tubes, 23-check valve with flange A, 24-check valve with flange B, 25-pneumatic motor, 26-propeller, 27-high pressure nitrogen gas bottle, 28-charge valve, 29-plugging device, 30-plugging device, 31-water pump, 32-adjustable back pressure valve A, 33-water tank, 34-visualized pressure tank, 35-liquid/vapor three-way outlet valve, 36-gas flow meter, 37-vapor magnetic inlet valve, 38-vapor inlet check valve, 39-adjustable back pressure valve B, 40-adjustable back pressure valve C, 41-one-way cock B, 42-vapor receiving tank, 43-vapor outlet check valve, 44-exhaust main pipe, 45-releasing device, 46-nucleating agent storage tank, 47-one-way cock C, 48-nucleating agent adding injector, 49-adjustable back pressure valve D)

3. Experimental Results
This series test is conducted by using LN2. By controlling the LN2 Dewar liquid outlet pressure and outflow, the different releasing pressures can be adjusted. The phase states of LN2 can be adjusted by controlling gas outlet pressure and flowing rate through the heat exchanger. The water flow direction and velocity can be adjusted by propeller location and rotation speed. Injecting occurring and ending time can be controlled by the plugging device. The leakage hole diameter is 5mm. The parameters for experiments are shown in Table 1~3.

In Table 1, there are some parameters mentioned in this paper. The surviving distance means the distance between leakage hole and cryogenic liquid completely boiling location. The ice blocking time and level respectively means interval time between two consecutively ice blocking process and the blocking effect such as Figure 2 shown.
### Table 1. Experimental run parameters

| Releasing pressure (Bar) | Surviving distance (mm) | Ice blocking time (s) | Ice blocking level |
|-------------------------|-------------------------|-----------------------|--------------------|
|                         | 170 110 20              | 170 110 20            | 170 110 20         |
| 1.0                     | 80 110 100              | 14 16 16              | I I I              |
| 1.5                     | 85 95 100               | 11 14 13              | I I I              |
| 2.0                     | 80 100 115              | 9 12 11               | I I II             |
| 2.5                     | 110 100 110             | 10 10 12              | II II II           |
| 3.0                     | 105 110 110             | 10 11 12              | II II II           |
| 3.5                     | 110 110 115             | 11 11 12              | II III III         |
| 4.0                     | 110 115 120             | 12 12 13              | III III III        |
| 4.5                     | 115 120 120             | 13 14 15              | III III III        |
| 5.0                     | 125 120 120             | 15 14 14              | III III III        |

### Table 2. Experimental run parameters in the condition of adding nucleating agents into water

| Releasing pressure (Bar) | Surviving distance (mm) | Ice blocking time (s) | Ice blocking level |
|-------------------------|-------------------------|-----------------------|--------------------|
|                         |                         | Adding | None | Adding | None | Adding | None |
| 1.0                     | 80                      | 80     | 12   | 14     | 14   | I      | I    |
| 1.5                     | 80                      | 85     | 10   | 11     | 11   | I      | I    |

### Table 3. Experimental run parameters in the condition of water flow

| Releasing pressure (Bar) | Surviving distance (mm) | Ice blocking time (s) | Ice blocking level |
|-------------------------|-------------------------|-----------------------|--------------------|
|                         | Propeller arranging vertically (100rpm) | Propeller arranging horizontally (100rpm) | none |
|                         | Propeller arranging vertically (100rpm) | Propeller arranging horizontally (100rpm) | none |
|                         | Propeller arranging vertically (100rpm) | Propeller arranging horizontally (100rpm) | none |
| 1.0                     | 75 70 80                 | 14 13 14              | I I I              |
| 1.5                     | 80 75 85                 | 11 10 11              | I I I              |
| 2.0                     | 80 75 80                 | 10 9 9               | I I I              |
| 2.5                     | 85 85 110                | 9 9 10               | II I II            |
| 3.0                     | 110 85 105               | 10 10 10             | II II II           |
| 3.5                     | 95 110 110               | 11 10 11             | II II II           |
| 4.0                     | 100 100 110              | 11 11 12             | III III III        |
| 4.5                     | 110 105 115              | 12 13 13             | III III III        |
| 5.0                     | 120 115 125              | 15 14 15             | III III III        |
Figure 2. Schematic diagram of ice blocking level ((a) Level I; (b) Level II; (c) Level III; (d) Ice run)

Figure 3. Surviving distance curve

Figure 4. Ice blocking time curve

4. Discussion

4.1 Effect of releasing pressure
As Table 1 and Figure 3&4 shown, the surviving distance increases sharply under a special releasing pressure. And ice blocking time first decreases and then increases. According to the Kelvin-Helmholtz instability [9-11], if velocity difference across a small amplitude perturbed interface between two fluids is sufficiently large, the interface will be unstable and given rise to break into small droplets, which
enlarge the heat-exchange surface. As a result of that, the heat transfer from water to LN$_2$ will increase. The ice will be easy to form near the leakage hole, which will limit the LN$_2$ further releasing into water. Furthermore, with the releasing pressure further increasing until over 3 bars, the ice cannot completely block the hole for a while, the surviving distance and ice blocking time continuously increases. That is because with the pressure differentials increasing, the ice will be easily washed away from the leakage hole.

Basing on the Kelvin-Helmholtz instability, the most dangerous wavelength is given by:

$$u_c = \frac{|u_{cl} - u_w|}{2\pi\sigma(\rho_{cl} + \rho_w)} \sqrt{\frac{2\pi\sigma(\rho_{cl} + \rho_w) + \frac{g\lambda_D(\rho_{cl} - \rho_w)(\rho_{cl} + \rho_w)}{2\pi\rho_{cl}\rho_w}}{\lambda_D\rho_{cl}\rho_w}}$$

(1)

(2)

If $g$ is set to zero, we get the dispersion relation for a vertical interface, which implies that

$$u_c = \frac{2\pi\sigma(\rho_{cl} + \rho_w)}{\lambda_D\rho_{cl}\rho_w}$$

(3)

Where $u_c$ is critical velocity, m/s; $u_{cl}$ is liquid cryogens velocity, m/s; $u_w$ is circumstance fluid velocity, m/s; $\rho_{cl}$ is liquid cryogens density, kg/m$^3$; $\rho_w$ is circumstance fluid density, kg/m$^3$; $\sigma$ is the interfacial tension, N/m; $\lambda_D$ is the most dangerous wavelength, m; $g$ is the gravitational acceleration, m/s$^2$.

4.2 Effect of releasing location

As Table 1 and Figure 3&4 shown, with releasing location getting close to water surface and releasing pressure being lower than 2.5 bars, both the surviving distance and the ice blocking time become long. That is because releasing location getting close to water is to increase the pressure difference, which will increase the heat transferring rate and easily cause ice run as the ice blocking level shown. According to the results, the pressure difference has more significant effect on the ice run. When releasing pressure increases over 2.5 bars, the differences of results on the three location conditions are unobvious.

4.3 Effect of adding nucleating agent

As Table 2 shown, adding nucleating agent is beneficial to shorten ice blocking time and the surviving distance. The reason is the nucleating agent adding into water could increase the number contents of ice nucleus which can accelerate the icing speed. That can be an emergency treatment meeting the requirement for cryogenic liquid leaking stoppage.

4.4 Effect of water flowing

As Table 3 and Figure 3&4 shown, the surviving distance of the propeller vertically arranging under the leakage hole and producing upward water flow is shorter than the distance in the condition for none water flow, but longer than the distance of horizontally water flow which is produced by the propeller arranging oppositely to the leakage hole. The reason is the water flow direction as mentioned in this series test is beneficial to reduce the pressure difference. That can be another emergency treatment meeting the requirement for cryogenic liquid leaking stoppage.

5. Conclusions

The process of LN$_2$ releasing into water was studied experimentally. Main conclusions can be drawn as following:

(1) The Kelvin-Helmholtz instability is used to analyse the process of LN$_2$ releasing into water. If velocity difference is sufficiently large, the interface will be unstable and given rise to break into small droplets, which enlarge the heat-exchange surface. As a result of that, the heat transfer from water to LN$_2$ will increase. The ice will be easy to form near the leakage hole, which will limit the LN$_2$ further injecting into water. Contractively, the velocity difference is also helpful to wash away the ice. So there will be a special pressure difference, which can simultaneously help to increase ice forming speed and limit the liquid surviving distance.

(2) Adding nucleating agent is helpful to provide ice nucleus into water, which can accelerate the ice
forming speed. It can be seen as an optional emergency treatment for blocking cryogenic liquid leaking.

(3) Water flow has some effect on changing pressure difference, which can affect the ice forming speed and liquid surviving distance as mentioned above.

Acknowledgments
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