Phenomena of Liquid Nitrogen Flashing under Rapid Depressurizations

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ABSTRACT

Flashing Experiment of liquid nitrogen in a pressure vessel was conducted under rapid depressurization rate. Observations of the explosive boiling behavior caused by quick opening of a electro-magnetic valve were undertaken by using a video camera. Pressure and temperature changes in the vessel were measured. Depressurization rates in these experiments fell in the range from 0.01 to 4.0MPa/s. Experimental results showed that the initial temperature distributions and depressurization rates have more intrinsic influence on these flashing phenomena. Relationship between pressure undershoot and depressurization rate was obtained. The rate of pressure recovery was found to increase with the rate of depressurization, which also resulted in the increase of the increment of pressure recovery. The empirical equation proposed by Alamgir and Lienhard was applied to predict the recovery pressure of the flashing of liquid nitrogen. To obtain more precise prediction of the pressure recovery, another factor such as an orifice diameter that affects the discharge condition of the recovery pressure.

1. INTRODUCTION

In recent years, a demand for cryogenic fluids as a coolant has been increasing because of the industrial development of low temperature technology. Since cryogenic fluids are commonly stored in a pressure state, a storage tank would be exposed itself to danger in high pressure if thermal insulation is broken down. Therefore, investigations of cryogenic fluids under such a depressurization condition are required in order to release a high pressure. When a liquid under high pressure is depressurized, the liquid in an equilibrium or sub-cooled state is brought into a superheated state. Then, the liquid starts changing its phase to resolve the non-equilibrium state. This phenomenon of explosive vaporization is called the flashing phenomenon and is of special interest in engineering for the designs of safety systems involving high-pressure and/or high-temperature liquids, particularly in connection with a loss-of-coolant accident (LOCA) in nuclear reactors [1-5] and LNG storage tanks [6]. While many works concerning with the flashing phenomenon have focused on hot water in a high rate of depressurization (over 100MPa/s), flashing of fluids other than water and under slow rate of depressurization have not been investigated sufficiently. Hanaoka [7] conducted blow down experiments for the Freons R-11 and R-113 to clarify the fundamental characteristics of the flashing under slow rate of depressurizations (0.1-2.0MPa/s) and concluded that the correlation of superheated limit of hot water in high depressurization rate examined by Alamgir and Lienhard [8] could not be applied to that of these fluids in low depressurization rate.

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Furthermore, the authors [9-11] conducted flashing experiments of liquid nitrogen from a low temperature technological point of view. These results showed that the pressure undershoots depend significantly on the rate of depressurization and initial temperature even when the depressurization rate is low. It is important to estimate increment of pressure recovery caused by the explosive flashing from a viewpoint of safety technology. The pressure recovery in a vessel is determined by the mass balance between discharged vapor and flashed vapor, while a pressure undershoot acts directly as a motive force of explosive boiling phenomena.

In this study, as a first step in the quantitative prediction of pressure recovery, rate of pressure recovery in the flashing of liquid nitrogen was examined. At first, the relationship between the rate of depressurization and the rate of pressure recovery was experimentally determined. Then, the increment of pressure recovery was related to the rate of pressure recovery. Comparison of the measured recovery pressure and that estimated from the empirical equation proposed by Alamgir and Lienhard [12] showed that the equation can be limitedly applied to the present results.

2. EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus is illustrated schematically in Fig.1. The apparatus consists of a liquid nitrogen tank, a cryostat made of stainless steel (vacuum jacket and pressure vessel), a vacuum pump, and a data-acquisition system. The vacuum jacket is 680mm in length, and 215mm in outer diameter and has a pair of BK7 glass windows (54mm x 374mm). The pressure vessel is 592mm in length, 50mm x 50mm in square cross-section and has a pair of acrylic windows (50mm x 360mm) for the observation of flashing events. An orifice of various in size (d=1, 3, 5, 10mm), which controls the rate of depressurization, is mounted on the top of vessel. A pressure transducer and four copper-constantan thermocouples were set in the pressure vessel. The thermocouples were located at 322, 258, 202 and 60mm from the bottom of the vessel.

To keep a higher level of thermal insulation, vacuum jacket was evacuated to the order of 10-4Pa, and then liquid nitrogen was supplied from a reservoir tank to the pressure vessel. After the pressure in the vessel was set to a prescribed level (200-550kPa) by means of self-pressurization. Then the flashing experiment was started by opening a electromagnetic valve which causes a sudden release of the vapor nitrogen from the vessel. The measurement of pressure was triggered by the valve-opening signal, and the data were logged and processed by a microcomputer in on-line mode. The explosive boiling behavior caused by the depressurization was observed by using a video camera.

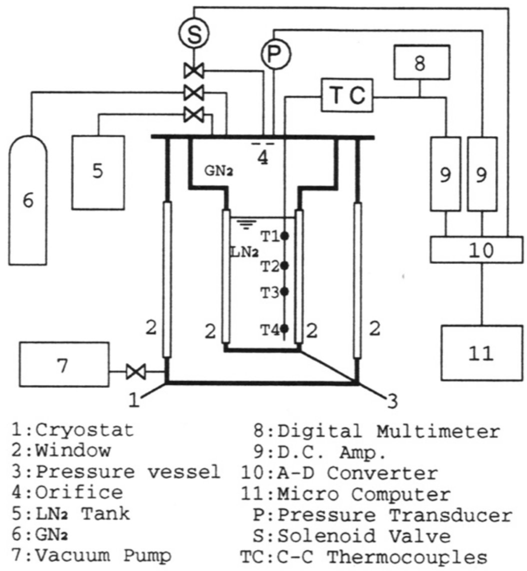

Figure 1: Experimental apparatus

3. RESULTS AND DISCUSSIONS

3.1. Flashing Behavior and Pressure Time Histories

Cryogenic fluids are commonly stored in a pressurized state. Thermal stratification is usually formed in the cryogenic storage tank [13]. The existence of thermal stratification affects the flashing phenomenon of cryogenic fluids. A few examples of the initial temperature distribution within the liquid nitrogen are indicated in Fig.2. This figure shows that these temperature distributions are almost the same. In addition, the liquid temperature is increasing height from the bottom of the vessel. This means that thermal stratification was formed in the liquid nitrogen. Even under such a same temperature condition indicated in Fig.2, different flashing behavior was observed depending upon the values of depressurization rate.

Photographs in Fig.3 show the visualized behavior of the flashing for the case of d=10mm, which corresponds to a high rate of depressurization. At the time 33.3ms after starting the depressurization, boiling starts from the vapor-liquid interface where the temperature is the highest in the liquid, and proceeds to the bottom along the wall of the vessel. In this period, boiling takes place at the wall of the vessel, and no significant boiling occurs in the inner part of the liquid. Therefore, the superheat in the core liquid increases with elapse of time without resolving by boiling. When the boiling from reaches the bottom of the vessel (100ms), violent boiling occurs in the whole liquid and vapor-liquid mixture spread throughout the vessel (500ms).

Figure 4 indicates the photographs of the flashing under a low rate of depressurization (d=1mm). In this case, boiling started at the top of the liquid develops slowly down to the bottom of the vessel and no explosive boiling takes place. Moderate boiling proceeds almost simultaneously both in the liquid and along the wall to the bottom of the vessel with resolving the superheat of the liquid.

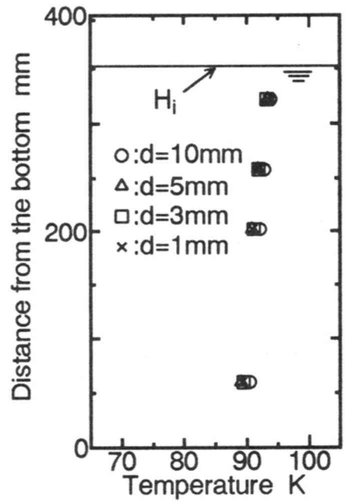

Figure 2: Distribution of liquid temperature in the liquid nitrogen.

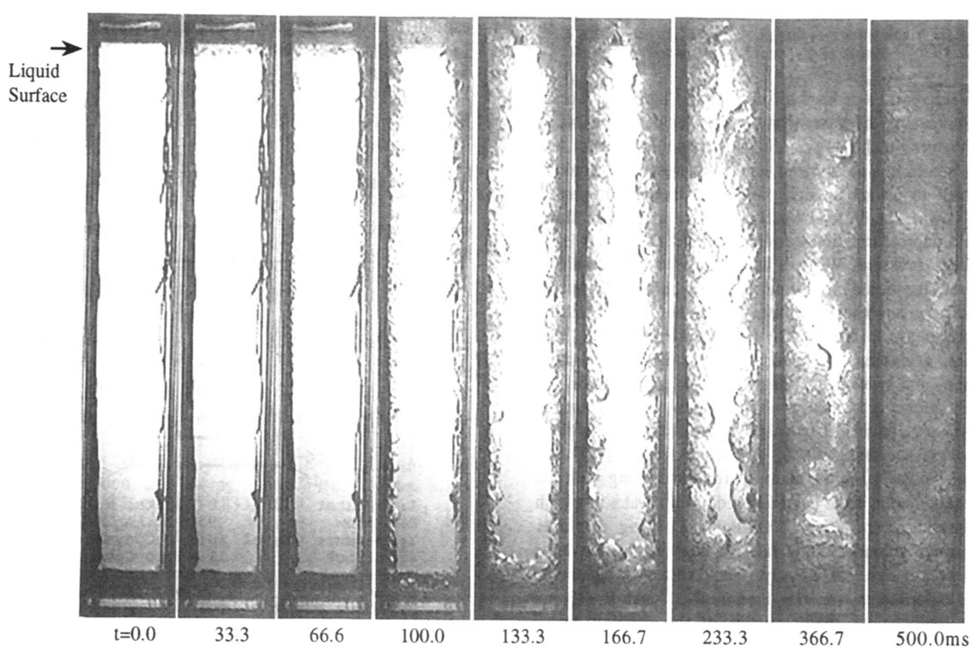

Figure 3: Photographs of the flashing (d=10mm, Σ_{max} =3595.3kPa/s)

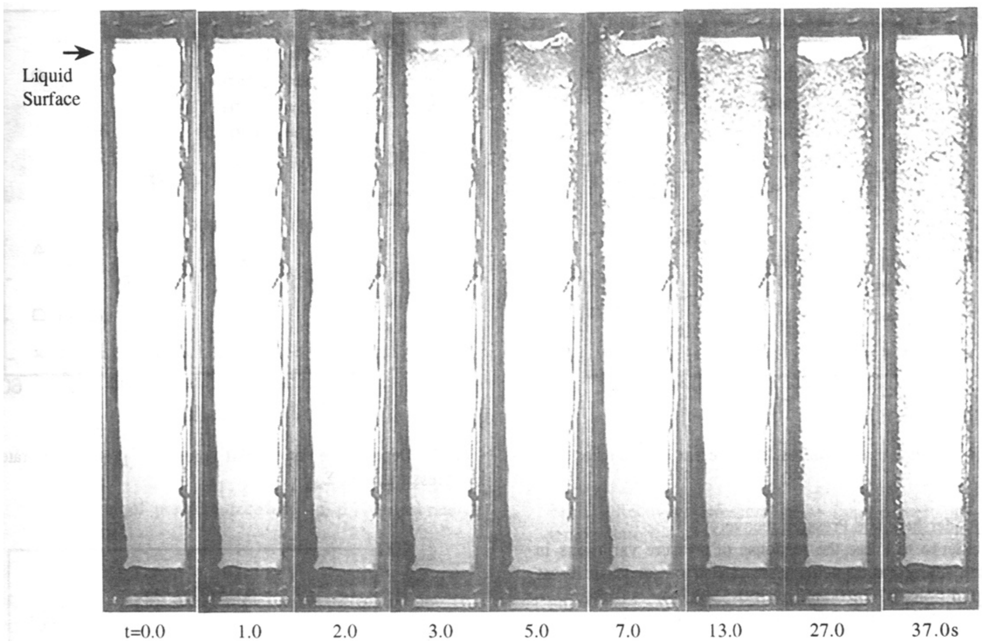

Figure 4: Photographs of the flashing (d=1mm, Σ_{max} = 67.4kPa/s)

A schematic diagram of the pressure time history during the flashing process is illustrated in Fig.5. Pressure in the vessel falls sharply from the initial pressure p_i to the minimum pressure p_n at the time t_n. Pressure undershoot is represented as (p_i-p_n), and the rate of depressurization Σ_{max} was defined as the maximum rate $-(dp/dt)_{max}$ during this process. After the pressure decreases to its minimum point p_n, the pressure begins to increase and reaches the maximum recovery pressure pr at the time tr. Increment of the pressure recovery is (p_r-p_n), and the rate of pressure recovery Γ was defined as $(p_r-p_n)/(t_r-t_n)$.

Figure 6 shows typical pressure time histories for the different orifice diameters. The initial pressure and liquid level are about 540kPa and about 350mm, respectively. In the case of d=10mm, pressure in the vessel falls abruptly to the value p_n, and then recovers up to the value p_r by the explosive boiling. Finally, the pressure approaches the atmospheric environment pressure. The rate of depressurization and pressure recovery decrease with decreasing the orifice size (5mm and 3mm). In the case of d=1mm, pressure decreases monotonously to the atmospheric pressure without indicating minimum pressure and recovery pressure. Rates of depressurization obtained from these experiments were 3595.3, 1365.9, 557.4 and 67.4kPa/s for d=10, 5, 3 and 1mm, respectively.

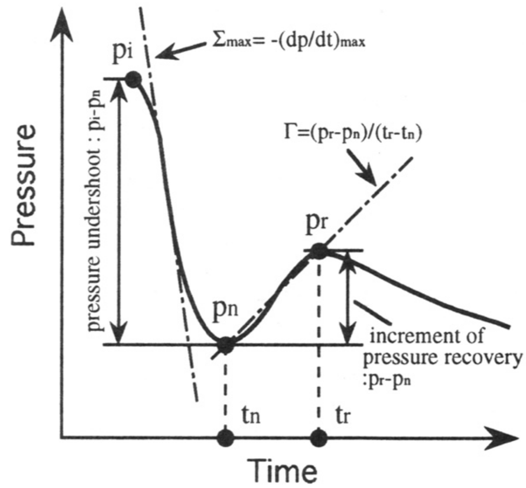

Figure 5: Illustration of pressure time history in flashing process.

Figure 6 shows typical pressure time histories for the different orifice diameters. The initial pressure and liquid level are about 540kPa and about 350mm, respectively. In the case of d=10mm, pressure in the vessel falls abruptly to the value p_n, and then recovers up to the value p_r by the explosive boiling. Finally, the pressure approaches the atmospheric environment pressure. The rate of depressurization and pressure recovery decrease with decreasing the orifice size (5mm and 3mm). In the case of d=1mm, pressure decreases monotonously to the atmospheric pressure without indicating minimum pressure and recovery pressure. Rates of depressurization obtained from these experiments were 3595.3, 1365.9, 557.4 and 67.4kPa/s for d=10, 5, 3 and 1mm, respectively.

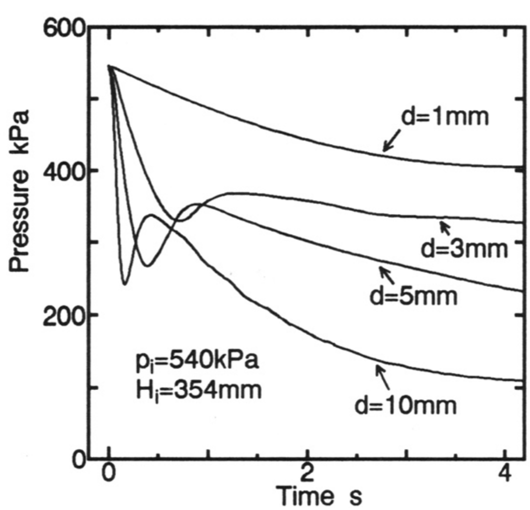

Figure 6: Pressure time histories for different orifice sizes.

3.2. Pressure undershoot and Pressure recovery

In order to examine the response of pressure variations in the vessel, many experiments were carried out under different initial conditions (d=1-10mm, pi=200-550kPa).

Figure 7 shows the relationship between the rate of depressurization and the initial pressure in the vessel. Rates of depressurization obtained in all those experiments were indicated in the same figure. The rate of depressurization changes considerably with the orifice size, and depends also on the initial pressure.

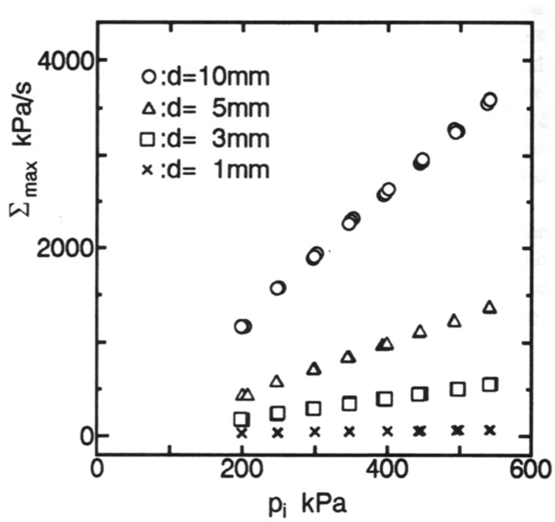

Figure 7: Dependence of initial pressure pi on the rate of depressurization max.

The pressure undershoot is important to give a motive force of explosive boiling phenomena. Figure 8 shows the relationship between the pressure undershoots (p_i-p_n) and the rates of depressurization. A pressure undershoots increases with increasing depressurization rates. Alamgir and Lienhard [5] conducted flashing experiments on hot-water. They reported that the pressure undershoot depends on the rate of depressurization and initial temperature except for the case below the depressurization rate of 400MPa/s. However, the results of Fig.8 indicates that there exist some correlations between the pressure undershoot and the depressurization rate even for the low rate of depressurization.

As shown in Fig.6, after taking its minimum point, the pressure in the vessel increases abruptly to a maximum recovery pressure due to the violent boiling. Such a behavior in the pressure recovery can be explained by the balance between the vapor discharged from the orifice and the vapor generated in the bulk of liquid by boiling. Two factors make the balance of vapor complicated in the process of pressure recovery.

One is the increase of the vapor discharged from the orifice with increasing $\sum_{max}$, which acts as decreasing the pressure in the vessel. The other factor is the increase in the generated vapor by increasing the depressurization rate since a large superheat in the liquid is attained by a high depressurization rate. This acts as increasing the pressure in the vessel. Moreover, these quantities of generated vapor and discharged vapor are linked with the pressure change in the vessel. Therefore, the prediction of the pressure in the recovery period is too difficult to analyze. So, actual index of the vapor balance, i.e., the measured rate of pressurization in the recovery process, is examined.

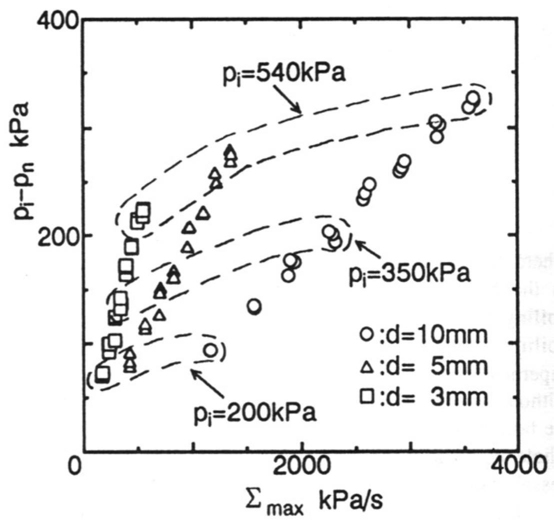

Figure 8: Relationship between pressure undershoot and rate of depressurization.

Figure 9 indicates the relationship between the rate of pressure recovery and the rate of depressurization. The rate of pressure recovery increase with the depressurization rate. This can be undershot that a high depressurization rate causes high superheat in the liquid which results in the successive explosive boiling.

Just like the pressure undershoots increases with the rate of depressurization, the increment of pressure recovery is expected to increase with the rate of pressure recovery. Figure 10 represents the relationship between the increment of pressure recovery (p_r-p_n) and Γ. As shown in this figure, dependence of (p_r-p_n) on Γ can be clearly found. Figure 7 and Fig.10 show that the use of the rate concept is very effective in the study of flashing under depressurization. Alamgir and Lienhard [8] proposed the following equation to estimate the recovery pressure.

$$Ja = \frac{\rho_f c_{pf}[T_i - T_{sat}(p_i)]}{\rho_g h_{fg}} = 1.26 \tag{1}$$

This equation was derived for hot water in uniform initial temperatures T_i. In this experiment, however, temperature difference exists initially in the liquid due to the formation of thermal stratification. Therefore, a reference temperature was introduced to represent the initial temperature of the liquid. The reference temperature T_{ref} was defined as the integral mean value of the liquid temperatures, which can be calculated from the measured temperature distribution in the liquid. The value of predicted recovery pressure pr can be calculated by the Eq.(1) if one substitute T_{ref} for T_r.

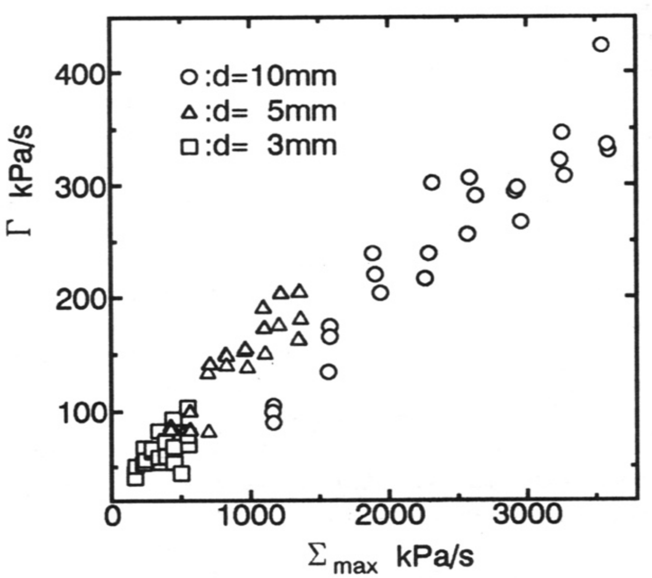

Figure 9: Rate of pressure recovery versus rate of depressurization.

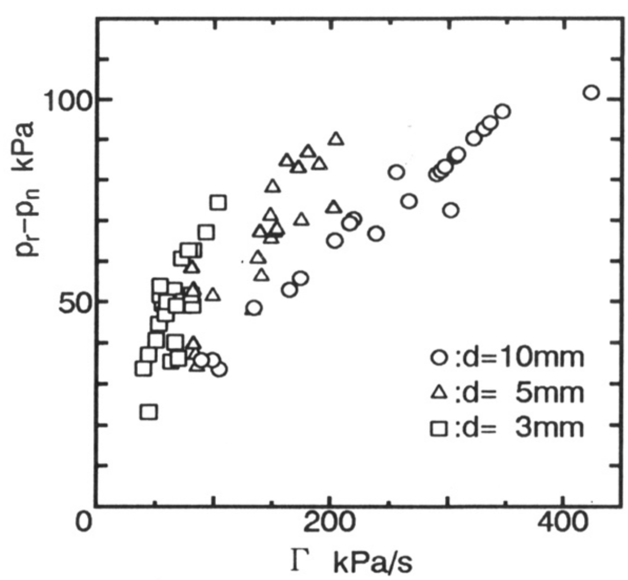

Figure 10: Increment of pressure recovery versus rate of pressure recovery.

Figure 11 shows the relationship between recovery pressure and reference temperature. In this figure, the solid curve represents the predicted value pr as a function of T_{ref}, in which ρ_f, c_{pf}, ρ_g and hf_g were evaluated as saturation properties corresponding to T_{ref}. In the same figure, the saturation pressure corresponding T_{ref} is also represented by the broken curve. As shown in this figure, these results show qualitative agreement with the predicted value given by T_{ref}. Some differences exist, however, in the recovery pressure depending upon the orifice size, and these differences increase with increasing T_{ref}. This result shows that the process of pressure recovery cannot be explained only by considering the thermal energy, and another factor such as an orifice diameter that affect the discharge characteristics should be take into account to estimate precisely the pressure behavior in the vessel.

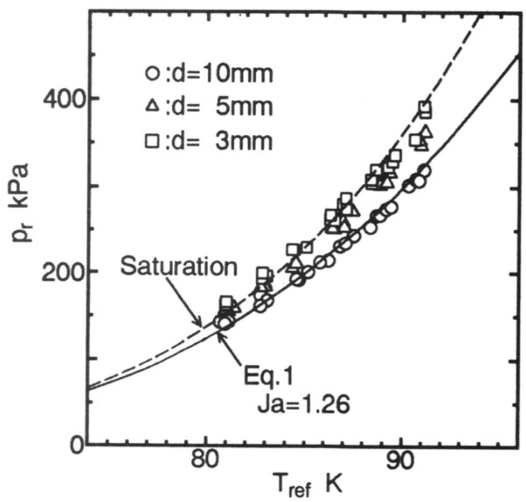

Figure 11: Recovery pressure as a function of the reference temperature.

CONCLUSIONS

An experimental study was conducted on the flashing phenomenon of cryogenic liquid nitrogen under rapid depressurization. The conclusion can be summarized as follows.

(1) Under the condition of higher depressurization rate, explosive boiling occurs in the whole liquid. In the case of low depressurization rate, moderate boiling progress from the upper-surface of the liquid to the lower part of the liquid.

(2) The pressure undershoot increases with increasing the rate of depressurization, that also results in the increase of the rate of pressurization and the increment of pressure recovery.

(3) The equation proposed by Alamgir and Lienhard to predict recovery pressure gives a good qualitative agreement with the present results. However, some quantitative difference exist in the recovery pressure depending upon the discharge conditions.

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REFERENCES

[1] Edwards, A. R. and O'Brien, T. P., 1970, "Studies of Phenomena Connected with the Depressurization of Water Reactors", J.Br. Nucl. Energy Soc., Vol.9, pp.125-135.

[2] Lienhard, J.H., Alamgir, Md. and Trela, M., 1978, "Early Response of Hot Water to Sudden Release from High Pressure", ASME Journal of Heat Transfer, Vol.100, No.3, pp.473-495.

[3] Polanco, G., Holdo, A. and Munday, G., 2009, "Mass flow determination in flashing openings", Int. Journal of Multiphysics, Vol.3, No.4, pp.401-406.

[4] Haque, E.E.U. and Hampson, P.R., 2014, "Modelling Phase Change in a 3D Thermal Transient Analysis", Int. Journal of Multiphysics, Vol.8, No.1, pp.49-68.

[5] Messahel, R., Cohen, B., Moatamedi, M, Boudlal, A., Souli, M. and Aquelet, N., 2015, "Numerical and experimental investigations of water hammers in nuclear industry", Int. Journal of Multiphysics, Vol.9, No.1, pp.21-36.

[6] Guler. M., Hannemann, R. J. and Sallet, D. W., 1979, "Unsteady Two-Phase Blowlowdown of a Flashing Liquid from a Finite Reservoir", Two-Phase, Heat & Mass Transf., Vol.2, Hemisphere, pp.781-795.

[7] Hanaoka, Y., Maeno, K., Zhao, L. and Heymann, G., A study of Liquid Flashing Penomenon Under Rapid Depressurization, JSME Int. J., vol.33, No.2, (1990), p.276.

[8] Alamgir,Md. and Lienhard,J.H., 1981, "Correlation of Pressure Undershoot During Hot-Water Depressurization", ASME Journal of Heat Transfer, Vol.103, pp.52-55.

[9] Yokoyama, S., Hanaoka, Y., Tokura, I. and Watanabe, T., 1992, "A Study of Liquid Nitrogen Flashing under Rapid Depressurization", Proc. 2nd JSME-KSME Thermal Engng. Conf., Vol.3, pp.321-326.

[10] Watanabe, T., Hanaoka, Y. and Tokura, I., 1995, "Flashing Phenomena of Liquid Nitrogen in a Pressure Vessel", Trans. JSME, (in Japanese), Vol.61, No.585, pp.1849-1854.

[11] Watanabe, T., Hanaoka, Y. and Tokura, I., 1998, "Flashing Phenomena of Liquid Nitrogen in a Pressure Vessel: Part 2: Mist formation and Behavior of the Liquid Surface in the Early Depressurization Process", Heat Trans. Japanese Research, Vol.27, No.5, pp.327-335.

[12] Alamgir, Md., Kan, C.Y. and Lienhard, J.H., 1980, "An Experimental Study of the Rapid Depressurization of Hot Water", Trans. ASME Journal of Heat Transfer, Vol.102, No.3, pp.433-438.

[13] Fan, S. C., Chu, J. C. and Scott, L. E., Thermal Stratification in Closed Cryogenic Containers, Adv. Cr. Eng., Vol.14, (1968), p.249.