Experimental Study on Boiling Mechanism of LN_2 Injection into Water

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***Abstract*—Aimed at studying the boiling phenomenon of LN_2injection into water, a visualization experimental system is built. The injection pressure can be adjusted in this system. The LN_2injection process can be recorded by high speed camera and pressure transducers. Combined the boiling theory and experimental results, the following conclusions can be obtained. The maximum pressure and the pressure increasing rate are depended on the injection pressure.LN_2 broke up into many small droplets because of the instability of the interface of LN_2 and N_2. When LN_2 is heated directly by the water, the heat transferring flux can be over 10^6 W/m^2.**

Keywords-LN_2*, *boiling mechanism, experimental study, injection, visual recording

I. INTRODUCTION

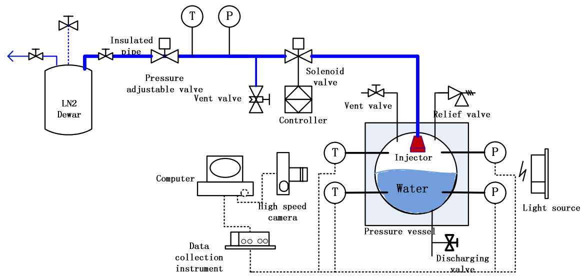
The characteristics of phenomena of LN_2 injection into water are high temperature difference (over 210K), high rate of growth of gas bubbles (milliseconds), high rate of temperature rising (over 106K/s), uncertain location and time. Therefore, this work built up a visualization experiment system for LN_2 injection into water. The system can record the whole process of boiling phenomenon of LN_2 injection process. It can meet the need of studying boiling mechanism of cryogenic liquid into water.

II. RESEARCH STATUS

A few experimental studies have been done for the injection of liquid nitrogen into water. Wen et al[1] built up a experiment system which is concerned about the expansion of a small amount of liquid nitrogen injected into a relatively large pool of water and heat transfer behavior during the process. Both the transient pressure and temperature profiles were experimentally measured and analyzed. The results shown that the pressure and the rate of pressure rise increase approximately linearly with increasing injection pressure and reach, respectively, to 284kPa and 500kPa/s at a liquid nitrogen injected. Clarke et al[2] built up a visualization experimental system of liquid nitrogen injection into water which was with synchronized pressure and temperature measurement , to obtain insight into this complex phenomenon. Pressurization rate in excess of 350bar/s were recorded and found to vary proportionally with injection pressure. Zhang[3] built up a experiment of draining the near-atmospheric liquid nitrogen directly into near atmospheric pressure water. Some pictures of the flow patterns and some experimental data about temperature during draining process were gotten and analyzed. The temperature measurement data were qualitatively analyzed. The estimated value and the observed value of the existing length of the liquid nitrogen column were compared.

III. EXPERIMENTAL SETUP

The experimental system using in this work consists of a liquid nitrogen Dewar, a small pressure vessel with viewing windows, a high speed camera, pressure and temperature sensors, data collection instrument and cryogenics solenoid valve, which are shown in Fig. 1.



(a)

(b)

Figure.1: Experimental system: (a) schematic of experiment; (b) pressure vessel picture

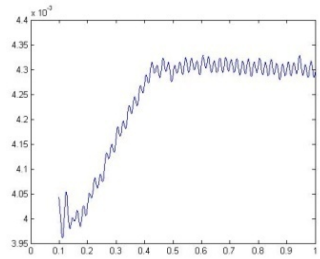
LN_2 is delivered through an insulated pipe form a controllable pressure Dewar, in liquid or gas phase at up to 16 bar. A pressure transducer and thermocouple are mounted upstream of the injector, which can sensor the pressure and temperature of the insulated pipe. The cryogenics solenoid valve is also mounted upstream of the injector and controlled by a controller which can control the valve open time. The injector is made of steel with 3mm inside diameter. The pressure vessel is a steel cylinder of radius 110mm and length 160mm with Perspex windows clamped onto each end. Two pressure sensors and two temperatures sensors are mounted on the pressure vessel and measure the pressure and temperature of gas and water respectively in the vessel. A safety valve and vent valve are fitted to the vessel to prevent pressurization above 40bar and vent the pre cooling gas respectively.

A high speed camera is positioned at one end of the vessel and a halogen light source is positioned at the other end of it. The camera can be used for imaging at rates up to 16000fps. All pressure and temperature data is acquired and stored through NI data collection instrument and LabVIEW software. Its recording rate is 1kHz.

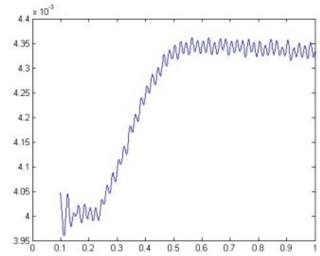
IV. Results and Discussion

In these series experiments, the injection pressure is varied from 0.18MPa to 0.73MPa. The injection during time is 0.1s, which is controlled by the controller. The injector diameter is 2mm, and 100mm above water level. LN2 temperature is -196℃, water temperature in vessel is 15℃ and air temperature is 7℃. The image size is 600×800, and rate is 1000fps. The pressure and temperature data collection rate is 1kHz.

A. Experiment Results



a.



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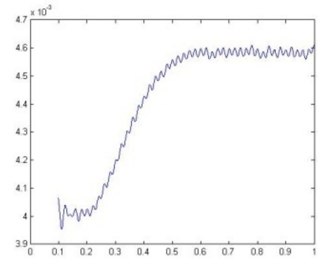

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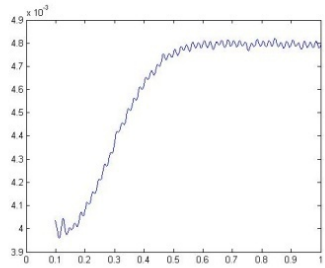

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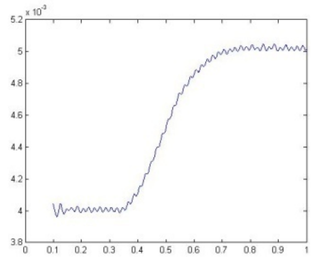

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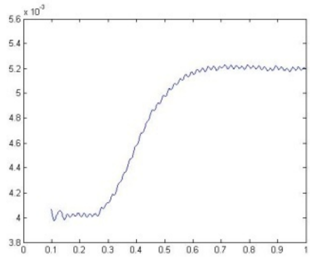

f.

Figure. 2: Vessel Pressure vs. Time in Different Injection Pressures: a.0.18MPa; b.0.27Mpa; c.0.38MPa; d.0.51MPa; e.0.63MPa; f.0.73MPa

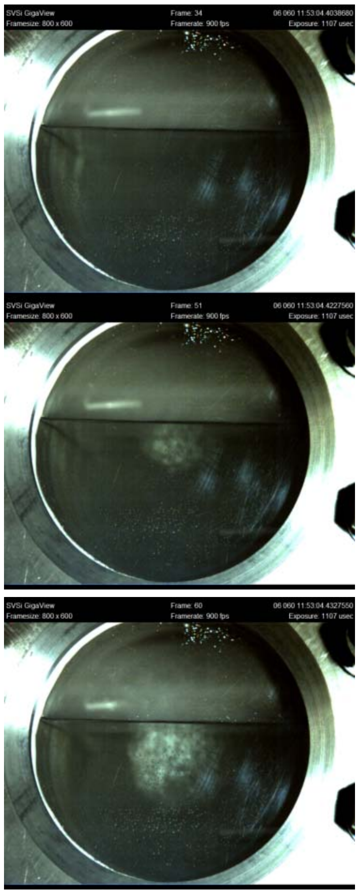

Figure.3: High Speed Images at 0.73MPa Injection Pressure

B. Results Analysis

The output current of the pressure transducer was 4-20mA that varied linearly with pressure of 0-3MPa. So the Fig.2 vertical coordinate (current) can be transformed into pressure value by the correction as:

$$P = 187.5 \times (Y - 0.004) \tag{1}$$

As a result of that, the Fig.2 can be concluded as Table 1.

TABLE 1: EXPERIMENTAL RESULT

No.	Injection Pressure (kPa)	Signal (mA)	Pressure (kPa)	Using Time (s)	Pressure Rate (kPa/s)
a	180	4.3	56	0.40	140
b	270	4.35	66	0.25	263
c	380	4.6	113	0.35	320
d	510	4.8	150	0.45	333
e	630	5	188	0.30	625
f	730	5.2	225	0.30	750

From the Tab.1, it can be found that the maximum pressure and the pressure increasing rate are depended on the injection pressure. At the injection pressure of 180kPa, the maximum pressure and maximum pressure increasing rate are respectively 56kPa and 140kPa/s, but the corresponding values are 225kPa and 750kPa/s at the injection pressure of 730kPa.

The pressure increasing rate in this work is about 20%~30% lower than the value obtain by Wen[1]. There are two mainly reason for this. Firstly, the pressure vessel volume in this study is 2.2 times bigger than Wen's vessel. All of these experiments, the pressure transducers are far away from the real boiling occurring position, the results will have some errors. Secondly, because of the different temperature between water and LN_2 is higher than the Leidenfrost temperature, so LN_2 is under a film boiling, which heat flux is low. But when the cylindrical LN2 broke up into many small droplets as a result of instability of the interface of LN_2 and N_2, LN_2 can be heated directly by the water. As a result of that the heat transferring rate is increased and pressure is also increased. With the injection velocity increasing, the size of small droplets is decreased. [4-6]

The heat transfer process of injection of LN_2 into water is very complicated. Using TNT equivalent model can simplify the process so that the heat transfer coefficient can be obtained. The following expressions relating the maximum pressure and the heat transfer flux.

$$W_{TNT} = k\frac{aW_{LN_2}Q_{LN_2}}{Q_{TNT}} \tag{2}$$

$$\Delta P = P_0(3.9Z^{-1.82} + 0.5Z^{-1}) \tag{3}$$

$$Z = R \cdot W_{TNT}^{-1/3} \tag{4}$$

$$H = L_V \cdot W_{LN_2}/(S \cdot t_d) \tag{5}$$

Where is TNTequivalent, is LN_2 mass which is fragmented, is surface burst coefficient, is equivalent coefficient, is bursting heat, is TNT bursting heat, ΔP is maximum pressure value, is distance from pressure transducer, is heat transfer flux, is latent heat of LN_2, is the time of pressure increasing. Combining Eqs. (2)-(5), the heat transferring flux can be over 106 W/m2.

From Fig.2, it cannot be easy to realize the vapor bubble growth process. A group of bubbles is grown at the same time and impacted each others. Further work is needed to search for optimal method to observe the bubble growth process of LN_2 injection into water.

V. CONCLUSIONS

A experimental study of LN_2 injection into water is done in this work. Combined the boiling theory and experimental results, the following conclusions can be obtained. The maximum pressure and the pressure increasing rate are depended on the injection pressure.LN_2 broke up into many small droplets because of the instability of the interface of LN_2 and N_2. When LN_2 is heated directly by the water, the heat transferring flux can be over $10^6 W/m^2$. The visual recording pictures cannot show how the bubbles grown, so some other optimal method should be put forward in the further study.

ACKNOWLEDGMENTS

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REFERENCES

[1] D.S. Wen, H.S. Chen, Y.L.Ding, P.Dearman.Liquid nitrogen injection into water: Pressure build-up and heat transfer, *Cryogenics*, pp. 740-748,2006.

[2]H. Clarke, A Martinez-Herasme, R. Crookes, D.S. Wen. Experimental study of jet structure and pressurization upon liquid nitrogen injection into water. *Multiphase Flow*, 36, pp. 940-949, 2010.

[3] ZHANG Linbo. Heat and Mass Transfer Analysis of Cryogenic Liquid with Water and Experimental Investigation. Hubei: *Huazhong University of Science and Technology*, pp. 35-46, 2006.

[4] Tianshu Li, Yanhua Yang, Minghao Yuan.Experimental investigation on the bursting of single molten droplet in coolant. *Nuclear Science and Technique*, 18(6), pp. 376-380, 2007.

[5] Yu Zou, Xiulan Huai, Lin Lin. Molecular dynamics simulation for homogeneous nucleation of water liquid nitrogen in explosive boiling.*Applied Thermal Engineering*, 30, pp. 895-863, 2010.

[6] Toshiaki Watanabe, Hironori Maehara, Shigeru Itoh. Explosive Evaporating Phenomena of Cryogenic Fluids by Direct Contracitng Normal Temperature.*Int, Jnl. Of Multiphysics*, 6 (2), pp. 107-114, 2012.