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Suppression of bubbles in subcooled liquid nitrogen under heat impulse

Kwanwoo Nam [a,*], Bok-Yeol Seok [a], Jung Joo Byun [b], Ho-Myung Chang [b,1]

[a] *Electro-Mechanical Research Institute, R&D Division, Hyundai Heavy Industries Co., Ltd., 102-18, Mabuk-dong, Giheung-gu, Yongin-si, Gyeonggi-do, 449-716, Republic of Korea*

[b] *Cryogenic Engineering Laboratory, Department of Mechanical Engineering, Hong Ik University, 72-1 Sangsu-dong, Mapo-gu, Seoul, 121-791, Republic of Korea*

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Abstract

This paper describes an experimental investigation to verify that subcooling of liquid nitrogen can suppress bubbles when an impulsive heat is applied. A heater is attached on a surface of substrate in liquid nitrogen which simulates the quench state of the superconducting coil in high temperature superconductor (HTS) system. A pulse of power input, whose period is around 100 ms, is applied to the heater in liquid nitrogen bath at temperatures between 77 K and 65 K. Two kinds of experiments are performed to scrutinize the thermal behavior of liquid nitrogen under the heat impulse. First, the temperature near the heater is directly measured during the heating and the recovery periods for different surface orientations (vertical, horizontal up and down). It is observed that the temperature history is strongly dependent on the orientation in saturated liquid, but nearly independent of the orientation in subcooled liquid. The main reason for this difference is that the generation of bubbles is less active in subcooled state than in saturated state. The subcooling of liquid nitrogen below 70 K at atmospheric pressure is found to be very effective in suppressing bubbles. Second, bubbles generated from the heater are recorded by a high-speed camera for different degrees of subcooling. The detached bubbles from the heater surface are quickly diminished in the liquid region under the subcooled condition of nitrogen. In the case of the subcooled condition at 65 K and 101 kPa, only vapor film is formed on the heater surface during the heating period when the heating power is within approximately 150 W/cm^2.

Keywords: Nitrogen (B); Quench (C); Two-phase flow (C); Flow visualization (D); Temperature sensors (D)

1. Introduction

Recently, subcooled liquid-nitrogen at around 65 K is widely used for cooling high temperature superconductor (HTS) power machines due to its advantages over saturated liquid nitrogen. The critical current density of HTS is considerably greater at 65 K than at 77 K, thus the size of superconducting elements can be reduced [1]. Another important benefit of subcooling the liquid is the suppression of bubbles that may be generated from an internal or external heat load. Since bubbles play a critical role in the degradation of electrical insulation performance of liquid nitrogen, subcooling is essential for high-voltage devices such as fault current limiters (FCL) or transformers.

A number of efforts have been directed at subcooled liquid-nitrogen systems for HTS power applications, and it is now a common practice in HTS systems to employ a cryocooler for continuous operation and to take advantage of the active natural convection of liquid nitrogen for temperature uniformity [2]. Several cryogenic systems had been successfully developed for small or full-scale HTS power system prototypes in subcooled liquid nitrogen [3–5].

In the subcooled nitrogen cooling systems, transient boiling heat transfer caused by an impulsive heat is important since the boiling heat transfer is closely related with the thermal stability and the electrical performance of HTS power machines. Although several researches have

* Corresponding author. Tel.: +82 31 289 5083; fax: +82 31 289 5050.
E-mail addresses: kwnam@hhi.co.kr (K. Nam), hmchang@hongik.ac.kr (H.-M. Chang).
1 Tel.: +82 2 320 1675; fax: +82 2 322 7003.

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been conducted for the transient boiling heat transfer in the saturated liquid nitrogen at 77 K [6–8], boiling phenomenon in the subcooled nitrogen such as the suppression of bubbles is still not clear.

In this study, we intend to verify with two parallel experimental methods that bubbles can be suppressed under the subcooled condition of liquid nitrogen when an impulsive heat is applied. First, the suppression of bubbles in subcooled condition is investigated by measuring the temperature history near the heater for different heater surface orientations. Second, the bubble behavior is directly recorded by a high-speed camera to clearly demonstrate the bubble suppression in the subcooled condition.

2. Temperature measurement experiment

2.1. Experimental apparatus and instrumentation

Fig. 1 is a schematic overview of our temperature measurement experiment. A single-stage GM cryocooler (Cryomech AL60) is mounted on the top plate of a cryostat, and a 35 l vessel of liquid nitrogen is placed at the upper position of a cryostat for close access to the cold head of the cryocooler. A circular copper plate (5 mm thick and 25 cm in diameter) is horizontally attached to the cold head as an extended cooling surface. The cooling capacity of the cryocooler is regulated by a Thermofoil^{TM} heater (Minco Model HK5562) attached on the cold head, which is excited by a DC power supply. Fig. 2 is a cool-down history to a subcooled liquid state at 65 K and 101 kPa. During the initial cool-down (about 13 h), liquid nitrogen is in a saturated state so that the cryostat pressure decreases in accordance with the vapor pressure of nitrogen. When the liquid

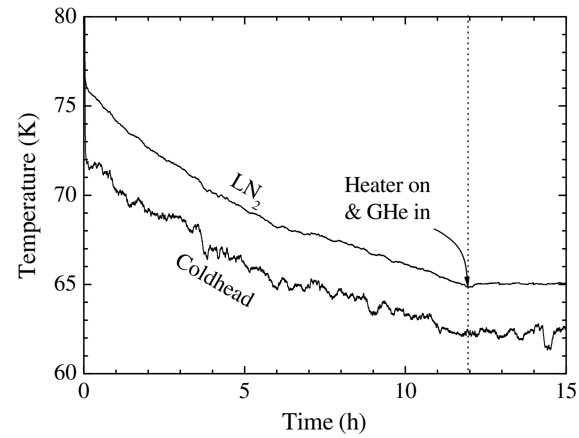

Fig. 2. Typical cool-down history to 65 K subcooled condition by a GM cryocooler.

reaches the intended temperature, the cold head heater is turned on at the preset value and helium gas is supplied to pressurize the cryostat to 101 kPa. The liquid temperature under the cooling plate is spatially very uniform by natural convection, and the test modules are suspended at a distance of approximately 5 cm below the plate.

Test module is prepared in this experiment as shown in Fig. 3. A square shape of Thermofoil^{TM} heater (Minco HK5583) is attached by epoxy on the surface of a rectangular GFRP plate (40 mm × 37 mm and 3 mm thick). Three different orientations (vertical, heating surface up and down) are tested and compared to examine the gravita-

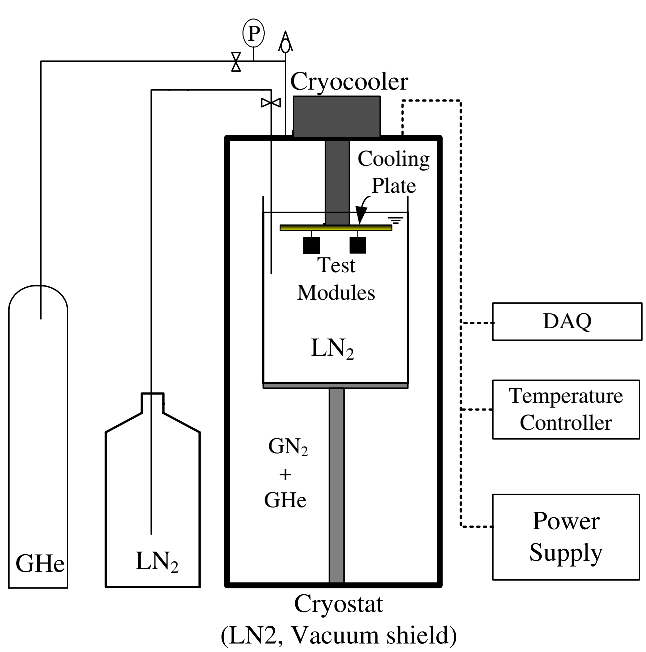

Fig. 1. Schematic overview of experimental apparatus for temperature measurement.

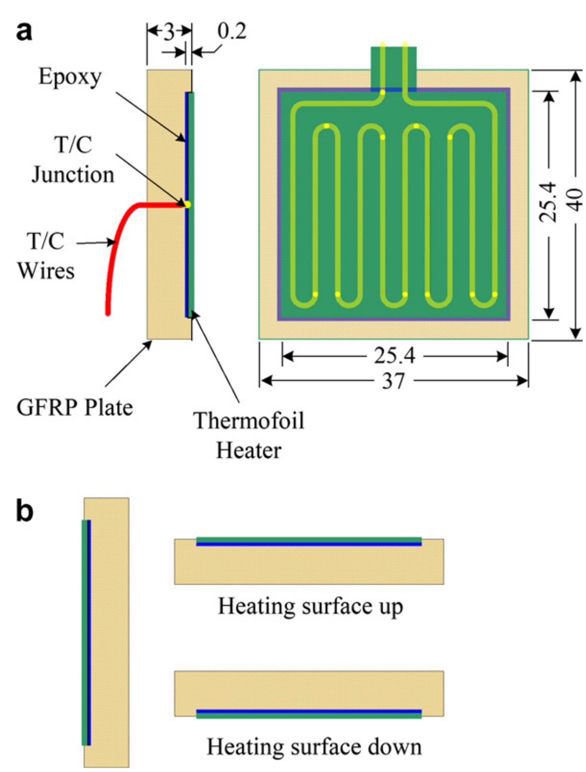

Fig. 3. Schematic of test module. (a) Dimensions of test module (unit: mm) and (b) orientations of test module.

tional effect of bubbles. A thermocouple (E-type, Omega model 5TC-TT-36AWG) is located in a direct contact with the heater at the center of the square and the thermocouple wires are connected through a tiny hole (2.0 mm diameter) from the opposite direction of heating surface. Although the thermocouple is attached on the heater surface, we have actually measured the temperature approximately at 0.2 mm away from the center of the heater, because the heater is 0.2 mm thick (or 0.1 mm from the center) and the thermocouple junction is also about 0.2 mm in diameter. Therefore, the experimental data presented below does not quantitatively represent the temperature of the heating surface, but does provide significant information about the diffusion of the applied heat pulse to the GFRP plate, depending upon the various cooling conditions of liquid.

In order to generate the heat impulse, a preset voltage is applied to the heater for 100 ms by an AC power supply (Pacific Power Smart Source™ 360-AMX). Fig. 4 is an example of the measured voltage applied to the heater. The heating power is considered as nearly constant over the heating period (that is, step-up and step-down profile), since the AC period (1/60 s) is very short in comparison with the thermal relaxation time constant in the heater and the electrical resistance of the heater is nearly constant over temperatures up to 600 K. In this experiment, the range of the heating power per unit area is 10 ∼ 150 W/cm^2. The temperature of the test modules is sampled and recorded every 1 ms with a high-speed data acquisition board (National Instrument DAQPad-6015). Additional thermocouples are attached at several axial locations of a vertical GFRP rod for the purpose of checking the liquid level and confirming the uniformity of the liquid temperature.

2.2. Effect of heating surface orientation and liquid temperature

Fig. 5a is the temperature history near the heater for three different orientations when 100 W/cm^2 is supplied

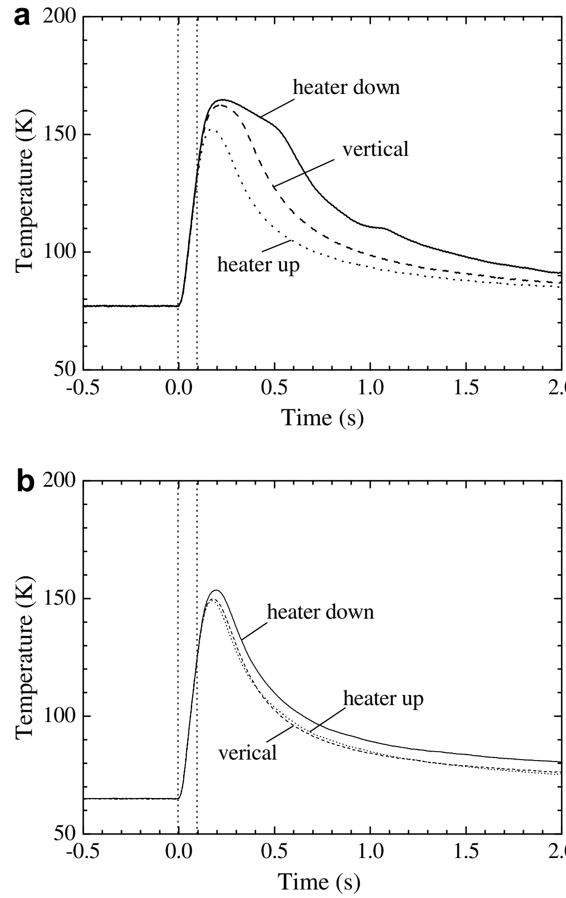

Fig. 5. Measured temperature history at different orientations for 100 W/cm^2 (a) 77 K, 101 kPa, (b) 65 K, 101 kPa.

at 77 K saturated condition. It is clearly noticed that the temperature-increasing rate is independent of the orientation during the heating period, but the recovery is faster for the heating surface up than the vertical surface, and slower for the heating surface down. These phenomena are closely related with the behavior of bubbles. Obviously, the bubbles can escape more easily from the heating surface

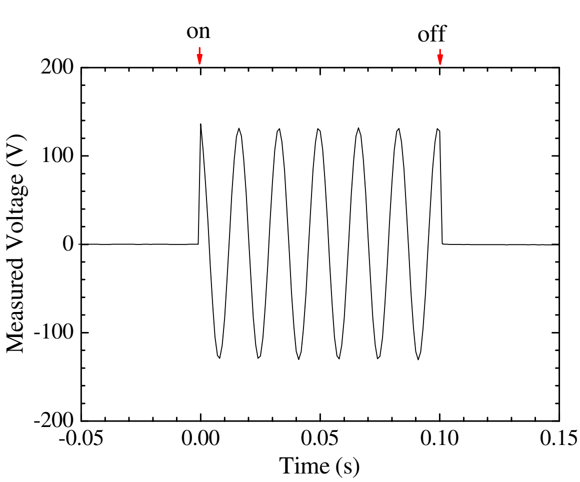

Fig. 4. An example of applied voltage to the heater ($V_{rms} = 90$ V, $f = 60$ Hz).

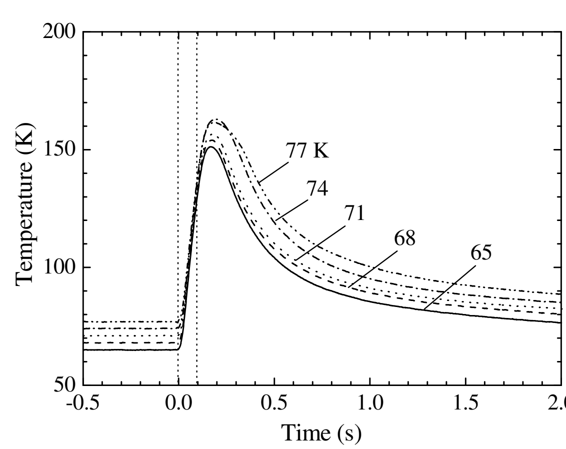

Fig. 6. Measured temperature history of vertical heater at different subcooling temperatures for 100 W/cm^2.

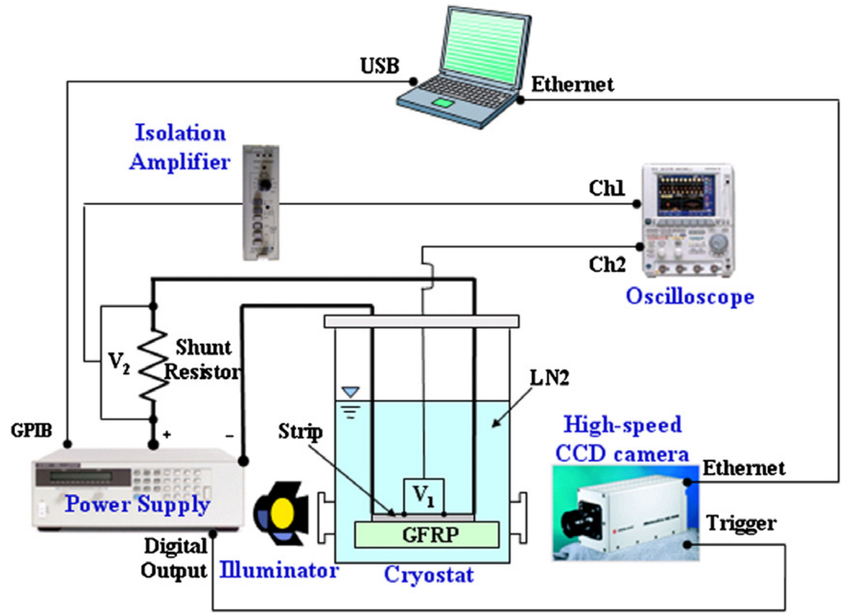

Fig. 7. Schematic overview of apparatus for visualization experiment.

when it faces up than when it faces down, which results in the difference of the recovery speed. On the other hand, the buoyant effect depending upon the surface orientations does not seriously affect the dynamic behavior of bubbles near the surface during the short heating period (100 ms).

Fig. 5b is the temperature history when liquid nitrogen is in a subcooled state at 65 K and all the other conditions are the same as in Fig. 5a. A distinctive feature of the curves in Fig. 5b is that the temperature change is much less dependent upon the heater orientation for the recovery period when compared with Fig. 5a. This means that the bubble behavior causes a little effect on the transient heat transfer of the heater under subcooled condition. Therefore, it seems plausible that even though the heat pulse may have caused temporary vaporization of liquid on the surface, the vapor is re-condensed immediately by the subcooled liquid.

We repeated the same heating procedure for the vertical orientation at various liquid-temperatures, and the temperature history is plotted in Fig. 6. It is right in general that the lower the liquid temperature is below 77 K, the lower is the peak temperature and the faster is the recovery. The curves in Fig. 6 can be divided into two groups, which means that the effect of subcooling becomes significant only if the degree of subcooling exceeds a certain limit (3–6°) in this specific case). We think this behavior is also closely related with the probability of bubbles on the surface in contact with the subcooled liquid. In Fig. 6, for example, no noticeable advantage in peak temperature and recovery is expected if liquid nitrogen is subcooled at 74 K, because 3 K of subcooling may not be enough to suppress bubbles. In order to take advantage of subcooling for HTS systems such as FCL, we strongly recommend that the liquid temperature should be less than 70 K at atmospheric pressure. In the next chapter, the bubble generation is directly observed by a high-speed camera to clearly show

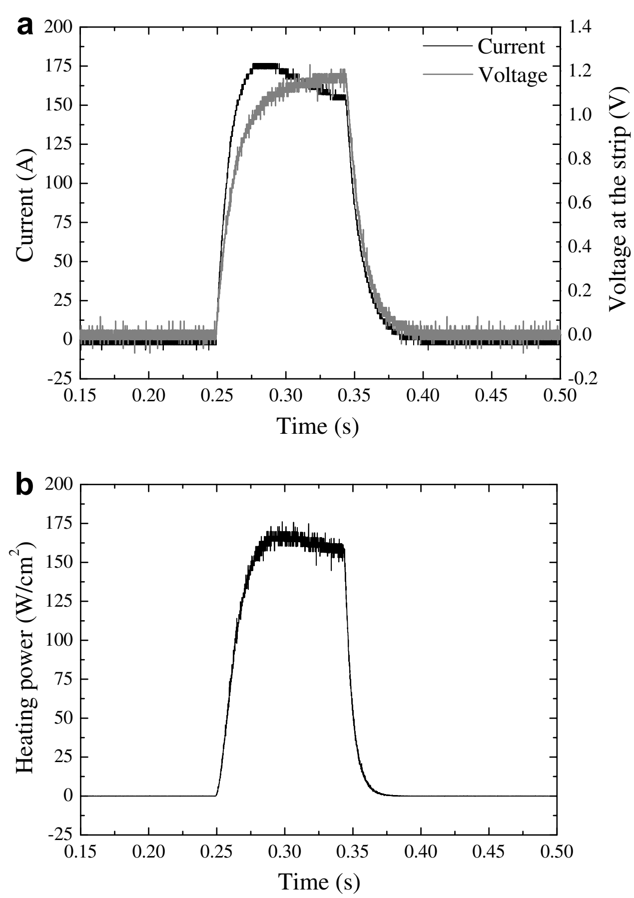

Fig. 8. An example of applied heating power for visualization experiment. (a) Current and voltage and (b) heating power profile.

the degree of the bubble suppression under subcooled operating condition.

3. Bubble visualization experiment

3.1. Experimental apparatus and instrumentation

The schematic diagram of overall experimental apparatus is shown in Fig. 7. The main functions of this experimental apparatus are to measure current and induced voltage through the heater and to observe through a cryostat window the behavior of nitrogen bubbles on the heater surface. A stainless steel strip is selected as a heating element and connected with the copper terminals by soft soldering method and is attached on the GFRP plate using epoxy. The thickness and the width of the strip are 0.3 mm and 4.1 mm, respectively. The distance between two copper terminals is 40 mm. Two signal wires are soldered on the surface of the strip in order to measure the resistivity of the strip. The distance between the signal wires is 14.0 mm.

The heat impulse is generated by a DC power supply (HP model 6671 A). The power supply is connected to a laptop computer through a GPIB-to-USB cable and an interactive program is developed to control the output of the power supply. The output current from the power supply is calculated from the voltage signal across a shunt resistor (2000 A–50 mV). The voltage signal across the shunt resistor is amplified by an isolation amplifier (YOKOGAWA model 3131). Fig. 8a is an example of the output current from the power supply and the induced voltage measured at the strip. The heat impulse profile per unit area corresponding to the current and voltage is shown in Fig. 8b. The area represents the surface area of the strip exposed to both liquid nitrogen and GFRP. The magnitude of heating power is calculated from the measured voltage and current at the strip. All the visualization results below are obtained under the impulsive heating as shown in Fig. 8b.

The test section is inserted in a cryostat, which has current leads, view ports and a vacuum jacket. The test section is aligned horizontally with the view ports and the strip faced upside in the cryostat. A high-speed CCD camera (Redlake model HG-100 K) is used to capture the generated bubbles from the heated strip. An illuminator is located on the opposite side of the camera, which brightens the test section inside the cryostat. The camera is triggered by the digital output from the DC power supply. The voltage signals from the shunt resistor (V_2) and the strip (V_1) are recorded in an oscilloscope (YOKOGAWA model DL1620).

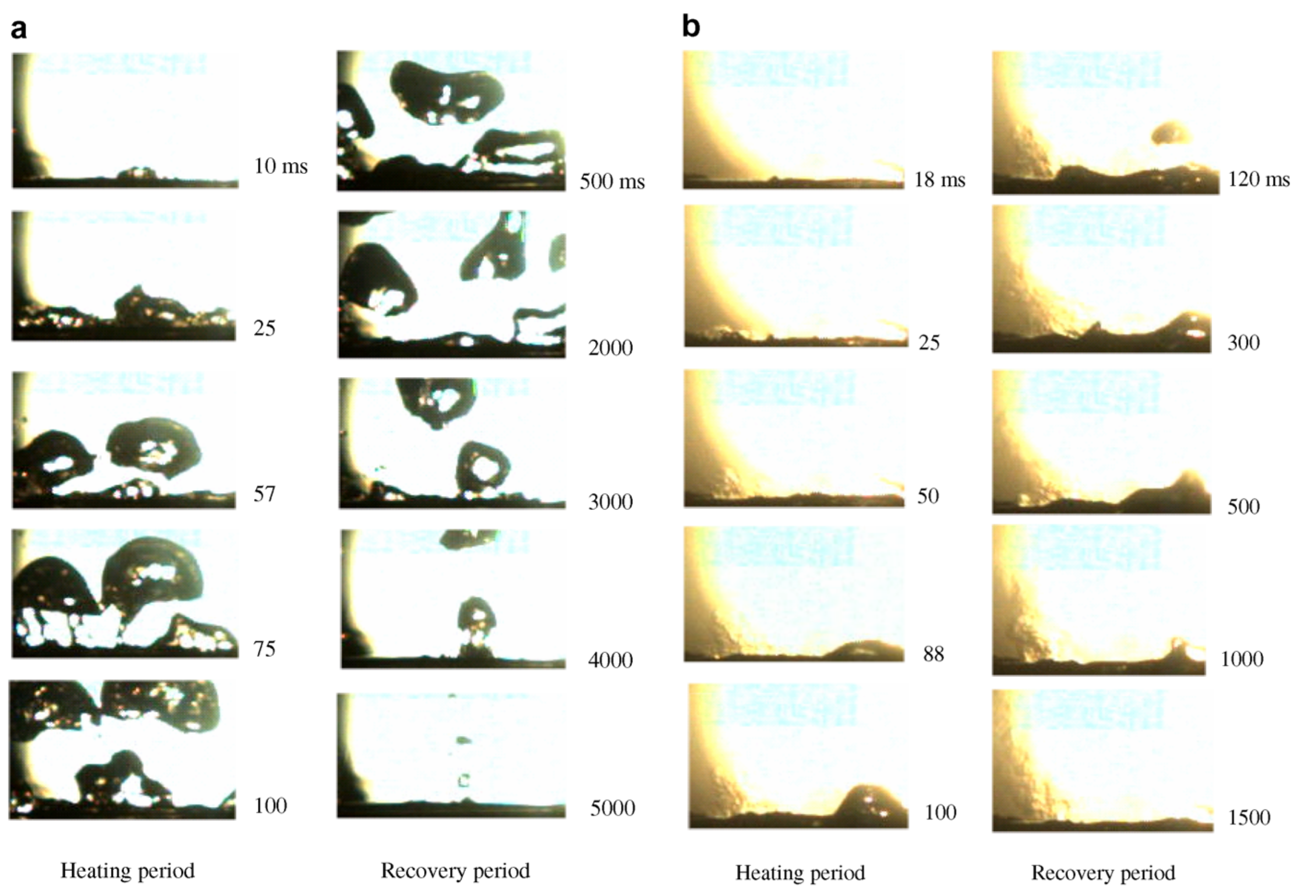

Fig. 9. Bubble generation history during the heating and the recovery period for different liquid nitrogen condition. (a) Saturated state at 77 K and (b) subcooled state at 65 K and 101 kPa.

A silicon-diode sensor (Lakeshore model DT670) is inserted in the cryostat and a dial pressure gauge is installed on the top plate of the cryostat to monitor the temperature of liquid nitrogen and pressure in the cryostat, respectively.

3.2. Visualization result of bubble suppression

In order to obtain the subcooled liquid nitrogen at 65 K, helium gas is supplied into the cryostat after the cryostat is evacuated down to the saturation pressure at 65 K (17 kPa) by a vacuum pump. Figs. 9 and 10 are the photographs of bubble generation for saturated and subcooled conditions just after the heat impulse starts. The bubbles are shown in the dark part of the photos as the illuminator is located on the opposite side of the camera. The width of each picture is approximately 20 mm.

Fig. 9a and b show the bubble generation history in saturated liquid nitrogen at 77 K and in subcooled liquid nitrogen at 65 K, respectively. Fig. 9b clearly demonstrates that the subcooled condition at 65 K and 101 kPa indeed suppresses the generated bubbles as compared with Fig. 9a. It is interesting to note that any bubble can not even be detached from the vapor film during the heating period for 65 K subcooled condition at atmospheric pressure. This may simplify a transient heat transfer model for calculating the temperature rise of the heated surface in subcooled liquid nitrogen because the modeling of complex bubble motion is not necessary. Fig. 9a and b also show that the recovery speed in the subcooled state is faster than in the saturated state due to the bubble suppression effect. The detached bubble can not move upward far away from the surface due to the strong re-condensation effect by nearby subcooled liquid as shown in Fig. 9b.

The effect of the degree of subcooling on the bubble suppression is shown in Fig. 10a through Fig. 10d. The degree of subcooling is regulated by helium gas pressure in the cryostat. The pressure is varied from 17 kPa (saturated condition without helium gas) to 70 kPa at 65 K. It is obvious from Fig. 10 that the suppression of the bubble generation is less effective as the pressure becomes low. The decrease of pressure corresponds to the decrease of subcooling effect. When the state of liquid nitrogen becomes the saturated condition at 65 K, the size of bubble is considerably bigger than that in the saturated condition at 77 K as shown in Fig. 9a and Fig. 10a. The main reason for this difference is that the density of nitrogen vapor is greatly reduced by a factor of five as temperature decreases from 77 K to 65 K maintaining the saturated state. Therefore,

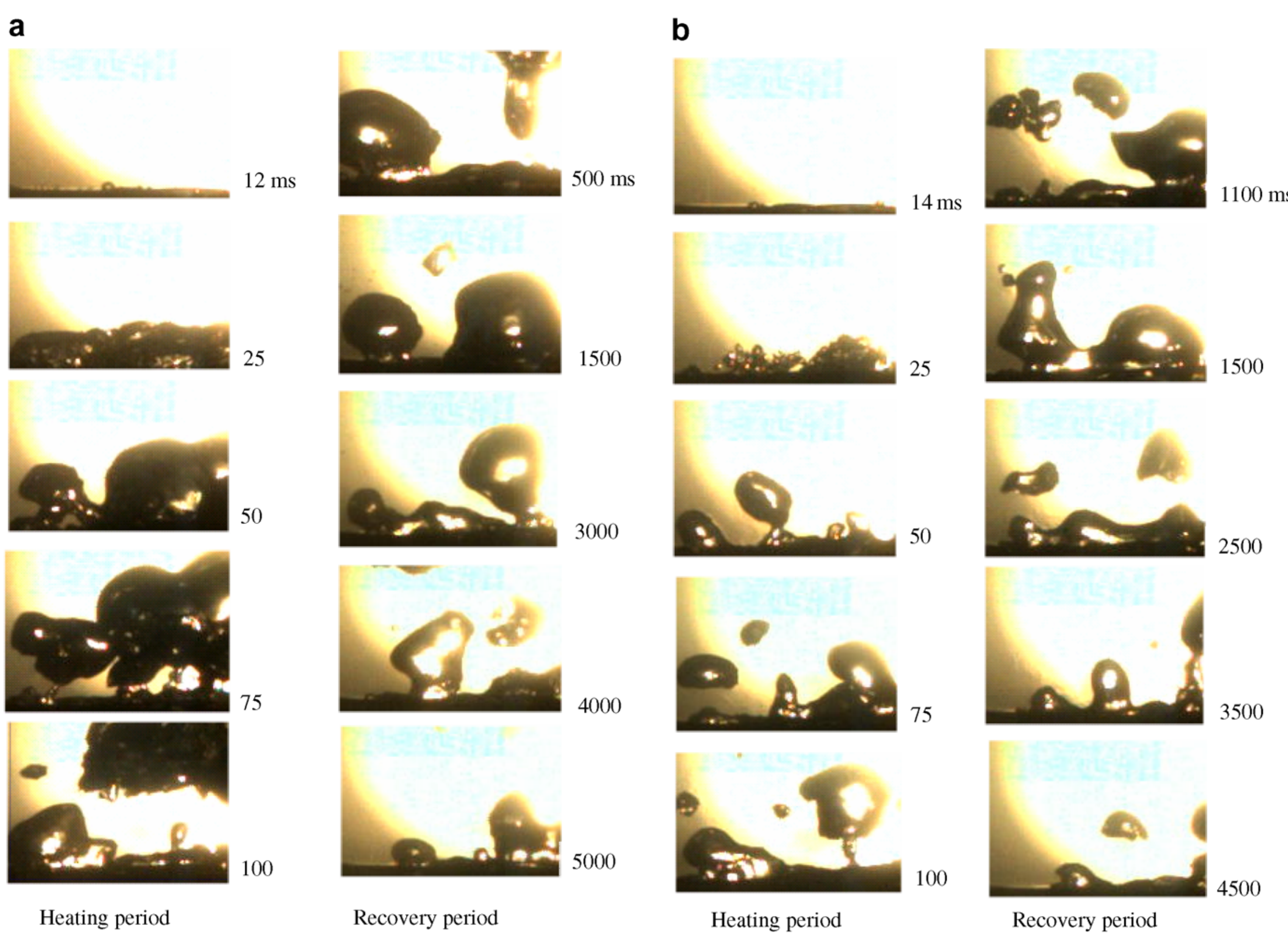

Fig. 10. Effect of degree of subcooling on the bubble suppression at 65 K (a) 17 kPa (no subcooling), (b) 25 kPa, (c) 50 kPa and (d) 70 kPa.

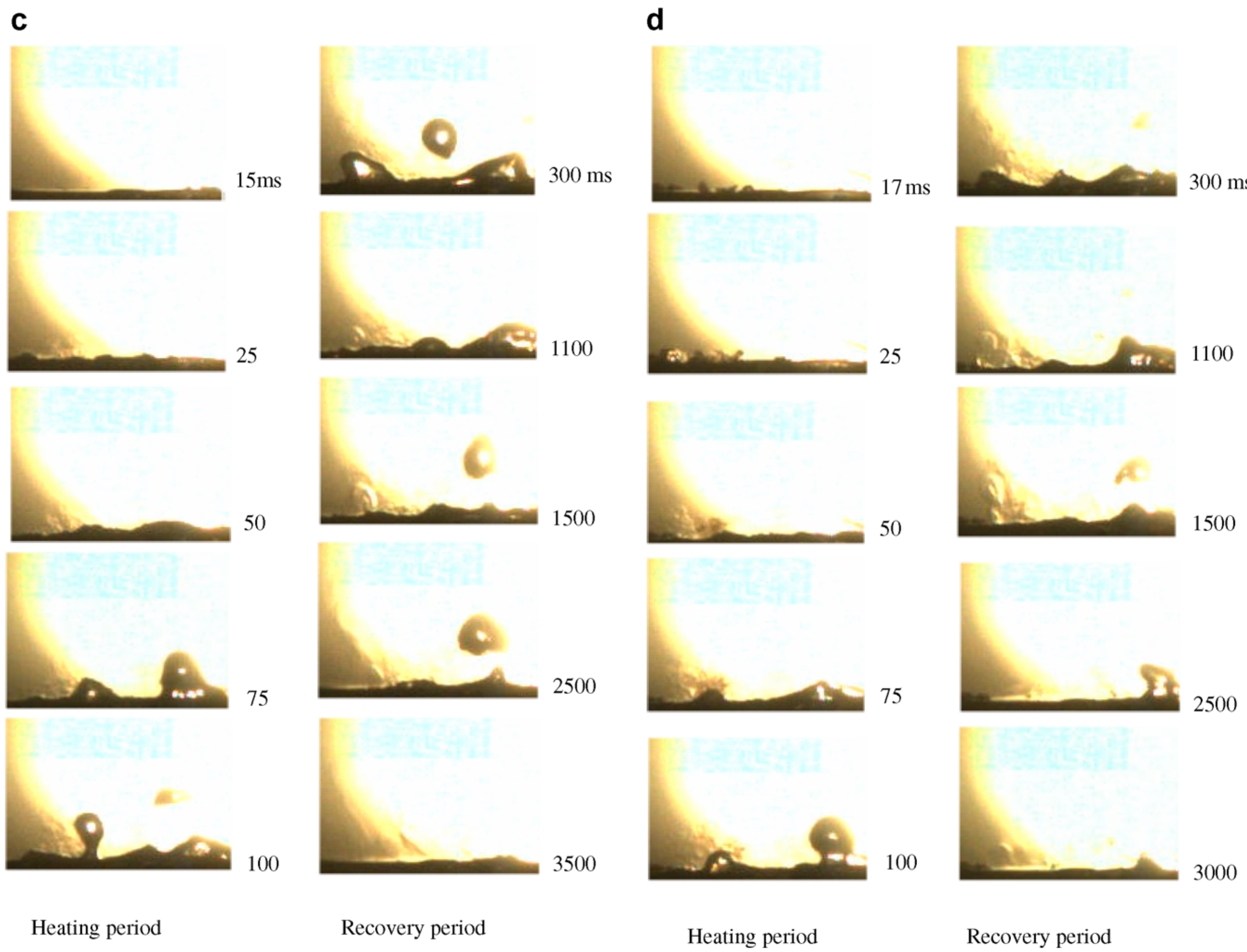

Fig 10. *(continued)*

the vapor bubble in the saturated liquid nitrogen at 65 K is easily expanded from the heated surface for the same heating power as the saturated state at 77 K. The generated bubble is extremely harmful for the insulation design of electric power machines due to its low breakdown voltage [9]. Consequently, the saturated liquid nitrogen at 65 K, in spite of its lower temperature than 77 K, is not suitable for the operation of high voltage HTS power machines due to the large size of the generated bubble during the quench.

4. Conclusions

Two parallel experimental methods lead us to a consistent conclusion that the subcooling of liquid nitrogen can effectively suppress bubbles when an impulsive heating is applied. From the temperature measurement experiment, the recovery speed is nearly independent of the heater orientation in subcooled condition, which indirectly shows that the generation of bubbles is less active in subcooled state than in saturated state. The subcooling temperature below 70 K at atmospheric pressure is effective in the suppression of bubbles. The visualization experiment reveals that the generated bubbles are re-condensed quickly in the subcooled liquid region. In the case of the subcooled state at 65 K and 101 kPa which is a typical operating condition of HTS machines, only vapor film is formed on the heater during the heating period when the heating power increases up to approximately 150 W/cm^2.

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