Cooling Rate and Lower Limit of Subcooled Film Boiling around a Vertical Finite-Length Cylinder to Subcooled Tap Water

Kaoru Toyoda

Maizuru National College of Technology, 234 Shiraya, Maizuru, Kyoto, 625-8511 Japan

Abstract

The shape and thickness of the vapor film under the bottom surface are important factors to understand the convective heat transfer by film boiling around a vertical finite-length cylinder as the vapor generated under the bottom surface grows thicker during flowing up along the vertical lateral surface and the vapor film covering the cylinder governs the total heat transfer rate. Both thicknesses of the vapor film and the scale generated owing to tap water might be comparable during subcooled film boiling. Therefore, the effect of scale on the shape and thickness of the vapor film should be examined experimentally. In this study, quenching experiments on film boiling heat transfer around a vertical finite-length aluminum cylinder to subcooled tap water were carried out to clarify the cooling characteristics and examine the effect of scale on film boiling. The test in experiments is repeated ten times in subcooled tap water with a liquid subcooling of 15 K at atmospheric pressure. The diameter and length of the test cylinder are 32 mm and 32 mm, respectively. The test cylinder was heated to about 560 degrees C in an electric furnace and then cooled in subcooled tap water with a submersion depth of 150mm. The body temperature was measured by a K-type sheath thermocouple placed near the center of the cylinder. The behavior of the vapor film around the cylinder was observed with still photography and video camera. The experimental data were presented in terms of cooling curve and cooling rate curve compared with the thickness of the vapor film at the center of the bottom surface. The effects of scale and the thickness of the vapor film at the center of the bottom surface on cooling rate and lower limit of film boiling were discussed.

Keywords: Film boiling, Lower limit of film boiling, Subcooled tap water, Scale, Cooling rate

1. Introduction

Cooling processes during film boiling around three-dimensional bodies occur in nuclear safety, metal quenching, manufacturing processes of materials, and so on. Many studies on the film boiling from a single surface [1, 2] have been carried out, such as a vertical surface, an upward facing surface, a horizontal cylinder, a sphere and so on; however it is still difficult to make accurate predictions about the heat transfer around three-dimensional bodies owing to insufficient knowledge of heat transfer processes.

The authors have proposed several practical correlations of the film boiling heat transfer from vertical finite-length cylinders, which achieved a certain result within the practical margin [3-5]. In these studies, data of the wall superheat at the lower limit of film boiling were also presented in order to show explicitly the lower limit where the film boiling correlations proposed by the authors were applicable. The correlations quantitatively evaluated heat transfer from the entire surface of the cylinder with three-surface model consisting of bottom, vertical lateral and top surface. For a vertical finite-length cylinder with flat bottom, a stable vapor film is formed under the downward facing horizontal circular surface and the vapor flows radially in the vapor film from the cylinder center to the edge by the hydrostatic pressure gradient due to both the vapor-liquid density difference and the gradient of vapor film thickness in the flow direction. The vapor reaching the edge flows up along the lateral surface with growing thicker by the vapor-liquid density difference and finally leaves from the top surface. Consequently, the shape and the thickness of the vapor film should be measured to improve the accuracy of the correlations as the vapor film covering the cylinder governs the total heat transfer. In addition, comprehensive investigations of the condition of the heat transfer surface and the thickness and shape of the vapor film are required to clarify the mechanism of the collapse of the vapor film as the condition of the heat transfer surface affects lower limit of film boiling [6]. In this study, the effect of scale on the shape and the thickness of the vapor film under the bottom surface which govern the heat transfer characteristics of the entire surface of a vertical finite-length cylinder will be examined experimentally by changing the surface condition using subcooled tap water from a practical perspective.

2. Experimental apparatus and procedure

Fig. 1 shows the experimental apparatus, made up of a cylinder, a boiling bath, cylinder-heating furnace, lifting device, temperature measurement system and observational system for quenching phenomena. The boiling bath with an inside dimension of 300×300×450 mm is made of steel, and glass windows are placed on the lateral and the bottom sides for viewing the quenching phenomena. The test liquid is tap water at atmospheric pressure and heated up indirectly by two 1 kW immersion heaters. The glass box with a dimension of 250×200×400 mm is placed between the heaters and the cylinder to prevent bubbles generated on the heaters from disturbing the test liquid around the cylinder. The water temperature is kept at 85°C by temperature controller.

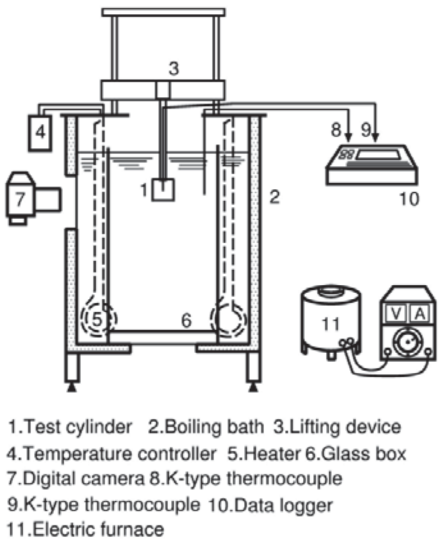

Fig. 1 Experimental apparatus

*Corresponding Author:E-mail: toyoda@maizuru-ct.ac.jp, 81-773-62-8936, 81-773-62-8936

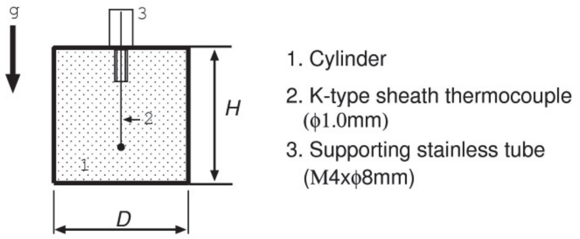

Fig. 2 Aluminum cylinder

Fig. 2 shows cross-sectional view of the finite-length cylinder used in this study. The diameter and the height are 32mm and 32mm respectively. The test cylinder is made of 99.7% pure aluminum to prevent surface oxidizing and of which the surface is mirror-finished. The temperature history is measured by K-type thermocouple with an outside diameter of 1mm placed at the position of 24mm from the top surface. The sampling time is 0.2 seconds. After heated to 560 degrees C in an electric furnace, the test cylinder was submerged with a depth of 150mm into subcooled tap water. The quenching phenomena around a cylinder were observed by viewing video camera footage and photograph image.

3. Measurement of temperature

The inner part of the test cylinder is assumed to be cooled uniformly and its temperature is calculated as a lumped parameter system because the test cylinder is made of aluminum which inherently has high thermal conductivity. A small Biot number which was estimated to be less than 0.04 and the numerical calculation results of the two-dimensional unsteady heat conduction in the cylinder confirm the assumption for a lumped parameter system. In this study, the lower limit of film boiling is defined as the point where the cooling rate, - $dT/d\tau$, gives a minimum value and the corresponding wall superheat is referred to as ΔT_{min}.

4. Observation of Film Boiling

Fig. 3 shows the behavior of the vapor film formed around the test cylinder of the first test. In these figures, τ and T show the elapsed time from the beginning of the cooling process and the temperature of the test cylinder respectively. The behavior of film boiling is calm and the thickness of the vapor film covering the test cylinder is thin. The vapor generated under the bottom surface flows upward along the vertical lateral surface and then leaves from the vapor liquid interface on the top surface. The vapor film under the bottom surface and the lower end of the lateral surface is stable and of which vapor liquid interface is approximately smooth, while the vapor liquid interfaces on the upper end of the lateral surface and top surface are wavy. As shown in Fig.3, concentric ripples are formed on the vapor liquid interface both under the bottom surface and on the vertical lateral surface. The vapor film under the bottom surface cycles through becoming thick or thin several times and then the vapor film collapses as shown in Fig.3 (d) to Fig.3 (p). The fluctuation in the thickness of the vapor film is not periodic. The collapse of the vapor film occurs at the lower corner of the cylinder as shown in Fig.3 (p) and spreads out the entire heat transfer surface by 5 seconds roughly. The propagation speed of the collapse of the vapor film becomes slower with increasing the test run number.

Fig. 3 Photographs of vapor film covering a vertical finite-length cylinder

5. Heat transfer surface

Fig.4 shows the surface of the cylinder before the test and after the test. The mirror-finished surface before the test whitened after the test. Scale seems to adhere to the surface of the cylinder as the surface of the cylinder does not whitened after heating up and cooling it in the air. With the mirror-finished surface the average surface roughness, Ra is 0.147μm, while for the surface to which scale adhered is 0.300μm using a laser microscope.

Ishikawa et al. [7] reported that the thickness of scale adhered to inner surface of boiler tubes is not uniform and thermal conductivity of the scale estimated from 1.7 to 2.4 W/m·K.

(a) Before the 1st test (b) After the 10th test

Fig.4 Conditions of the surface

6. Results and discussion

6.1 Cooling curves

Fig.5 shows cooling curves taking the test run number as a parameter. The surface of the cylinder is mirror-finished only once before the first test. The temperature of bulk liquid is at 85 degree C. The solid circle in each cooling curve shows the lower limit of film boiling, where the corresponding cooling rate gives a minimum value. The test run number does not substantially affect slope of the cooling curve. However, the lower limit of film boiling shift to shorter elapsed time and higher temperature with increasing the test run number. The tendency was same in experiments while the lower limit of film boiling was not agree with the result of the other experiment.

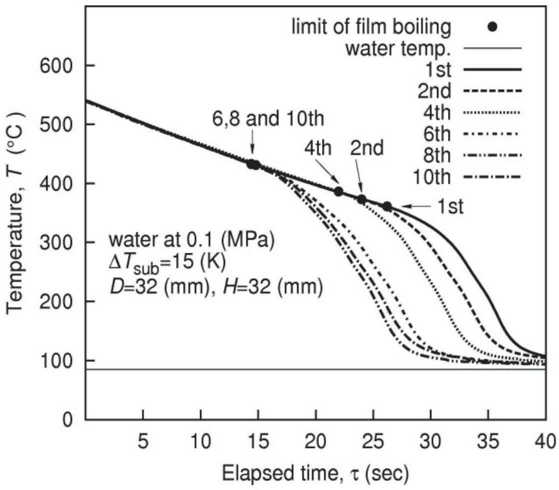

Fig. 5 Cooling curves

6.2. Vapor film thickness at the center of the bottom surface

Fig.6 shows the cooling rate, - dT/dτ, and the thickness of the vapor film at the center of the bottom surface, δ, against the elapsed time, τ. Prior to the test, the surface of the cylinder is mirror-finished, which is the same condition as the first test in Fig.5. The symbols from (a) to (p) in Fig.6 illustrate the symbols in Fig.3 as shown before. The thickness of vapor film at the center of the bottom surface is measured by the binary image in using the digital still image extracted from motion picture taken by 30 frames per second and the shutter speed of 1/4000 seconds. The maximum error of measurement for the thickness of the vapor film at the center of the bottom surface was estimated to be less than 0.1 mm.The thickness of the vapor film at the center of the bottom surface reaches a maximum at 3.2 seconds and has a tendency to become thinner with duration. From 16 seconds to 34 seconds, the thickness of vapor film at the center of the bottom surface cycles through becoming thick or thin several times and then the vapor film collapses. From 16 seconds to 22 seconds, the thickness of the vapor film affects the cooling rate: the cooling rate increases when the thickness of the vapor film decreases and the cooling rate decreases when the thickness of the vapor film increases.

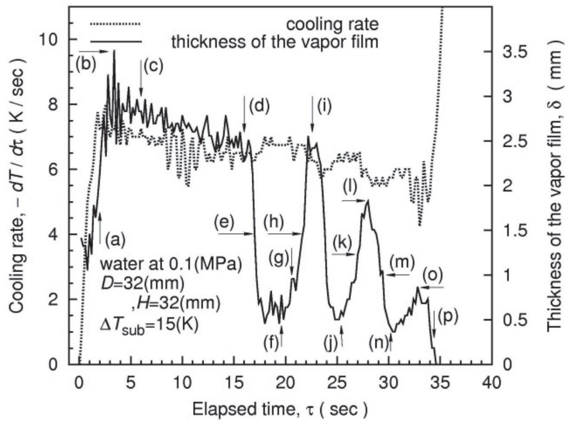

Fig. 6 Cooling rate and vapor film thickness variations

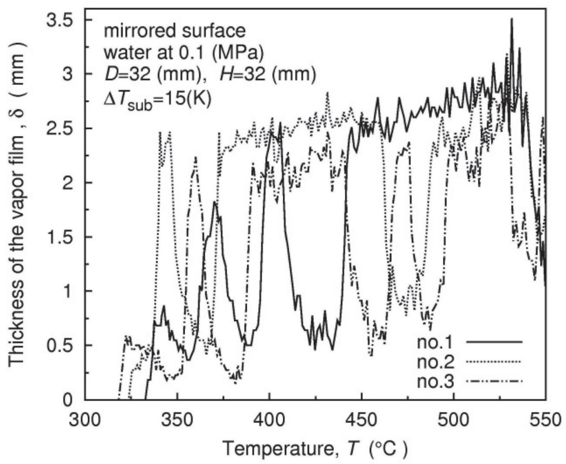

Fig. 7 Vapor film thickness variations

Fig. 7 shows the thickness of the vapor film at the center of the bottom surface against temperature. Prior to the test, the surface of the cylinder is mirror-finished every time, which is the same condition as the first test in Fig.5. The fluctuation of the thickness of the vapor film is not periodic. The start point where the thickness of vapor film becomes thin does not have reproducibility in the three results.

6.3 Lower limit of film boiling

Fig.8 shows the wall superheat at the lower limit of film boiling, ΔT_{min}, against liquid subcooling, ΔT_{sub}, taking the test run number as a parameter. The figure also shows the following relationships: equations of Momoki et al. [5] for the wall superheat at the lower limit of film boiling and Lienhard [8] for the thermodynamic limit of liquid superheat. The experimental results presented by solid circles in the figure are higher than the wall superheat at the lower limit of film boiling by Momoki et al. and the thermodynamic limit of liquid superheat by Lienhard. The wall superheat at the lower limit of film boiling depends on the test run number and increases with it. The wall superheat at the lower limit of film boiling appears to depend on the scale, the shape of the vapor film and the turbulence of the liquid outside of the vapor-liquid interface with high-speed vapor flow around the lower corner of the cylinder and so on. Additional research is required to elucidate the mechanism of the vapor film collapse.

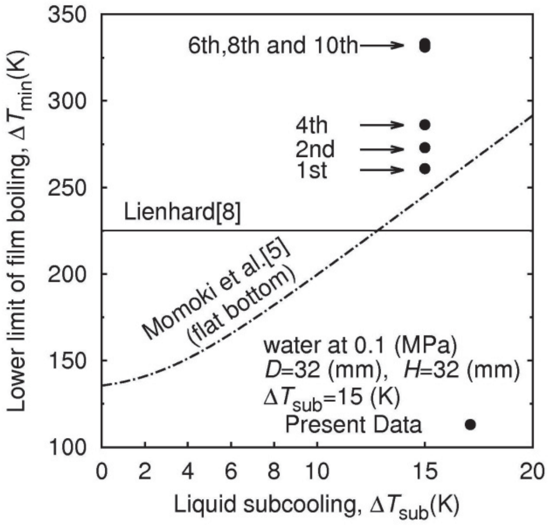

Fig. 8 Lower limit of film boiling

7. Conclusions

The effect of scale on the shape and the thickness of the vapor film under the bottom surface which govern the heat transfer characteristics of the entire surface of a vertical finite-length cylinder were clarified experimentally by changing the surface condition using subcooled tap water and the following conclusions were obtained.

- The vapor film under the bottom surface cycles through becoming thick or thin several times and then the vapor film collapses.
- The fluctuation of the vapor film thickness is not periodic.
- The propagation speed of the collapse of the vapor film becomes slower as increasing the test run number.
- The lower limit of film boiling depends on the test run number and increases with it.

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