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International Journal of Heat and Mass Transfer 45 (2002) 4361–4366

International Journal of HEAT and MASS TRANSFER

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Technical Note

Thermal mixing in a water tank during heating process

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Received 29 August 2001; received in revised form 11 April 2002

Abstract

For application to the thermal analyses and designs of passive residual heat removal systems adopted in advanced reactors, thermal mixing characteristics in a water tank have been studied experimentally. Through the tests a fixed heat flux is supplied continuously from the two heating tubes installed horizontally or vertically in the tank until the water is saturated. According to the results, it is identified that the elapsed time to saturate the water is almost the same regardless of tube orientations. Moreover, it is demonstrated that vertical thermal stratification is formed along the tank during the heating process.

1. Introduction

One of the most effective ways to improve current pressurized water reactors is to adopt passive decay heat removal systems for the purpose of long-time core cooling without any external power supply and operators action. In the systems, water and/or steam circulate naturally to prevent core melting [1,2]. One of the most important facilities for the system is a passive heat exchanger that transfers core decay heat to the cold water in the water storage tank under atmospheric pressure. To find out a possible way to improve the heat exchanger design, Chun and Kang [3] had studied extensively to obtain the effect of geometric parameters on the saturated pool boiling heat transfer. Nevertheless, no detailed study has been done yet to identify the thermal mixing characteristics in the water during the heating process.

Since the water in the tank is subcooled initially, it takes more than 2 h (for the case of AP600 IRWST, in-containment refueling water storage tank) to reach the saturation temperature [4]. Accordingly, assumption of the saturated water for the initial tank condition could result in erroneous results. According to Judd et al. [5] heating surface temperature can be increased due to active site density decrease in subcooled liquid state. This means that the temperature of the tube inside (the primary side of the nuclear power plant for the present) is also increased, and this increase could be a cause of departure from nucleate boiling at the surface of the fuel bundles in a nuclear reactor. Therefore, it is necessary to obtain a proper heat transfer coefficient during the heating times to avoid a severe accident due to the increase of the water temperature in the primary side. To calculate the heat transfer coefficient it is necessary to identify the thermal mixing in the water. Corletti and Hochreiter [6] performed an experiment to characterize the mixing behavior of the scaled IRWST. For the test, they used a cylindrical tank and a vertical heat exchanger. However, more detailed analyses on the mixing behavior and heat transfer are needed. Moreover, to expand the applicability of the results to the other geometries it is necessary to identify the mixing characteristics for the other sets of water tank and heat exchangers.

In this study, some tests have been performed for a cubical type water tank and horizontal or vertical heat exchangers to obtain the thermal mixing in the water tank. In addition, heat transfer coefficients on the tube surface have been obtained.

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0017-9310/02/$ - see front matter
PII: S0017-9310(02)00146-1

Nomenclature

A	heat transfer area	q''	heat flux
D	tube outer diameter	t	time
H	height from the tank bottom	T_s	tube wall temperature
h_b	boiling heat transfer coefficient	T_{sat}	saturated water temperature
I	supplied current	T_{wat}	water temperature
L	tube length	V	supplied voltage
q	input power	ΔT	temperature difference ($T_s - T_{wat}$)

2. Experiments

A schematic view of the present experimental apparatus and the locations of thermocouples are shown in Fig. 1. The water storage tank is made of stainless steel and has a rectangular cross section (790 × 860 mm) and a height of 1000 mm. This tank has a glass view port (595 × 790 mm) which permits viewing of the tubes and photographing. The heat exchanger tubes are simulated by resistance heaters made of stainless steel tubes ($L =$ 530.5 mm, $D = 19.05$ mm). The tube surface are polished uni-directionally (vertically) by sandpaper (#800) and the root mean square value of the surface roughness is 60.9 nm (measured by the phase measuring interferometer). The surface temperatures of the tube were instrumented with five thermocouples outside the surface of the tube. The thermocouple tip (about 10 mm) has been bent at an angle of 90° and brazed to the tube wall. For vertical tube tests, the heated tubes are placed at 80 mm from the tank bottom and 290 mm from both sides. In horizontal tube tests, on the other hand, the tubes are situated at 400 mm from the tank bottom and 130 mm from both sides.

After the water storage tank is filled with water until the initial water level is reached at 730 mm, the water is then heated using two tubular heaters at constant heat flux (i.e., $q'' = 145$ kW/m^2). Through the heating process, temperatures of the water and tube surfaces are measured. When the water temperature is reached at a saturation value (i.e., 100 °C since all the tests are run at atmospheric pressure condition) the tests are terminated. The uncertainty (errors from measurement, instruments, and environmental conditions) in the heat flux and surface roughness is estimated to be ±1.0% and ±5.0 nm,

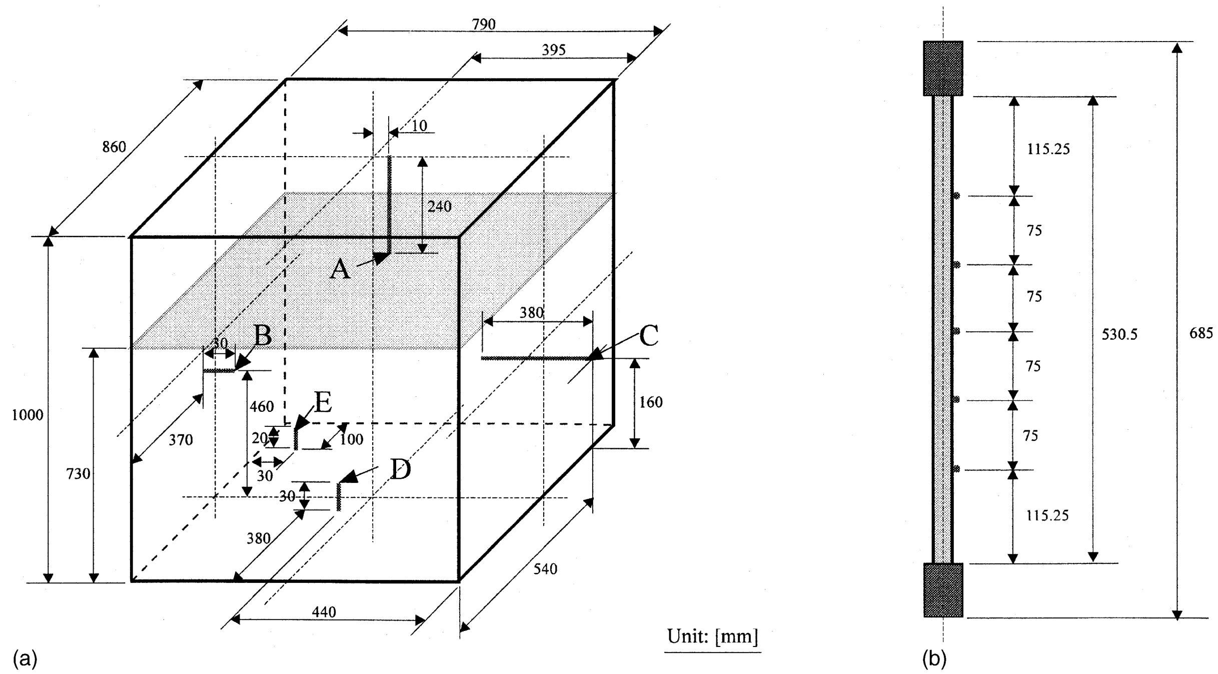


Fig. 1. Locations of the thermocouples: (a) water storage tank, (b) heated tube.

respectively. The uncertainty in the measured temperature is estimated to be ± 0.7 K including errors from thermocouple compensation (± 0.1 K), multiplexer reading (± 0.1 K), and thermocouple sensing (± 0.5 K).

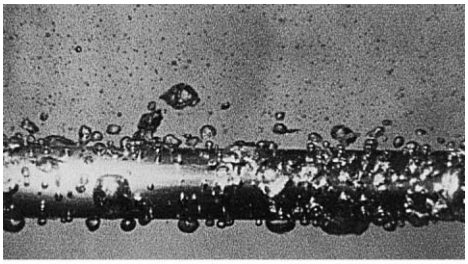
The heat flux from the electrically heated tube surface is calculated from the measured values of the power input as follows:

$$q'' = \frac{q}{A} = \frac{VI}{\pi DL} = h_{\mathrm{b}}(T_{\mathrm{s}} - T_{\mathrm{wat}}) = h_{\mathrm{b}}\Delta T \tag{1}$$

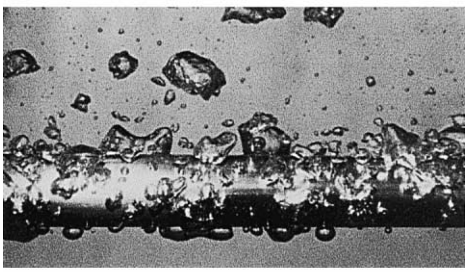
where V and I are the supplied voltage (in volt) and current (in ampere), and D and L are the outside diameter and the length of the heated tube, respectively. T_{s} and T_{wat} represent the measured temperatures of the tube surface and the water, respectively.

3. Results and discussion

Subcooled boiling phenomena on a horizontal tube surface is shown in Fig. 2. For the test, three thermocouples are newly installed. Fig. 2(a) and (b) show results for the different water subcooling while heat flux supply is kept constant. As the subcooling is higher (for the case of Fig. 2(a)) bubbles departed from the surface disappear rapidly. Moreover, relatively small bubbles can be observed due to weak bubble coalescence with other bubbles. When the water subcooling becomes less after some more heating (for the case of Fig. 2(b)), bigger bubbles are observed and bubbles departed from the surface move upward. But, the bubble size and the frequency of departure are very smaller than the saturated boiling [3]. Fig. 3 shows subcooled boiling phenomena on the tube surface installed vertically. Bubbles on the vertical tube surface are smaller than that of horizontal tube.



(a) T/C1=94.5 ℃, T/C2=71.1 ℃, and T/C3=22.1 ℃

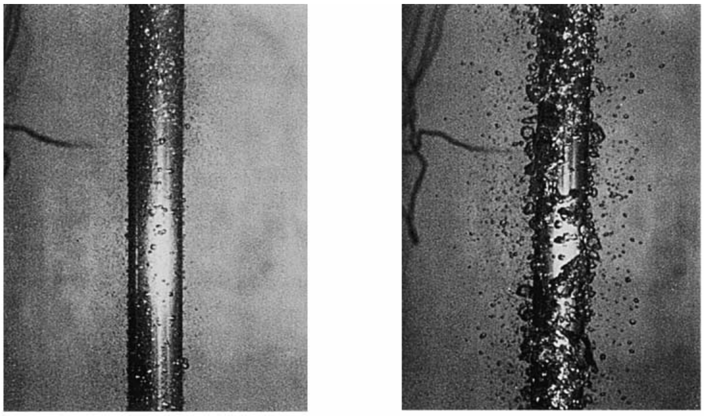


(b) T/C1=96.6 ℃, T/C2=97.0 ℃, and T/C3=23.2 ℃

Fig. 2. Bubble generation on the horizontal tube surface in the subcooled water (elevation of the thermocouples are T/C1 = 550 mm, T/C2 = 300 mm, and T/C3 = 50 mm).

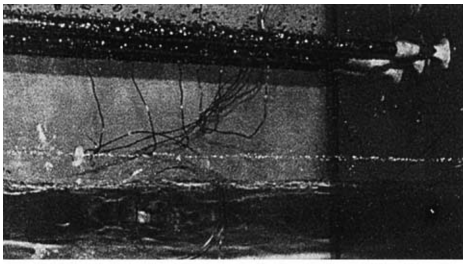
It is demonstrated that vertical thermal stratification is formed along the tank in which a clear interface could be observed during heating process as Corletti and Hochreiter [6] observed. Fig. 4 shows the interface for both horizontal and vertical tubes. There is a large vertical temperature gradient between the upper and the lower parts of the interface. The upper part heated up very fast whereas the lower part is being around the initial water temperature for a long time. The temperature of the lower part remains almost the initial water condition. At 10,000 s, when the uppermost elevation is at 97.3 °C, there is an 80.5 °C vertical gradient between the upper elevation (460 mm) and lower elevation (20 mm) for the case of horizontal tubes. As the heating continues the interface moves downward. Two thermal-hydraulic mechanisms can be suggested for the movement: first, heat transfer (advection + conduction) due to temperature differences. Since there are much temperature difference through the interface, the cold liquid moves upward as heat transferred from the hotter region. Second, shearing force due to liquid flow. The liquid over interface circulates through the space along the tube, water surface, and the interface whereas the liquid under the interface remains almost static. The difference in velocity generates shearing force through the interface, and it tears out the cold liquid to the upper region. This is very much similar to the mixing of stratified liquids by mechanical stirring [7]. For the present case, the action of bubbles provides the mechanical stirring.

The vertical temperature distribution through the water tank is shown in Fig. 5. The variation of the temperatures is measured at five different elevations (Fig. 1) during the heating process. The heated plume that surrounds the tubes flows up to the top of the tank and spreads across the top of the tank as a hot liquid layer. This hot liquid layer displaces colder liquid that flows down the tank and is drawn to the hot tubes, completing the natural circulation pattern. The rapid temperature increase shown in the figure is due to vertical thermal stratification. As the interface touches a thermocouple, then, its temperature increases suddenly. However, somewhat different mixing behavior is observed between horizontal and vertical tubes. The graph of temperature versus time for the thermocouple C (150 mm above tank bottom) well represents the difference. The temperature for the thermocouple C remains almost at the initial condition in horizontal tubes before the interface meets the thermocouple. Otherwise, it increases continuously in vertical tubes. This is due to the characteristics of horizontal and vertical tube [8]. In

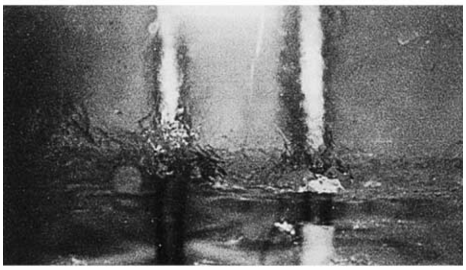


(a) T/C1=75.2 ℃, T/C2=67.8 ℃, and T/C3=22.9 ℃ (b) T/C1=96.0 ℃, T/C2=96.5 ℃, and T/C3=26.5 ℃

Fig. 3. Bubble generation on the vertical tube surface in the subcooled water (elevation of the thermocouples are $T/C1 = 550$ mm, $T/C2 = 300$ mm, and $T/C3 = 50$ mm).



(a) Horizontal Tube



(b) Vertical Tube

Fig. 4. Thermal stratification layer.

horizontal tubes, liquid over the tubes is heated rapidly whereas liquid under the tubes is heated slowly before the hot and active water flow approaches. However, in vertical tubes, bubbles departed from the tube surface moves toward the water surface agitating and warming the relevant water. Therefore, preliminary liquid heating by the bubbles is expected in vertical tubes. Since heat supply is somewhat distributed through the tank height in vertical tubes, the time to meet the thermal interface (i.e., abrupt temperature difference layer) is slower than the horizontal tubes. Nevertheless, the time for the water to be saturated is almost same for both tube cases (i.e. about 18,000 s). There is excellent radial mixing (see the temperatures of D and E) for both horizontal and vertical tubes as Corletti and Hochreiter [6] observed.

Fig. 6 shows the local heat transfer coefficient on the tube surface versus height from the tank bottom for the vertical tubes. Several test results for various heating times are plotted. Since the upper regions are heated up earlier than the lower sides, faster fluid velocity and stronger bubble agitation are expected at the upper elevation. These changes in fluid velocity and bubble agitation result in the increase in heat transfer coefficient. At 10,000 s, the values of heat transfer coefficients at the lower elevation (195.25 mm) and higher elevation (495.25 mm) are 3.8 and 9.29 kW/m^2 K, respectively. As time passes these changes get larger. The ratio between two heat transfer coefficients at the upper and lower elevations are 1.28 ($= 3.9/3.04$) at 5000 s whereas it is 2.44 ($= 9.29/3.8$) at 10,000 s.

Fig. 7 shows the changes in heat transfer coefficients due to water subcooling. The data for the subcooled water in the figure are local values and have been calculated using the measured temperatures of the tube surface and the water at same elevation. The datum for the saturated water, on the other hand, has been calculated by the empirical correlation suggested by Kang [1]. There are many changes in heat transfer coefficients as the level of water subcooling changes. The heat transfer coefficient gets increased as the level of subcooling is decreased. The same results had been reported by Celata et al. [9] for the boiling of binary mixtures. As shown in the figure the heat transfer coefficient for the saturated water is five times ($= 15.4/3.08$) larger than that for the highly subcooled water (i.e., $T_{sat} - T_{wat} = 59.2$ K). The major cause for the difference is presumed as weak liquid agitation and the active site density decrease in the subcooled water. The data for the subcooled and saturated water can be fitted as a fourth order polynomial curve as shown in the figure.

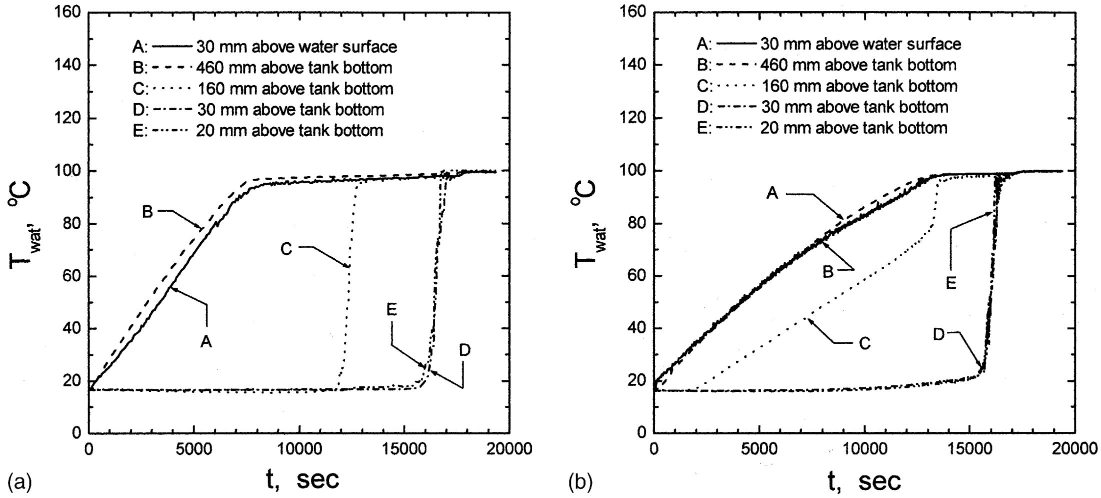


Fig. 5. Water temperature versus heating time: (a) horizontal tubes, (b) vertical tubes.

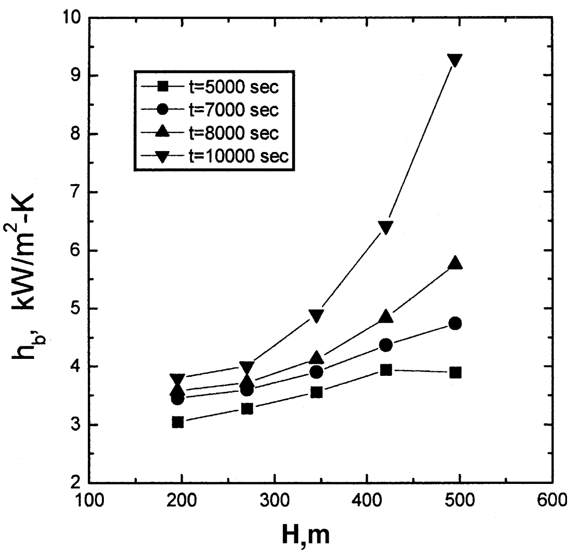


Fig. 6. Heat transfer coefficient versus height from the tank bottom for various heating time (vertical tubes).

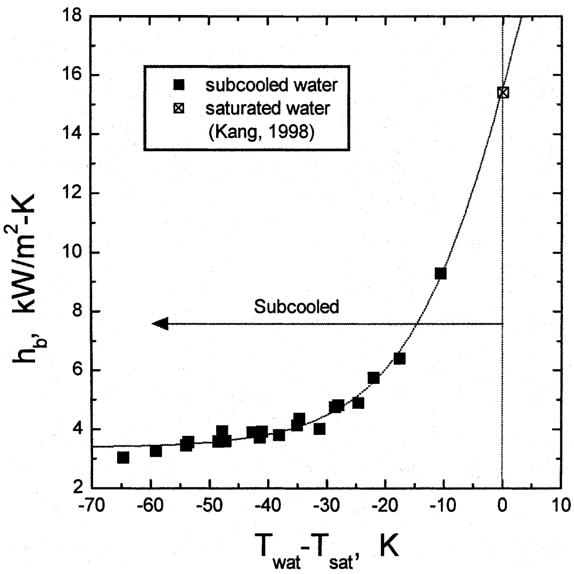


Fig. 7. Variation in heat transfer coefficient due to water subcooling (vertical tubes).

4. Conclusions

The major conclusions drawn from this experimental investigation may be stated as follows:

(1) The elapsed time to saturate the water is almost the same regardless of tube orientations.
(2) It is demonstrated that vertical thermal stratification is formed along the tank.
(3) A large vertical temperature gradient is measured between the upper and the lower parts of the interface whereas there is excellent radial mixing.
(4) There are many changes in heat transfer coefficients due to water subcooling.

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