TRANSIENT HEAT TRANSFER DURING QUENCHING OF A VERTICAL HOT SURFACE WITH BOTTOM FLOODING

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Transient boiling heat transfer on a vertical surface of a rectangular parallelepiped was measured during bottom flooding. This study is conducted to make it clear 1) that the analytical solution for two dimensional inverse heat conduction problem (2D-IHCP) [1] proposed by the authors, is applicable to estimate transient heat transfer and position of wetting front from measured solid temperatures, 2) that how flooding velocity, coolant temperature and thermal properties of solid affect on cooling heat transfer and rewetting velocity and 3) that thermal conditions governed establishment of wetting situation on a hot surface and rewetting velocity. The solution of 2D-IHCP successfully estimates wall temperature, heat flux and position of wetting front from measured block temperatures.

INTRODUCTION

Since heat transfer rate on a surface whose temperature is higher than Leidenfrost temperature, dramatically changes whether the surface is wetted or not, rewetting process plays important roles during transient cooling like quenching of material, emergency core cooling system. The wetting velocity specifies distribution of coexisting multiple transfer regions such as film boiling, transition boiling, nucleate boiling and convective heat transfer. Therefore, what governs the rewetting phenomenon becomes very important to estimate transient cooling of a hot surface with liquid. Recently outer wall cooling of a reactor pressure vessel (RPV) with water has been studied to evaluate safety assessment during the severe hypothetical accident when deposit of melted core heats the bottom of the inner wall. The feature is that the wall has larger heat capacity than existing study's one, and heat conduction in a solid is strongly coupled with the heat transfer on a hot surface.

EXPERIMENTAL SET-UP AND PROCEDURE

The whole of experimental setup shown in Fig.1 is made up of the three parts, 1) boiling vessel, 2) liquid supply system and 3) data acquisition system. The boiling vessel contains a rectangular parallelepiped whose height, width and thickness are 100, 120 and 20 mm respectively, and one vertical surface of 100 x 20 mm serves as a cooling surface. The block is made of copper, brass (70%Cu, 30%Zn) or carbon steel (0.45%C). Longitudinal temperature distributions (in x direction) along the center at two depths of $y = 2$, 5 mm from the surface are measured with 16 thermocouples. During experiment the cooling surface is also observed with a video camera to record moving water level and wetting front. The liquid supply system feeds water at temperature of 20, 50 or 80 ^{o}C from the storage tank to the bottom of boiling vessel at a flooding velocity u_l of 1, 3 or 9 mm/s. Time averaged flooding velocity u_l is decided from the video image. The data acquisition system samples and records the block temperatures and liquid temperature. The experimental procedure is as follows.

The block 2 is uniformly heated at 300 ^{o}C by the block heater 3 and the adiabatic heaters 4. Nitrogen gas replaces the air in the boiling vessel 1 to prevent the hot surface from oxidizing.

After steady state of each temperature reading is confirmed, all heaters are cut off and then the cock 9 is open to start an experiment.

EXPERIMENTAL FINDINGS AND DISCUSSION

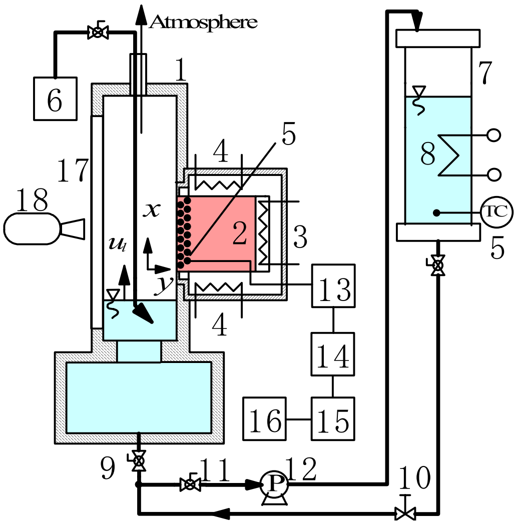
Observation of Boiling Phenomenon

Figure 2 shows a typical boiling situation during flooding. Indeed the photo is slightly obscure due to capturing from video image, but we can know that heat transfer area is divided into three regions, namely, film boiling, nucleate boiling and natural convection. The wetting front, which separates non-wetted and wetted area, moves up behind the rising water level. Distance between the water level and the wetting front shows a tendency to be longer as decrease in liquid subcooling or increase in flooding velocity and thermal inertia $\rho c \lambda$ of the block.

Estimated Surface Temperature and Heat Flux

A typical temperature history in the copper block is shown in Fig.3. The hollow and solid symbols denote block temperatures at the depths 2 and 5 mm, and t_f denoted by the dashed line gives the time when water level reached the top of the heated surface. Each arrow gives the time arriving water level at the measuring position. As shown in Fig.3, a decrease in temperature at each position occurs prior to arrival of rising water level. On the contrary of this, the block temperature with poor heat conductivity like carbon steel is found to decrease immediately after the water level reached to the measuring position. (Figure is omitted.)

Figures 4 (a) and (b) depict estimated distributions of wall temperature T_w and heat flux q_w against t and x with the solution of 2D-IHCP. The solid and dashed lines on the two surfaces show the change in T_w or q_w along the locus of position $x_{qmax}(t)$ where q_w reaches maximum heat flux q_{max} at each time and along the locus of wetting front $x_{wet}(t)$ decided by observations. As shown in this figure, $x_{qmax}(t)$ comes out behind $x_{wet}(t)$. The dash and dot line on the x-t plane gives the locus of water level. It should be noted that uncertainty of measuring position in machining of thermocouple wells makes estimated results unstable, especially in q_w, which requires a higher accuracy in the measurement than T_w. So we had to use a smoothed spline interpolation to regularize the error in the measuring positions. Then a stable estimated heat flux such as Fig.4 (b) was obtained.



1.Boiling vessel 2.Rectangular hot block 3.Block heater 4.Adiabatic heater 5.Thermocouple 6. Nitrogen gas cylinder 7.Liquid storage tank 8.Tank heater 9.Cock 10.Flow control valve 11.Recirculation cock 12.Pump 13.Ice box 14.Voltage amplifier 15.A/D converter 16.Personal computer 17.Window 18.Video camera

Fig.1 A schematic of the experimental apparatus

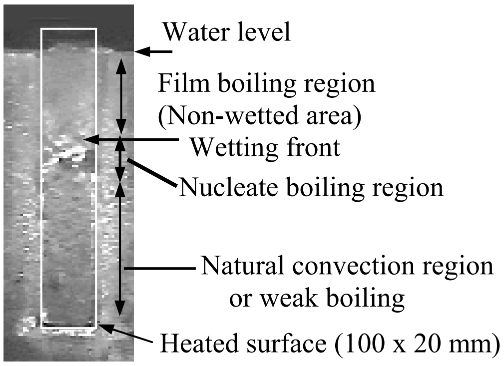


Fig.2 Photograph of boiling on the heated surface during quenching for copper block at u_l = 3 mm/s and ΔT_{sub} = 50 K.

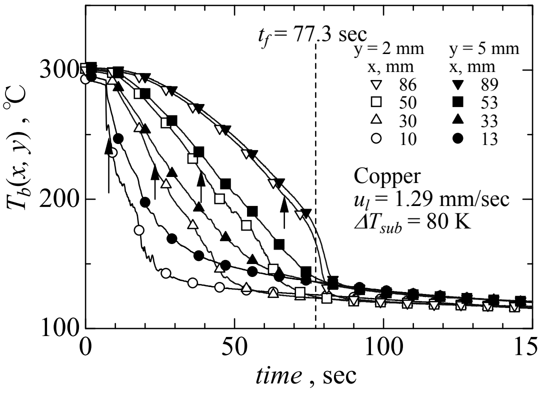


Fig.3 Block temperature history for copper block at u_l = 1.29 mm/s and ΔT_{sub} = 80 K.

From Fig.4 we can find the locus of x_{qmax} is very closed to that of x_{wet}. The maximum heat flux at each position takes around 2.5 MW/m^2 except for the bottom side (x < 20 mm). This value strongly depends on the material of block and u_f, and it is hardly changed with liquid subcooling. The wall temperature along $x_{qmax}(t)$ takes the constant value of 125 K and this value almost depends on the material.

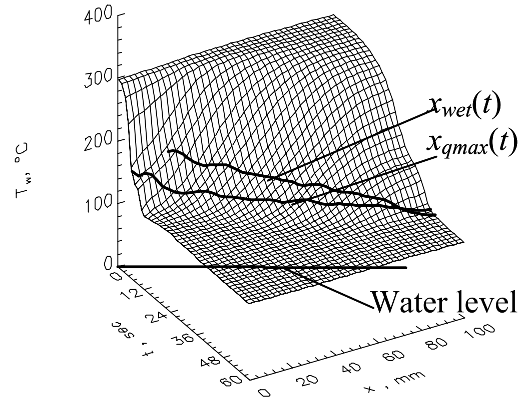
Estimation of Locus of Wetting Front

Figure 5 shows the locus of x_{qmax} (solid symbol), x_{wet} (hollow symbol) and the water level (solid line) against non-dimensional time t/t_f. t/t_f =1 means the heated surface is completely soaked into water. Corresponding experimental conditions are for the copper and brass block at the flooding velocity of 1 mm/sec. We can know that the maximum heat flux occurs near the wetting point where violent nucleate boiling occurs as shown in Fig.2 and both positions seem to be very close except for around terminate time. The lower liquid temperature and lower thermal conductivity make the wetting front close to the liquid level of rising liquid than the higher ones. This difference is due to amount of the heat transfer to the liquid and heat conduction to the solid. In other words, the earlier wetting is made when the surface temperature is quickly cooled to reach a temperature at which wetting can establish.

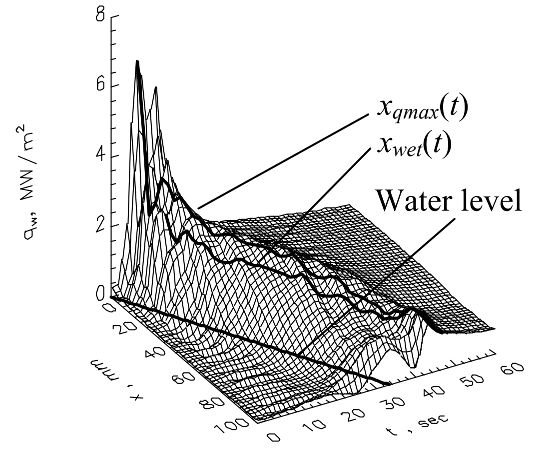
CONCLUSION

The two dimensional inverse solution proposed by the authors[1] is applied to estimate wall temperature and wall heat flux with the temperatures measured in the block. The wetting front appears to move slightly behind the position at which the maximum heat flux takes place and the locus of maximum heat flux is able to the approximation of the wetting front.

This study is the first step of the ongoing study and has focused on acquiring transient cooling data during quenching and observation of moving wetting front. In future work, we will elucidate the characteristic of wetting velocity and coefficient of heat transfer for each heat transfer mode.



(a) Wall temperature



(b) Wall heat flux

Fig.4 Estimated wall temperature and wall heat flux for copper block at u_l = 3 mm/s and ΔT_{sub} = 50 K

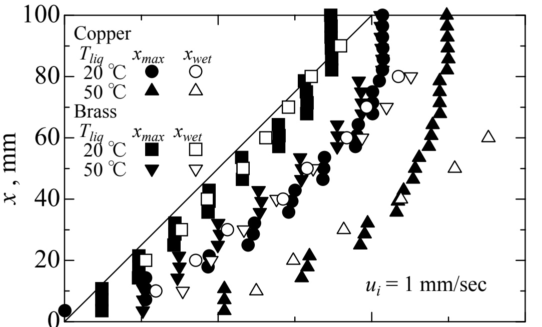


Fig.5 Change in location of observed wetting front and maximum heat flux at fixed velocity u_l = 1 mm/sec.

REFERENCES

1. Monde, M., Arima, H., Mitsutake, Y., Liu, W., and Hammad, J., Analytical Solution for Two-Dimensional Inverse Heat Conduction Problem Using Laplace Transformation (in Japanese), Trans. Japan Society of Mechanical Engineers, Vol. 68, No.672, pp 2306-2312, 2002.