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Effect of coolant vapor quality on rewetting phenomena

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Abstract—The effect of the coolant vapor quality on the rewetting process in bottom flooding has been experimentally studied. The flow visualization showed that when the coolant vapor quality was greater than about 1%, a completely different flow pattern was noted from that observed when the coolant had no vapor quality. For a given test condition, an increasing vapor quality was accompanied by an increasing rewetting velocity. The results from the experiment are discussed in terms of the deduced heat transfer coefficient distribution and rewetting temperature.

1. INTRODUCTION

REWETTING of hot surfaces by coolant water in nuclear reactors would take place at the end of a postulated loss-of-coolant accident. The propagation of the rewetting front strongly depends on the heat transfer coefficient distribution in the region of the front and the rewetting temperature. Since the rewetting phenomena in a confined space are primarily 'hydrodynamically' controlled and the vapor quality affects the flow regimes (patterns) of the injected coolant water, it can be deduced that the rewetting phenomena will definitely be affected by the vapor quality of the coolant.

A large number of experimental and analytical studies on rewetting phenomena in various modes have been made during the last two decades [1–5]. Under certain conditions, the coolant through the emergency core cooling system may attain positive quality at the inlet of the fuel channel due to the heat transfer from the surroundings. There seems to be, however, only one experimental study in which the thermodynamic vapor quality of the injected coolant has been changed to determine its effect on the rewetting velocity [6]. The effect of the increased vapor quality at the inlet was to increase the rewetting velocity. No other information was available.

In a study of the minimum film boiling temperature for water during film boiling collapse under steady-states Greoneveld *et al.* [7] observed that the minimum film boiling temperature increased distinctly with increasing local subcooling (negative quality region). This effect seemed to disappear in the positive quality region and the authors set the correlation of the minimum temperature to a constant value in this region.

Since the rewetting velocity in all modes of flooding depends on the rewetting temperature (this is not exactly equivalent to the minimum film boiling temperature during steady states; see ref. [7] for further discussion) and the effective heat transfer coefficient distribution in the region of the propagating rewetting front, the constant rewetting temperature deduced from the observation made by Greoneveld *et al.* must affect the resulting rewetting phenomena.

In the present paper, a study of the effect of the vapor quality in the incoming coolant in bottom flooding of a single tube is reported. Although studies obtained from realistic rod bundle geometries should yield practical information, the physical mechanisms involved are often obscured by the complex experimental conditions. The various parametric results from the experiment are discussed in terms of deduced heat transfer coefficient distributions and rewetting temperature.

2. EXPERIMENT

2.1. *Apparatus and test procedure*

The main heat transfer loop used in the present study has been reported previously [5, 8]. The loop was originally designed to allow reflooding experiments to be carried out on test-sections of up to 4 m in length, at any angle between vertical and horizontal.

In order to introduce positive vapor quality at the inlet of the test-section, the main loop has been modified. This was done by adding a steam generator and a mixing (calming) section just ahead of the test-section.

The coolant water from the demineralizer was preheated to a subcooling of about 30°C and was further heated up to a subcooling of about 2 to 5°C in the main heater. A small degree of coolant subcooling at this point was maintained so that the coolant flowing

NOMENCLATURE

Bi	Biot number, $h\delta/k$
c	specific heat of solid surface
G	coolant flow rate
h	heat transfer coefficient
k	thermal conductivity of solid surface
Pe	Peclet number, $c\rho\delta u/k$
T	temperature
T^*	dimensionless temperature, $(T_q - T_s)/(T_w - T_q)$
t	time
u	velocity
x	coolant vapor quality
z	axial distance of the heated section from the entrance.

Greek symbols

δ	thickness of solid surface
ρ	density of solid surface.

Subscripts

c	coolant
q	rewetting or quenching.

through the measuring devices (either a venturi or a turbine flow meter) would remain in liquid phase.

Two pressure transducers together with thermocouples were located at the inlet sections of both the steam generator and the test-section.

The test-section used was made of stainless steel 304 with a heated length of about 2 m. The outside and inside diameters were 15.8 and 13.8 mm, respectively. Eight chromel–alumel thermocouples were spot-welded every 0.20 m apart to the outside surface along the axial location to monitor the temperature during the test. The test-section was separately heated by a 30 kVA, 1500 amp a.c. power supply and was well insulated with Fiberfrex. The terminal clamps, made of copper, were attached to both ends of the test-section.

To obtain a physical insight into the present problem, a separate test-section of quartz tubing wound with nicrome wire for heating was placed parallel to the main test-section in the loop for flow visualization.

All the tests reported here were conducted at atmospheric pressure. The details of other experimental procedures are given in ref. [5].

2.2. *Data reduction*

The signals from the thermocouples and from the transducers (for flow rate, pressure, and electric power to the steam generator and to the test-section) were recorded by chart-recorders and/or digital recorders.

The rewetting velocities were calculated by

$$\Delta u_{ij} = \Delta z_{ij}/\Delta t_{ij} \tag{1}$$

where $\Delta u_{ij}(=u_q)$ is the rate of the rewetting from propagation between two particular points (thermocouples) of interest, Δz_{ij} is the axial distance between the two points and Δt_{ij} is the time interval taken between these two rewetting fronts. The rewetting temperature is sometimes referred to as Leidenfrost, calefaction, sputtering, quenching temperature, or the temperature corresponding to the minimum boiling heat flux, and often they are all considered to have the same values.

The rewetting temperature in the present study is obtained by taking the intersection of the gradients of the temperature–time trace before the point where there is a rapid fall in temperature and at the steepest portion of the fall. This definition was also used by other workers [9–11] and corresponds to the definition of 'upstream wall temperature' used by Yu *et al.* [12]. The rewetting temperature so defined almost coincides with those at the minimum heat flux during the rewetting transient [5].

This temperature, however, is not expected to be equal to the minimum rewetting temperature or sputtering temperature as defined by Bennett [13] or the thermodynamically controlled Leidenfrost temperature defined by Spiegler [14]. Our 'rewetting' temperature T_q is not really the true rewetting temperature, which usually cannot be measured, rather it is an upstream temperature below which heat transfer becomes effective in reducing the dry side wall temperature such that true rewetting can take place. Further details can be found in refs [5] and [7].

The flow vapor quality of the coolant at the inlet of the test-section is calculated from an energy balance. The local flow quality increase at the position where the rewetting front is passing through is almost negligible because the wall temperature in the wet region is very close to that of the injected coolant water, T_c.

The surface heat transfer coefficients are calculated from the temperature and time trace data by using the energy balance for the length Δz [15]. It was assumed that the axial conduction through the wall may be approximated as being one-dimensional.

3. RESULTS AND DISCUSSIONS

Since the end effects are very severe in all flooding experiments [5, 8], the present paper only reports the results obtained from the center portion of the test-section where the initial wall temperature is reasonably uniform.

No comparison will be made with many analytical models available as this requires the values of both 'effective' or 'local' heat transfer coefficients near the rewetting front and the rewetting temperature.

For a given test condition, an increasing vapor quality is always accompanied with increased rewetting velocity. The pressure fluctuation during the reflooding increased with increasing vapor quality in the coolant. Up to ± 7 kPa was observed at $x = 33\%$. The details of the results are discussed below individually.

3.1. *Visualization*

The local heat transfer coefficient essential to any analytical model depends on the flow regimes during the rewetting transient.

In Fig. 1 an illustration of bottom-flooding obtained from the present study is presented, which is deduced from high speed photography. It is interesting to note from the figure that the coolant vapor quality is quite significant. The inlet coolant could be either bubbly, slug or annular depending on its vapor quality.

For the vapor quality less than about 0.5%, the general flow pattern of the rewetting flow during a bottom flooding is similar to that of the flow with no vapor quality as seen in Fig. 1(a). However, when the quality of flow vapor is greater than about 1 to 2%, the coolant is injected into the test-section in an annular flow pattern. Since the coolant cannot wet the surface in the region ahead of the front due to the wall temperature which is higher than the rewetting temperature, the annular flow becomes what is called here the 'double annular flow' pattern as can be seen in Fig. 1(b). Obviously this particular flow regime will bring a different heat transfer mechanism.

3.2. *Effect of initial wall temperature coupled with coolant vapor quality*

In all flooding modes, it is known that an increase in initial wall temperature is accompanied by decreasing rewetting velocity and that the effect of increasing coolant inlet subcooling is to increase the rewetting velocity.

In Fig. 2, the effect of the initial wall temperature at different coolant inlet vapor qualities is illustrated. For a given vapor quality, the effect of the initial wall temperature was the same as in all other modes of flooding; an increase in wall temperature is to decrease the rewetting velocity. The effect of the increased vapor quality in the inlet coolant for a given initial wall temperature is, however, to increase the rewetting velocity.

For a comparison, the coolant inlet subcooling is also presented in Fig. 2 as a negative quality and it can be seen that the effect of the absolute values of vapor quality is nearly symmetric with respect to the axis at $x = 0$. This is simply coincidental as the heat transfer

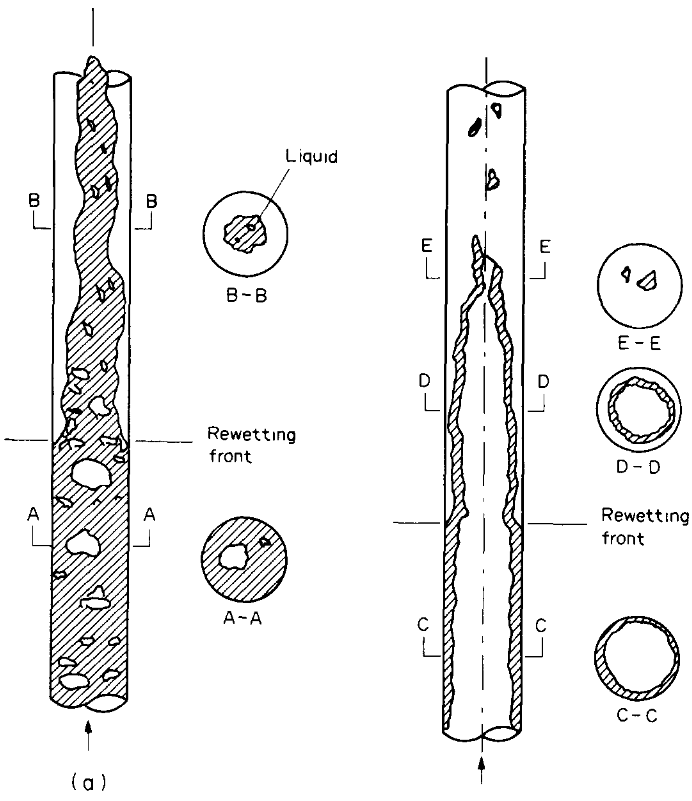

FIG. 1. Flow visualization; effect of coolant vapor quality.

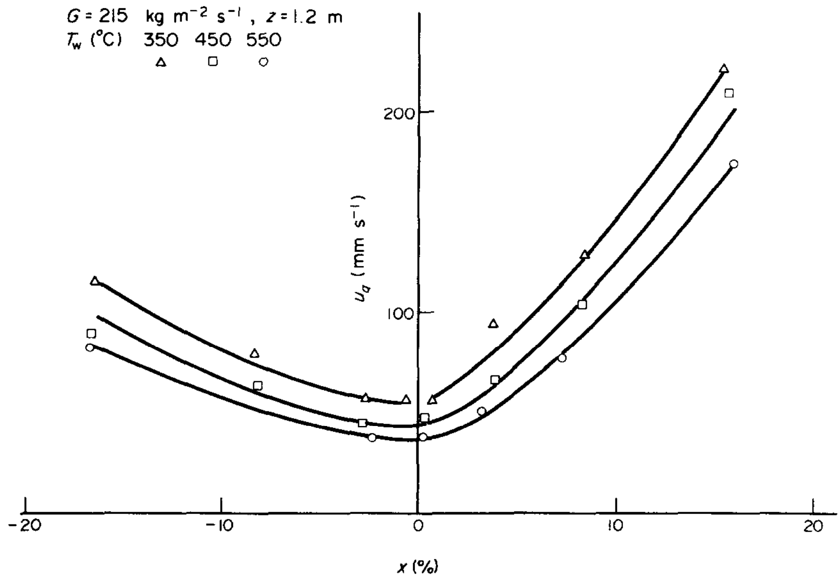

FIG. 2. Effect of initial wall temperature on rewetting velocity.

mechanisms involved are quite different from each other as one can deduce from Fig. 1. For negative quality it is the degree of liquid subcooling which dominates the basic boiling phenomena, whereas it is the void fraction due to the positive quality that induces high convective 'double annular flow boiling' for positive quality. The definition for 'double annular flow boiling' has been discussed in Section 3.1.

3.3. *Effect of coolant flow rate coupled with inlet coolant vapor quality*

Most of the theoretical analyses on the rewetting process do not explicitly recognize the effect of coolant flow rate nor that of coolant vapor quality, both positive and negative. This is because the analysis usually requires prescribed values of 'effective' or 'local' heat transfer coefficients in the region of the propagating front and the rewetting temperature. The functional relationship of these two parameters with other variables is rarely studied.

All but a few of the experimental studies for different modes of flooding showed that an increase in rewetting velocity was observed with increased coolant flow rate. Our analysis for bottom flooding [16] correctly predicted this trend.

The overall effect of the coolant flow rate coupled with the coolant inlet vapor quality is illustrated in Fig. 3. For a given value of vapor quality, the rewetting time decreased with increasing coolant flow rate. The figure also shows that the effect of increased vapor quality at the inlet for a given coolant flow rate is to increase the rewetting velocity.

3.4. *Variation of rewetting velocity as a function of axial position coupled with coolant inlet vapor quality*

In all three modes of flooding (top, bottom and

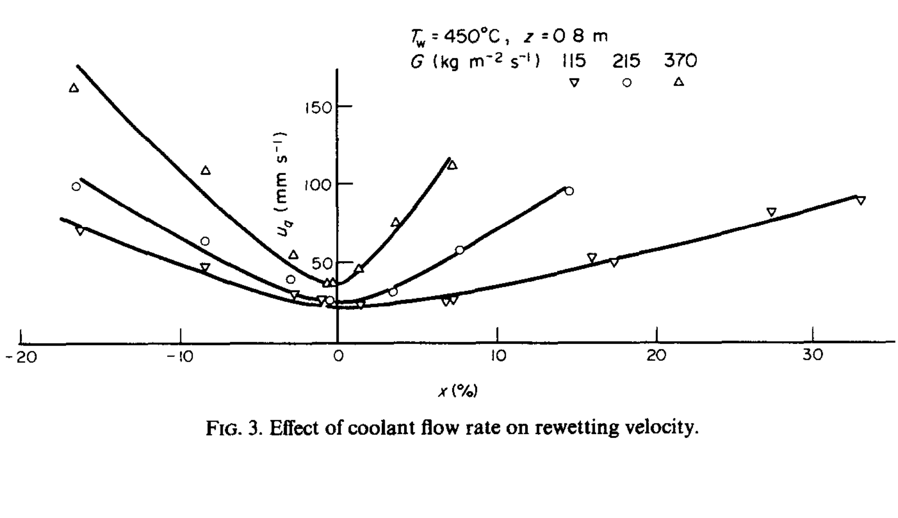

FIG. 3. Effect of coolant flow rate on rewetting velocity.

horizontal), many experimental studies showed that for vapor quality less than zero (liquid phase), the rewetting front proceeds at an almost constant velocity along the flow channel. The heat input from the wall to the coolant which arrives at the rewetting front is usually too small to raise the coolant temperature. The precursory cooling ahead of the front could cause an increase in rewetting velocity because the front is passing into a region of lower wall temperature as the coolant proceeds to downstream. With increased coolant flow rate, especially at high initial wall temperature, the precursory cooling could be significant and consequently it could cause the wall temperature to decrease in the absence of high heat generation. Our previous results [5] with three 4-m-long test-sections showed that there was often a slight increase in the rewetting velocity as the front proceeds along the test-section at high coolant flow rate and/or high initial wall temperature.

As seen in Fig. 4, the present study showed that the effect is significant in the region of positive vapor quality. With increased coolant vapor quality there is a large increase in the rewetting velocity as the propagating front moves along the axial direction. This may be due to the increased precusory cooling with increased coolant vapor quality.

3.5. *Heat transfer coefficients and rewetting temperature*

The effect of any variable on the rewetting phenomena must ultimately be explained in terms of the two most important parameters which control the process; heat transfer coefficient distribution in the region of the rewetting front and rewetting temperature. An attempt is made in the following discussion to explain the effects of various variables coupled with the coolant vapor quality on the rewetting transient in the bottom flooding mode in terms of these two parameters.

3.5.1. *Rewetting temperature.* The rewetting temperature as a function of coolant vapor quality and subcooling are shown in Fig. 5, which illustrates the temperature–time traces at different values of coolant vapor quality, x. For the convenience of comparison, the traces are matched at the time of quenching, t_q. From such traces as shown in the figure, the values of the rewetting temperature are obtained and some results are presented in Fig. 6. It can be observed that for a given initial wall temperature, the rewetting temperature is not at all affected by the coolant vapor quality while it is strongly affected by the degree of coolant subcooling.

This does not imply that the rewetting temperature is a thermodynamic property in the region of positive vapor quality while it is a hydrodynamically controlled one in the region of negative vapor quality. Even in the region of positive vapor quality, the rewetting temperature is dependent on the initial wall temperature as seen in Fig. 6. The same trend can also be clearly seen in Fig. 5.

3.5.2. *Heat transfer coefficients.* The heat transfer coefficient distribution in the so-called 'dry' region ahead of the front, as a function of the coolant vapor quality, is illustrated in Fig. 7.

It has been shown by an analysis [16] that the most important parameters controlling the rewetting process are the rewetting temperature and the heat

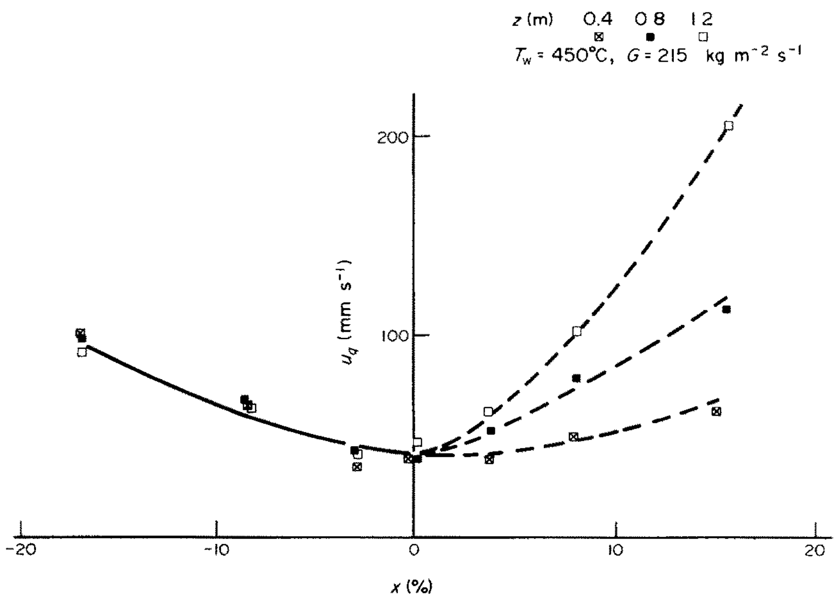

FIG. 4. Variation of rewetting velocity as a function of axial position.

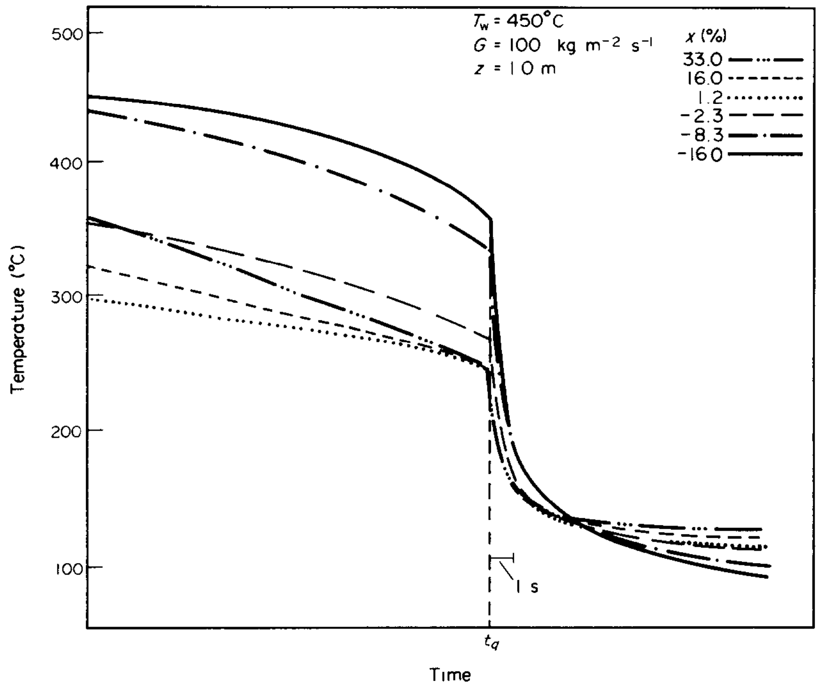

FIG. 5. Effect of coolant inlet vapor quality on temperature–time traces.

transfer distribution in the 'dry' region. Therefore with such data as shown in Figs. 6 and 7, the *qualitative* effect of the vapor quality (both positive and negative) on the rewetting velocity can be deduced from such a simple one-dimensional analysis as proposed by Yamanouchi [9], that is:

$$Pe = Bi^{0.5} \cdot T^*. \tag{2}$$

It can be seen that the higher the vapor quality, the larger the effective heat transfer coefficient in the 'dry'

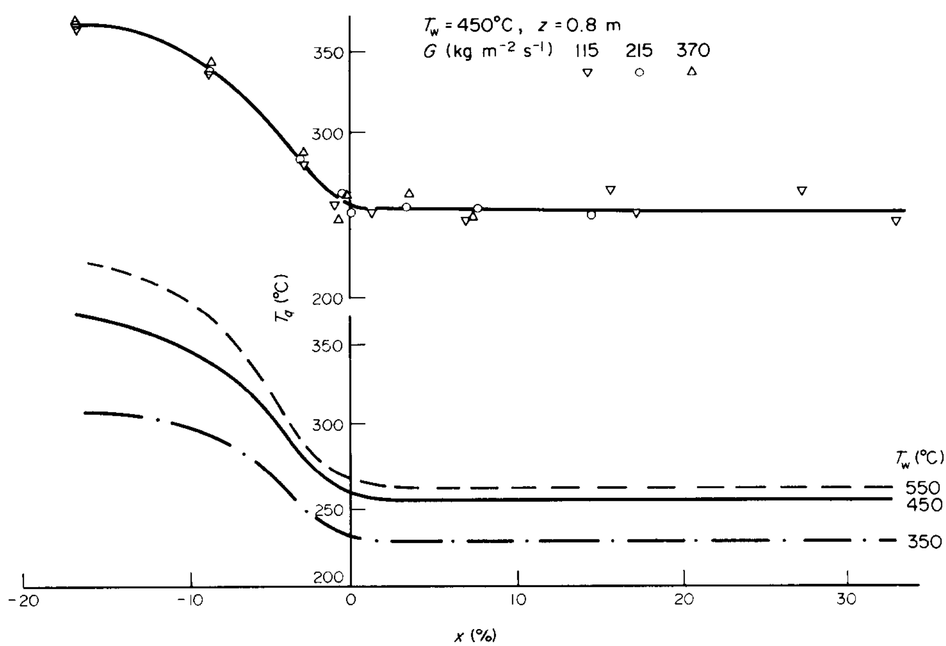

FIG. 6. Variation of rewetting temperature.

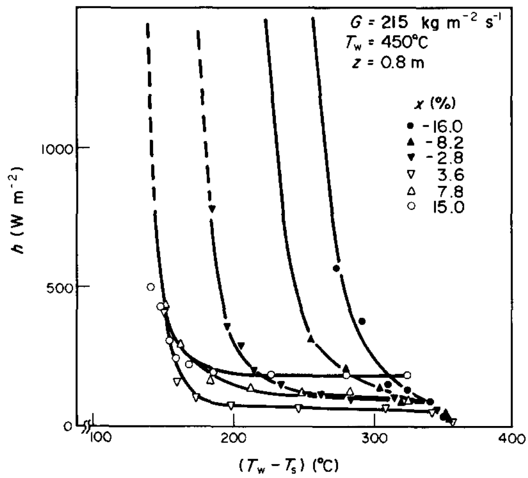

FIG. 7. Heat transfer coefficient in 'dry' region.

region. This is consistent with the trend given by equation (2). The effect of vapor quality on the heat transfer coefficient in the 'dry' region can be clearly seen in Fig. 5.

4. CONCLUDING REMARKS

(1) The visual study showed that when the coolant vapor quality was greater than about 1%, a completely different flow pattern was observed during the rewetting transient from that observed when the coolant had no vapor quality.

(2) The experimental results showed that

—for equal experimental conditions, the rewetting velocity increased with increase in coolant vapor quality,

—the rewetting temperature seems to be independent of coolant vapor quality and coolant flow rate but affected by the initial wall temperature,

—the higher the coolant vapor quality, the higher the heat transfer coefficients in the 'dry' region.

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EFFET DE LA QUALITE DE VAPEUR DU REFRIGERANT SUR LE PHENOMENE DE REMOUILLAGE

Résumé—On étudie expérimentalement l'effet sur le remouillage en engorgement de la qualité de vapeur du réfrigérant. La visualisation de l'écoulement montre que lorsque la qualité de vapeur est supérieure à 1% environ, une configuration d'écoulement complètement différent apparaît par rapport au cas où la qualité est nulle. Pour une condition d'essai donnée, un accroissement de la qualité de vapeur s'accompagne d'une augmentation de la vitesse de remouillage. Les résultats expérimentaux sont discutés en terme de distribution du coefficient de transfert et de température de remouillage.

DER EINFLUSS DES DAMPFGEHALTES IM KÜHLMITTEL AUF WIEDERBENETZUNGSERSCHEINUNGEN

Zusammenfassung—Der Einfluß des Kühlmitteldampfgehaltes auf den Wiederbenetzungsvorgang bei der Bodenüberflutung wurde experimentell untersucht. Die Sichtbarmachung der Strömung zeigte, daß, wenn der Kühlmitteldampfgehalt größer als etwa 1% war, ein völlig anderes Strömungsmuster festgestellt wurde als dann, wenn das Kühlmittel dampffrei war. Unter festgelegten Versuchsbedingungen stieg die Wiederbenetzungsgeschwindigkeit mit steigendem Dampfgehalt an. Die Ergebnisse der Untersuchung werden in Form der Wärmeübergangskoeffizientenverteilung und der Wiederbenetzungstemperaturen diskutiert.

ВЛИЯНИЕ КАЧЕСТВА ПАРА ОХЛАДИТЕЛЯ НА ЯВЛЕНИЕ ПОВТОРНОГО СМАЧИВАНИЯ

Аннотация—Экспериментально изучалось влияние качества пара охладителя на процесс повторного смачивания при донном затоплении. Проведенная визуализация течения показала, что при улучшении качества пара охладителя примерно на 1% наблюдалась структура течения, совершенно отличная от той, которая была отмечена при использовании охладителя с обычным качеством пара. При данных условиях эксперимента улучшению качества пара сопутствовало увеличение скорости повторного смачивания. Результаты эксперимента обсуждаются исходя из распределения полученных коэффициентов теплообмена и температуры повторного смачивания.