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Direct-Contact Condensation Regime Map for Core Makeup Tank of Passive Reactors

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Abstract

The condensation regime map in the core makeup tank of passive reactors is experimentally investigated. The condensation regimes identified through the experiments are divided into three distinct ones: sonic jet, subsonic jet, and steam cavity. The steam cavity regime is a unique regime of downward injection with the present geometry not previously observed in other experiments. The condensation regime map is constructed using Froude number and Jacob number. It turns out that the buoyancy force has a large influence on the regime transition because the regime map using the Froude number better fits data with different geometries than other dimensionless parameters. Simple correlations for the regime boundaries are proposed using the Froude number and the Jacob number.

I. Introduction

Gravity-driven injection is an important mechanism for passive safety injection systems of advanced light water reactors. This mechanism is adopted by AP600[1], SBWR[2], and CP1300[3]. In the case of CP1300, the core makeup tank (CMT) with a pressurizer pressure balance line (PRZ PBL) is a passive high pressure injection system. The CMT can provide cold water at any reactor coolant system (RCS) pressure by gravity force because its pressure is equilibrated with the RCS pressure through PRZ PBL. The major merit of the CMT is that it is considered to provide a more reliable means to replenish the reactor coolant inventory without operator action. Despite such potential for the gravity-driven injection of the CMT, there are few published experimental data showing its thermal-hydraulic characteristics, especially the direct-contact condensation in the CMT. The objectives of this paper are to classify the condensation regime and to develop regime transition criteria for the CMT.

Direct contact condensation of steam in subcooled liquid is a common event encountered in two-phase systems. Many researchers have performed experiments with a vertical vent pipe immersed into a subcooled pool.

Fukuda and Saito[4] classified the condensation regimes into five types on the basis of the interface shape, back flow of water into the vertical vent pipe, pressure variations and sound. However, they did not discuss the regime transition criteria. Chan and Lee[5] proposed the boundaries of various condensation regimes on the flow regime map based on two criteria: (a) the location of the steam region relative to the pipe exit and (b) the location at which a steam bubble detaches from the source. Simpson and Chan[6] experimentally examined the basic mechanism of vapor jet condensation in a subsonic jet. They observed that the periodic interfacial motion of a subsonic steam jet could be subdivided into three basic intervals: bubble growth, bubble translation, and bubble separation(necking). The heat transfer coefficient was largest in the necking interval and the subsonic pressure transient was marked by periodic impulse. These impulses originated from the necking of the steam bubble. Aya and Nariai[7] classified the oscillation patterns taking place in the vertical vent tubes based mainly on the shape of the pressure oscillation. Using the linear stability analysis, they suggested the transition criteria among various pressure oscillation regimes in terms of water subcooling, steam flow rate, geometrical dimensions, water and steam properties. Liang and Griffith[9] proposed the chugging transition criterion from the transition conduction model and the jetting transition criterion from the two-layer turbulent eddy transfer model. They showed that these models were consistent with the experimental data of their own upward injection experiments.

Through the literature survey, it was found that there is no earlier research concerning the transition criteria of the condensation regimes when steam is condensed out of a steam pipe connected to the CMT. Unlike the vent pipe in the BWR suppression pool, there is a solid boundary directly connected to the pipe exit in the CMT to inhibit the steam bubble moving upward along the pipe and flatly adhering to the top surface of tank because of buoyancy force. In the present study, the direct contact condensation regime map for the CMT type geometry is constructed, and the major nondimensional parameters are identified to fit the data. In addition, simple transition correlations are developed using the dimensionless numbers.

II. Experimental setup and instrumentation

The experimental facility is schematically shown in Figure 1. It consists of three major parts : the test section simulating the CMT, the steam generator simulating the pressurizer, and the instrumentation system.

The test section includes a heater, a heater controller to control the water temperature, front and back visual windows, and a drain line as shown in Figure 1. The test section is a tank with 0.85m height and 0.65m diameter. The visual windows are the reinforced glass with 0.30m diameter. Through the windows, the phenomena occurring at the exit of the steam pipe can be observed and recorded using a high speed camera. The steam generator which functions as a pressurizer is a stainless steel cylinder which is connected to the stainless steel hemisphere. The total height is 2 m and the total volume is 1.332 m^3. The capacity of the heater is 108KW. To find the chugging boundary, a thermocouple is installed at the exit of the steam feed line. Ten resistance temperature detectors(RTD) are used for measurement of the vertical distribution of water in the test section. Three vortex flowmeters made by Omega Co. are used to measure the steam flow rates from the steam generator, the drain water flow rate from the bottom of the test section.

III. Condensation Regime Map

1. Condensation regime map

The high-speed film shows that the steam jet at sonic speed has a stable cone shape. This regime is not included in the present regime map because of the limitation of the steam flow meter. However, the transition criterion from the subsonic jet to the sonic jet can be expressed in terms of Mach number.

From the viewpoint of an interfacial area, the boundaries of various condensation regimes on the regime map are established by two criteria : (a) whether or not the steam bubbles detach from the source, (b) whether or not the water periodically enters the exit of the steam feed line. The regime map from the present experiments is shown in Figure 2.

At low pool temperature and low steam mass flux, water begins to enter the steam pipe periodically. This is called "chugging". The chugging process is shown in Figure 3. In this regime, no bubble detachment occurs. As the steam flux increases, the detachment occurs and the detached bubble collapses immediately. At this time Transition I begins. In Transition I, both chugging and bubble condensing exist.

At higher steam mass flux of more than 45 Kg/m^2sec, the remaining bubble always exists at the exit of the steam pipe, and after the bubble growth and separation occur, it collapses. At this time the subsonic jet region begins. Figure 4 shows the bubble separation of the subsonic jet. Chan and Lee[2] observed that in the subsonic jet, the boundary between oscillatory bubble and oscillatory cone jet exists. From the viewpoint of an interfacial area, the oscillatory bubble and the oscillatory cone jet are classified as the subsonic jet.

At high pool temperature, above 60 °C – 70 °C, the cylindrical bubble adhering to the exit of the steam feed line is observed as shown in Figure 5. This bubble does not collapse but oscillates vertically. There has been no research performed to investigate this regime. This bubble was not observed in the geometry like BWR suppression pool. It is believed that this regime may result from the effect of the CMT type geometry. This regime is named steam cavity because it is similar to the air cavity of Cheslak's experiment[9].

Figure 6 shows the comparison of the present map with Fukuda and Saito[4] and Chan and Lee[5]. The horizontal line in Fukuda and Saito[4]'s data corresponds to the transition from chugging to the region without the pressure oscillation and the vigorous sound. The results show that for the vent pipe having the larger diameter, the boundary of chugging and the subsonic jet lies on the higher steam mass flux and the higher pool water temperature than for the vent pipe having the smaller diameter. The larger the diameter of the vent pipe is, the larger the size of the bubble is, and thus the condensation rate increases. This is why the boundary of chugging and subsonic jet with the larger diameter of the steam pipe is shifted to the larger steam mass flux.

Liang and Griffith[9] developed the transition criteria among condensation regimes using Reynolds number and Jacob number for upward steam injection experiments. As shown in Figure 7, in case of downward injection experiments, it is found that the regime map using Froude number and Jacob number better fits the transition of the chugging and the steam cavity than other dimensionless parameters. The physical meaning of Reynolds number is the ratio of inertia force and surface tension. In upward injection experiments, buoyance force and steam injection have same direction, and so buoyance force does not have much effect on regime transition than inertia force. The Froude number consists of inertia force and buoyancy force. In downward injection experiments, buoyance force interacts with steam injection inversely. As a result, buoyancy force as well as inertia force have dominant effect on regime transition.

3. Simple correlations for regime boundaries

To develop a set of simple correlations to define the regime boundaries, the condensation regime map of the present data is simplified using straight lines as the regime boundaries as shown in Figure 8. Through linear fitting, the following correlations can be obtained for the regime boundaries:

- between steam cavity and other regimes

Fr + 17 Ja -2367 =0, (1)

- between chugging and subsonic jet

Fr = 212. (2)

To quantify the degree of uncertainty of the simple correlations, uncertainty analysis is needed. If the inaccuracy of each instrument is known, the error bound of the computed result is estimated by the following method[10]. Consider the problem of computing a quantity N, where N is a known function of n independent variables, u_1, u_2, ..., u_n. That is,

$$N = f(u_1, u_2, \ldots, u_n) \tag{3}$$

The u's are the measured quantities and are in error by $\pm\delta u_1$, $\pm\delta u_2$, ..., $\pm\delta u_n$, respectively. These errors will cause an error δN in the computed result N;

$$N \pm \delta N = f(u_1 \pm \delta u_1, u_2 \pm \delta u_2, \ldots, u_n \pm \delta u_n) \tag{4}$$

Expanding the function f in a Taylor series, we get

$$N \pm \delta N = f(u_1, u_2, \ldots, u_n)$$

$$+ \delta u_1 \frac{\partial f}{\partial u_1} + \delta u_2 \frac{\partial f}{\partial u_2} + \ldots + \delta u_n \frac{\partial f}{\partial u_n}$$

$$+ \frac{1}{2}\left[(\delta u_1)^2 \frac{\partial^2 f}{\partial u_2} + (\delta u_2)^2 \frac{\partial^2 f}{\partial u_2} + \ldots + (\delta u_n)^2 \frac{\partial^2 f}{\partial u_n} \right] + \ldots \tag{5}$$

Subtracting Eqs. (3) from (5) and neglecting the 2nd and higher order terms, we obtain the absolute error such as

$$\delta N = \left| \delta u_1 \frac{\partial f}{\partial u_1} \right| + \left| \delta u_2 \frac{\partial f}{\partial u_2} \right| + \ldots + \left| \delta u_n \frac{\partial f}{\partial u_n} \right| \tag{6}$$

where all the derivatives are to be evaluated at the known values of u_1, u_2, ..., u_n. The absolute-value signs are used because some of the partial derivatives might be negative.

In the steam cavity transition correlation, measured values are steam mass flux and water subcooling. Introducing Eq. (1) into Eq. (6), the following equation can be obtained:

$$\delta N = \left| \delta u_i \frac{\partial f}{\partial u_i} \right| = \left| \delta Q_s \frac{\partial f}{\partial Q_s} \right| + \left| \delta \Delta T \frac{\partial f}{\partial \Delta T} \right| \tag{7}$$

$$= \left| \delta Q_s \frac{\partial Fr}{\partial Q_s} \right| + \left| 17 \delta \Delta T \frac{\partial Ja}{\partial \Delta T} \right| \tag{8}$$

The steam flowmeter accuracy is within 2.5 % of the full scale reading. The water temperatures in the test section are measured using RTD whose error limit are 1 %. The terms on the right side of Eq. (11) can be expressed as follows, respectively:

$$\delta Q_s \frac{\partial Fr}{\partial Q_s} = 0.05 Fr, \tag{9}$$

$$17 \Delta T \frac{\partial Ja}{\partial \Delta T} = 0.01 Ja. \tag{10}$$

Introducing the above equations into Eq. (10), the absolute error in the steam cavity transition is as follows:

$$\delta N = |0.05 Fr| + |0.17 Ja| \tag{11}$$

In the chugging-subsonic jet transition, the absolute error is as follows:

$$\delta N = |0.05 Fr| \tag{12}$$

IV. Summary

In present study, the direct-contact condensation regime map is constructed for the makeup tank of passive reactor such as AP600, CP1300, and SBWR. The condensation regimes identified are divided into three regimes: sonic jet, subsonic jet, and steam cavity. Buoyance force has a strong influence on the regime transition because the regime map by using the Fr and Ja numbers well fits the data with different geometry. The simple correlations for the regime boundaries are developed by using the Fr and Ja numbers.

V. References

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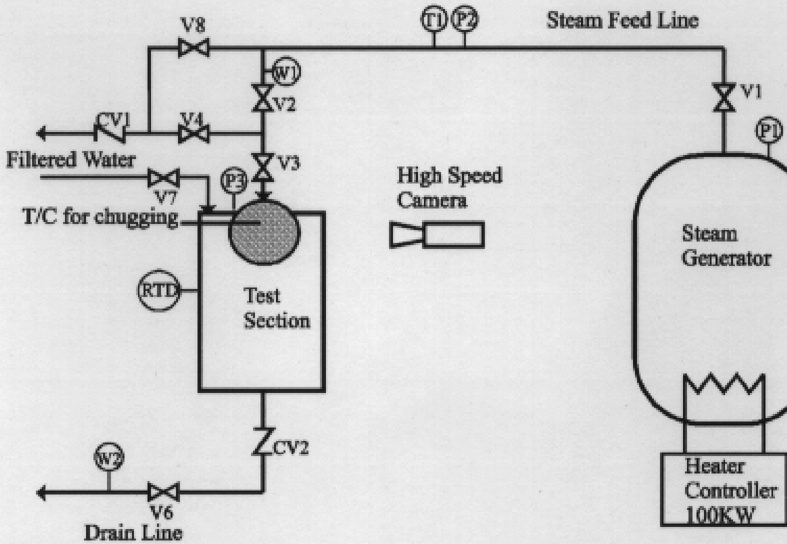

Figure 1 A systematic diagram of test facility

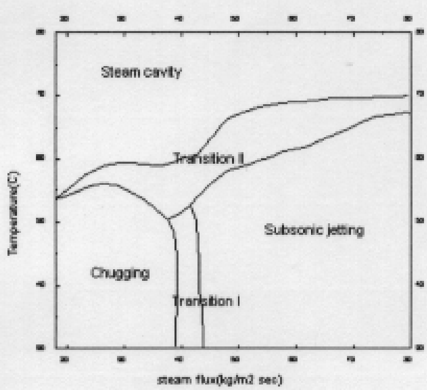

Figure 2. Condensation regime map

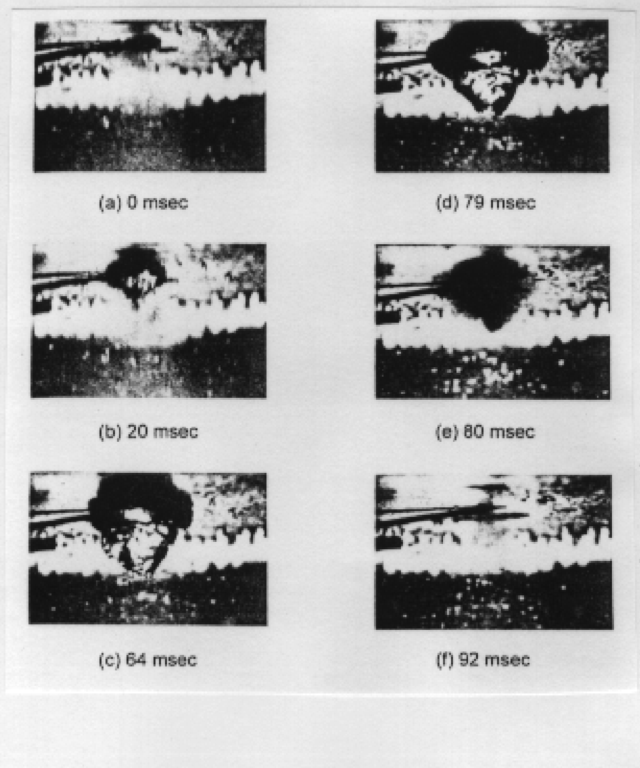

Figure 3. The process of chugging

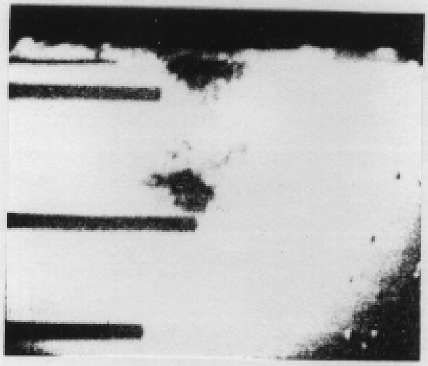

Figure 4. Subsonic jet

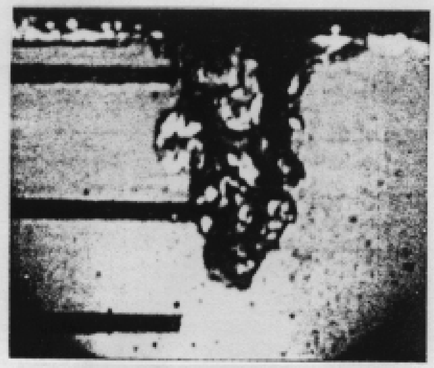

Figure 5. Steam cavity

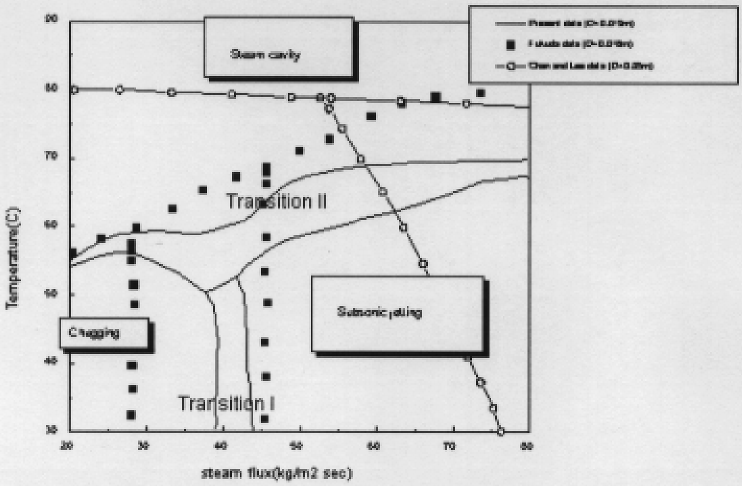

Figure 6. The comparison of present map with other maps

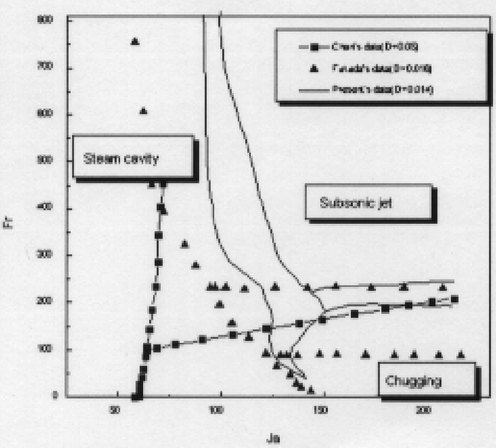

Figure 7. nondimensional regime maps in terms of Fr and Jr

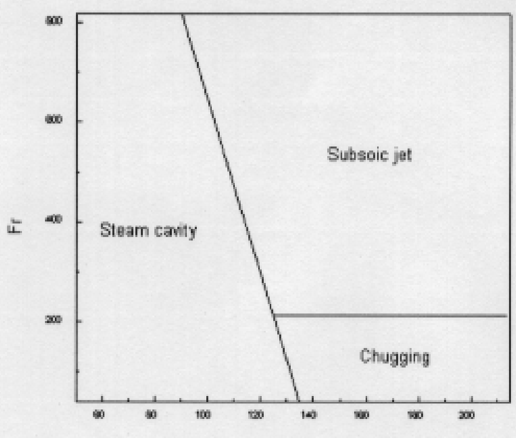

Figure 8. Boundaries for each regime