FUEL-COOLANT INTERACTIONS IN A JET CONTACT MODE

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ABSTRACT

Molten fuel-coolant interactions in a jet contact mode was studied with respect to the safety of liquid-metal-cooled fast reactors (LMFRs). From a series of molten Wood's metal (melting point: 79 °C, density: ~8400 kg/m^3) jet-water interaction experiments, several distinct modes of interaction behaviors were observed for various combinations of initial temperature conditions of the two fluids. A semi-empirical model for a minimum film boiling temperature criterion was developed and used to reasonably explain the different interaction modes. It was concluded that energetic jet-water interactions are only possible under relatively narrow initial thermal conditions. Preliminary extrapolation of the present results to an oxide fuel-sodium system suggests that mild interactions with short breakup length and coolable debris formation should be most likely in LMFRs.

1. INTRODUCTION

After a postulated core disruptive accident (CDA) terminates neutronically, a large amount of molten core materials remaining in the core relocates into lower core structures filled with single-phase sodium. If this post-accident relocation takes place in a jet mode, it may directly challenge the reactor vessel integrity. In order to establish a successful scenario of in-vessel material retention in the CDA evaluation, it is necessary to study the behaviors of molten jet penetration and interactions. For this reason, extensive experimental programs have been conducted these years on molten jet interaction with structure and coolant. For the former concern of jet-structure interactions, our previous studies [1-3] have dealt with the erosion behavior of the structure plate by the high-temperature molten jet under the condition with and without solidified crust of jet materials on the melting surface. We have derived experimental correlations for assessing the erosion rate. Using these correlations, we have revealed the inherent mitigation mechanism that when the molten oxide jet with high melting point falls down onto the structure plate, solidified crust of the oxide can significantly reduce the erosion rate. The major results of the molten jet-structure interaction experiments are summarized in our separate paper in this meeting [4].

With respect to the jet-coolant interactions, or more generally fuel-coolant interactions (FCIs), we are concerned about: their energetics potentially challenging the mechanical integrity of the coolant boundary, and melt quenching to form a coolable debris bed. A number of FCI experiments have been conducted with respect to LMFR safety; more recently steam explosion is one of central questions in light water reactor safety. These studies are reviewed first with emphasis on molten jet behavior and FCIs in a jet pouring mode.

The breakup behavior of the molten core materials jet have been studied theoretically by Epstein & Fauske [5]. They found that the instability of the steam film formed on the jet surface plays an important role in the jet breakup behavior. The results of a linear Kelvin-

Helmholtz instability analysis indicated that the breakup length is significantly extended by the presence of steam film on the melt surface. Wang et al. [6,7] developed an analytical model for jet erosion based on the assumption that the Kelvin-Helmholtz instability determines the length scale and the growth rate of the interfacial disturbances. They found that the jet breakup length is sensitive to the initial jet temperature, water subcooling, and the physical state of the ambient water. More sophisticated models, for example by Bürger et al. [8,9] and Sienicki et al. [10], reasonably explain jet breakup lengths for various combinations of jet and coolant materials.

On the other hand, the experimental study on jet breakup behaviors with simulant materials have been performed by Saito et al. [11] , Spencer et al. [12] and Schneider et al.[13]. Saito et al. studied the penetration behaviors of water jet into freon-11 and liquid nitrogen. Obtained empirical correlation for the breakup length can also predict well the experimental results of the breakup length which were obtained by Spencer et al. with hot and very heavy jets such as Wood's metal jet injected into the water pool. Saito's correlation was interpreted analytically and confirmed to agree well with the results from the experiments with Wood's metal jet and freon-11 by Schneider et al. [13]. Magallon et al. [14] performed two experiments that quantities of the order of 100 kg of molten pure UO_2 (~3000 °C) was poured into 130 kg of sodium at 400 °C and 0.1 MPa contained in a test tube of a 0.28-m-diameter and a height of 2.5 m. Only limited quantities of UO_2 melt can penetrate and fragment into sodium at one time. The FCIs observed after sodium reached elevated temperature around saturation was interpreted as so-called vapor explosions. The penetration distance of molten fuel into sodium did not exceed 1 m. Further interpretation of the tests would require a model capable of better describing the premixing process of molten fuel penetrating sodium.

The main objective of this paper is to address a question as to what are the necessary conditions for energetic FCIs in a contact mode of jet-type melt penetration into the coolant. From a series of out-of-pile simulant molten jet-water interaction experiments, different modes of interaction behaviors are observed depending on the initial thermal conditions [15,16]. One of these modes exhibits a typical energetic FCI behavior: quiet jet penetration with film boiling, followed by onset of local interaction propagating to an entire jet length almost coherently. The previous studies [6-13] on jet breakup length considering the hydrodynamic aspects cannot distinguish different FCI modes observed in our experiments. This study therefore focuses more on thermodynamic aspects of jet penetration into and interactions with the coolant. A semi-empirical model of a criterion of minimum film boiling temperature is developed mainly based on the experiments by Dhir and Purohit [17]. The model is then applied to the present experiments to interpret and distinguish the different modes of jet FCI behavior. Finally the results are extrapolated to LMFR accident situations to further discuss their relevance to and implication on safety evaluation.

2. EXPERIMENTAL FACILITY

The current experimental studies include a series of simulant melt-coolant interaction experiments conducted in the MELT-II facility, in which up to 20 liters of melt is generated by an induction-heating technique. A schematic diagram of MELT-II is shown in Fig. 1. The facility consists of the melting section, the nozzle section and the test section. The test section is exchangeable to perform two types of experiments: melt jet-structure interactions and melt jet-coolant interactions. The experimental program specifically aims at investigating jet-mode molten fuel relocation down to the reactor inlet plenum following the neutronic accident termination. The former series of experimental program has been completed and reported by Saito et al. [1] and Sato et al. [3], and the latter program is focused at present.

In the first series of molten jet-coolant interaction test program, Wood's metal (composition: [Bi: 60 %, Sn: 20 %, In: 20 %], the melting point 79 °C and the density 8400 kg/m^3) and water are used as simulants. Wood's metal is heated in an induction furnace in the melting section, transferred to the heating vessel of the test section and then poured into a water pool in a liquid jet mode. The nozzle section to generate a smooth jet flow is immersed a few centimeters into the water to eliminate unfavorable effects of the pool surface. The test section is depicted in Fig. 2 with its dimensions and instrumentation. The main experimental parameters are the initial temperatures of melt and water. The melt temperature was varied between 92 and 614 °C and the jet diameter between 5.7 and 14 mm with its jet velocity of 2 - 3 m/s resulted under the gravity. The water temperature was varied between 8 and 97 °C to examine the effect of coolant subcooling. All the experiments are performed under atmospheric pressure. A high-speed video camera (~3000 fps) and X-ray cinematography (1000 fps) were used for optical measurements. The range and combination of the temperatures of the two fluids were selected such that various modes of interactions would be realized in the experiments.

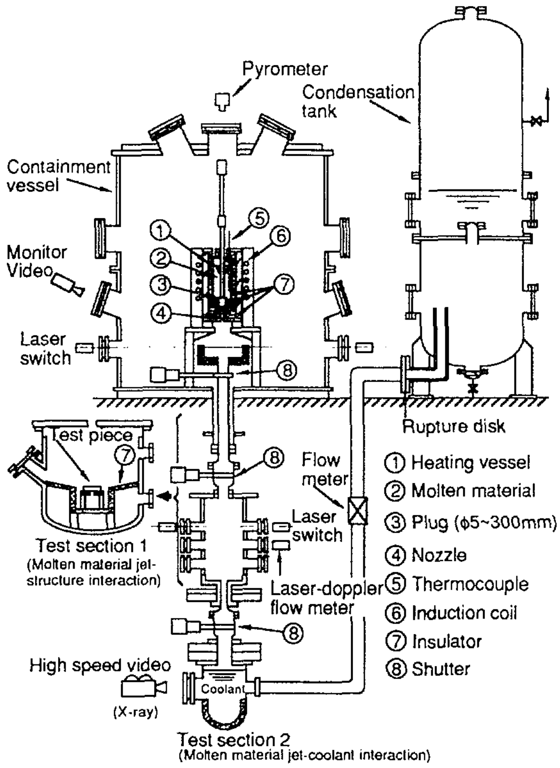

Fig. 1. MELT-II experimental facility.

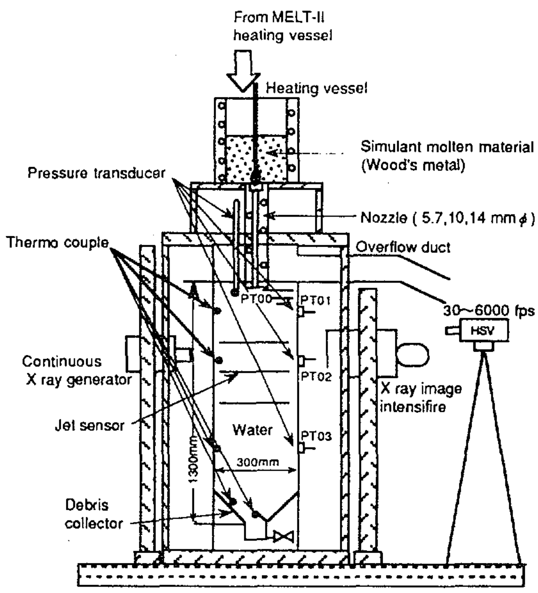

Fig. 2. Jet FCI test section.

3. EXPERIMENTAL RESULTS

In the present experiments, four distinct modes of interaction behaviors were observed for various combinations of initial temperatures of Wood's metal and water. These modes, called hereinafter as modes A, B, C and D, were determined primarily from video film observation and pressure signals. Typical pressure transients measured are shown in Fig. 3. Apparent pressure events are measured only in modes B and D, and no appreciable pressure spikes are observed in modes A and C. In the rest of this section, each mode of interaction is explained qualitatively based on pressure signals and optically observed behaviors.

Mode A interactions occur when the water temperature is high and the jet temperature is low. This mode is characterized by penetration of the water by the intact liquid jet with continuous water boiling. The pressure signals in Fig. 3 show that boiling was relatively quiet at least at the inlet. It is considered that mode A exhibited film boiling around the jet and resulted in low vapor production rate. After stable penetration, the jet breaks up at the maximum penetration length. The experimental correlation for the jet breakup length obtained from the previous water jet/freon-11 and water jet/liquid nitrogen experiments by Saito et al. [11]:

$$\frac{L}{D} = 2.1\sqrt{\frac{\rho_j}{\rho_c} Fr} \; , \qquad (1)$$

agreed well with the present data. This suggests that the correlation be applicable to a higher density jet condition as well.

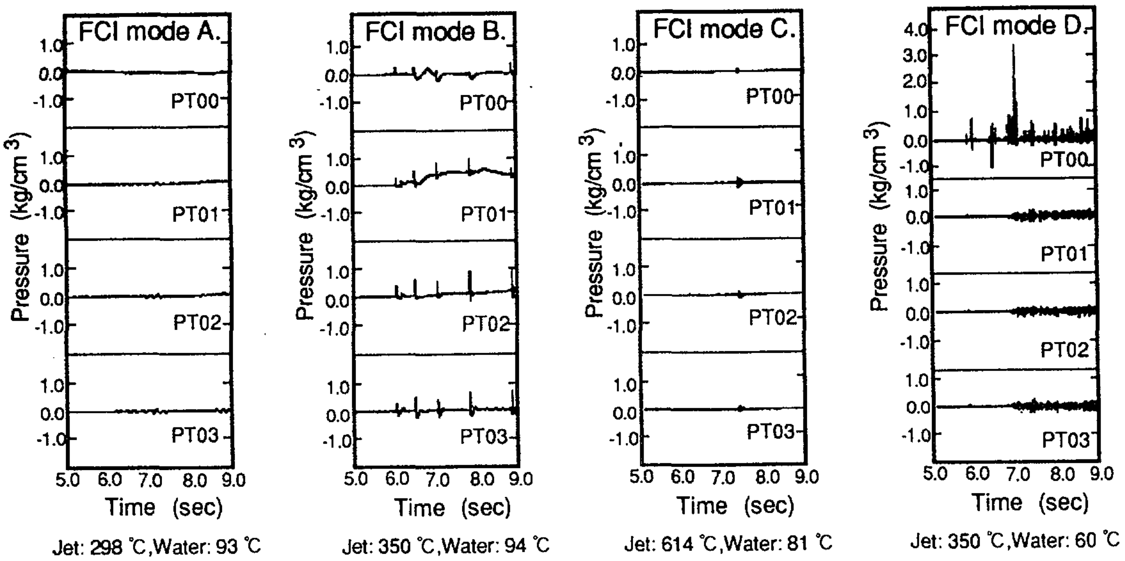

Fig. 3. Pressure transient observed in the four modes of FCIs.

Mode B interactions occur when both the jet and water temperatures are high. This mode is characterized by a series of pressure pulses (see Fig. 3) which appear to disperse the existing jet material. The pulses originate somewhere between the inlet and at tens of centimeters into the water. The jet can penetrate the water between pressure pulses. We interpret that mode B exhibits typical FCI behavior: quiet periods of film boiling punctuated by coherent breakdown of the vapor film, causing rapid heating of the coolant and violent pressure events. This is the only interaction mode that we may have energetic FCIs in the jet contact mode, although the pressure events observed in Fig. 3 are not excessive with their peaks about 0.2 MPa at most. It is noted that the coherent breakup of the entire jet in mode B is much different from the jet breakup at its maximum penetration length in mode A. The jet may penetrate to the breakup length or sometimes FCIs are triggered before the maximum penetration is reached. The difference from mode A is discussed further in Section 5.

Mode C is the interactions observed with much higher jet temperature in the region beyond mode B. In mode C, stable penetration of the intact jet was observed similar to mode A. No marked pressure events were observed in Fig. 3. The jet breakup occurs beyond the maximum penetration length but the observed boiling in this region did not disperse the existing jet. Under this high temperature condition of the jet, the vapor generation rate is so high that the coherent collapse of the vapor film is prevented. The instantaneous contact temperature is estimated to well exceed the critical point of water and hence the vapor in the vicinity of the jet behaves essentially like noncondensable gas.

Mode D is the interactions observed with low water temperature (or high water subcooling). In this case the vapor film cannot exist stably, allowing rapid melt-to-water heat transfer in a nucleate or transition boiling regime. Small-scale interactions take place continuously at the water surface with no jet penetration. Since only a small mass of the melt participates in each interaction event, a whole FCI phenomenon cannot be energetic. Although the pressure spikes measured in the experiments look violent (see Fig. 3), the pressure events are observed only at the water surface. This is another indication that the interactions in mode D are local and small-scale.

The above observation reveals that different interaction modes are possible, with sufficient reproducibility, depending on the initial jet and water temperatures. The present experimental conditions are plotted in Fig. 4, in which the regions of the four FCI modes are shown as a map of initial temperatures of the two fluids. Several lines drawn in the figure show the conditions that the instantaneous contact interface temperature is equal to representative temperatures such as the saturation and critical temperatures of the coolant and the melting temperature of Wood's metal. Here the instantaneous contact interface temperature, T_i is defined as:

$$T_i = \frac{(\sqrt{k\rho c})_c T_c + (\sqrt{k\rho c})_h T_h}{(\sqrt{k\rho c})_c + (\sqrt{k\rho c})_h} \ . \tag{2}$$

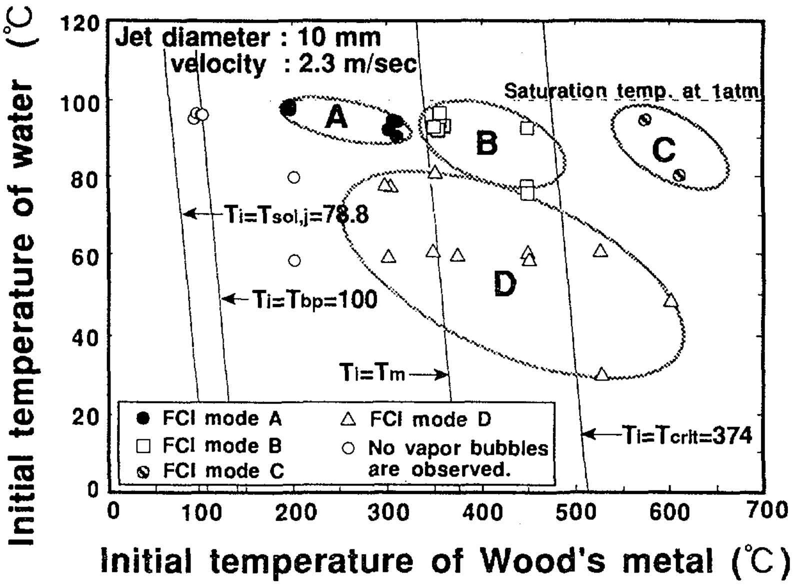

Fig. 4. Regions of the four FCI modes as a map of initial temperature of the two fluids.

4. MINIMUM FILM BOILING TEMPERATURE CRITERION

From the experimental results discussed in the previous section and the temperature map of the possible FCI modes in Fig. 4, the most important nature of jet-type interactions is a condition whether the film boiling condition is met. This distinguishes the mode D interaction from the others. Also we are concerned about the necessary conditions for energetic FCIs, that is mode B interactions. These are discussed in this section. We first review and derive a new criterion for the minimum film boiling temperature (MFBT) and then apply this model to our experiments.

There are basically two competing theories, hydrodynamic and thermodynamic, as to what determines the MFBT. The hydrodynamic theory was originally proposed by Berenson [18] and later modified by Henry [19] to take into account of transient wetting. This model assumes that vapor removal from a film is due to Taylor instabilities on the vapor/coolant interface. Henry's correlation is in good agreement with Farahat's sodium boiling data [20], but unfortunately the hydrodynamic model is not strictly applicable to spheres with diameters less than a few centimeters. Therefore we will concentrate more on the thermodynamic theory, which was originally proposed by Spiegler et al. [21] and later elaborated by Baumeister [22] and Gunnerson and Cronenberg [23]. The theory involves calculation of the maximum superheat temperature of the coolant, which is defined as the vaporization temperature in the absence of nucleation sites. When the wall temperature exceeds this temperature, film boiling is deemed to occur. The simplest form of the maximum superheat temperature of a liquid is given by:

$$T_m = \frac{27}{32} T_{crit} \ . \tag{3}$$

This equation represents the maximum possible wall temperature at which film boiling is initiated. Actually film boiling can be initiated even at lower wall temperature. It is therefore proposed that the MFBT is defined as a function of a single parameter experimentally determined.

$$\Delta T_{min} = C\,(T_m - T_{sat})\ . \tag{4}$$

Olek's empirical correlation [24] suggests that a value $C = 0.6$ for sodium and $C = 0.64$ for water. A simple criterion of the MFBT in Eq. (4) is thus applicable to many liquids including sodium when the liquid temperature is closed to its saturation temperature.

The measurement of the MFBT by Dhir and Purohit [17] involves quenching of various hot metal spheres in water at various subcoolings. The data show a pronounced dependence of MFBT on liquid subcooling, which is not taken into account in Eq. (4). This effect can be explained by considering the film boiling heat transfer. When the coolant is at the saturation temperature, all the heat transferred through a vapor film is used to vaporize the coolant and hence to sustain the film. On the other hand, with the subcooled coolant, a fraction of the heat transferred is removed from the vapor/liquid interface. Therefore a certain criterion must exist to sustain the film boiling based on this heat balance argument that the heat transfer through the vapor film, by conduction and radiation, should be larger than the heat transfer from the interface to the bulk of the coolant. This relation is written as:

$$\left(\frac{D}{\delta} + Nu_r\right)\Delta T_s > \gamma Nu_c \Delta T_{sub}\ . \tag{5}$$

As the subcooling is increased, less vapor is produced and the vapor film cannot be sustained unless its thickness decreases. Eventually if the vapor film is very thin, a stable film can be no longer sustained. Thus it is postulated that there exists a minimum vapor film thickness, which may physically represent surface roughness of a sphere or any disturbances on the vapor/liquid interface.

Based on these arguments, a formula recommended for MFBT is a combination of Eqs. (4) and (5) and is described as:

$$\Delta T_{min} = C\,(T_m - T_{sat}) + \frac{\gamma Nu_c \Delta T_{sub}}{\left(\frac{D}{\delta_{min}} + Nu_r\right)}\ . \tag{6}$$

The first term on the right hand side of Eq. (6) describes the MFBT in a liquid at its saturation temperature, while the second term represents a correction for the dependence of the MFBT on coolant subcooling. Essentially there are two parameters in this equation to be determined from experimental data. For an empirical constant C , a value of 0.6 reasonably reproduces the saturated MFBT for various liquids, including water and liquid metal. For the minimum film thickness, δ_{min} , in the second term, a value of 100 μm can be chosen to best fit Dhir and Purohit's data with water. As described in Section 7., fair agreement with sodium data by Farahat [20] was also obtained with these parameter values within large scatter of data points.

Another important consideration in applying Eq. (6) is how to define the surface temperature. If frequent transient wetting of the hot surface by coolant is assumed at the MFBT, the surface can be significantly cooled. Current experimental evidence indicates that such transient wetting can occur during saturated boiling, although contact with coolant becomes less frequent with subcooling as discussed by Kikuchi et al. [25]. In this case the surface temperature may better be replaced by a contact interface temperature in Eq. (2). However such transient wetting and the resultant good thermal contact become unlikely if the interface temperature exceeds the maximum superheat of the coolant. Above this temperature level, transient wetting is no longer possible and hence the surface is cooled only by heat transfer through the vapor film.

5. APPLICATION TO JET FCI EXPERIMENTS

A model of the MFBT in the previous section is strictly based on experimental data for various solid spheres immersed into coolant. It is however useful to apply the model to jet-type FCI experiments described in this paper. Using the empirical constants to best fit Dhir and Purohit's data with metal spheres of 19 mm-diameter (Fig. 5), the jet diameter of 1 cm and the water saturation temperature of 100 °C, Eq. (6) is deduced to:

$$\Delta T_{min} = 102 + 4.1 \Delta T_{sub}^{5/4} , \quad (7)$$

where the radiation term is neglected because it is not important in a low temperature range of the experiments. Because of a small diameter of the jet, the surface temperature calculated using Eq. (7) is regarded simply as the minimum jet temperature to initiate film boiling. If transient wetting is postulated, however, the surface temperature is more likely to be the contact temperature and hence must be converted to the jet temperature using Eq. (2). As discussed earlier, this is only applied where interface temperatures do not exceed the maximum superheat temperature of water.

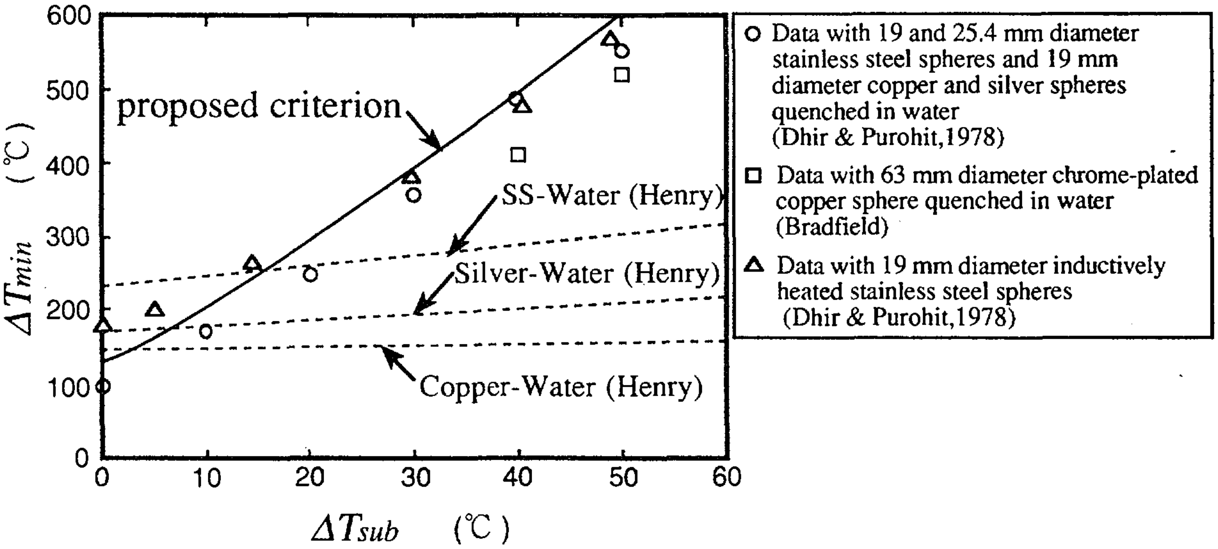

Fig. 5. MFBT criterion for water.

Equation (7), with and without transient wetting, is plotted on the previous temperature map in Fig. 4 and shown in Fig. 6. The shaded region represents the condition under which film boiling is predicted to occur. Figure 6 clearly indicates that the present MFBT criterion is successful in distinguishing mode D interactions from the other modes. Further the model explains physical reasoning that high water subcooling in mode D prevents the formation of a vapor film greater than the minimum thickness.

Mode B interactions occur within the film boiling region when the interface temperature exceeds water's maximum superheat and hence stable vapor film can be formed. Rather coherent collapse of the vapor film appears to occur at some distance from the jet inlet and this results in entire jet breakup and rather coherent interaction. Mode A conditions appear to be very close to the MFBT in the region where transient wetting might be predicted. Thus transient wetting of the jet surface might prevent coherent collapse of the vapor film in this case. Qualitatively, this distinguishes mode A from mode B interactions. In mode B, a stable vapor film is formed initially, but as the jet penetrates into the coolant its surface is cooled by the heat transfer through the film. When the jet temperature is cooled below the MFBT, the vapor film is forced to collapse locally. The effect of jet cooling is confirmed by comparing a pair of two mode B experiments. There is a tendency that an axial location of vapor film collapse becomes deepened as the initial temperature increases. Actually with higher temperature the jet must penetrate a longer distance before it is cooled below the MFBT.

The collapse of the vapor film leads to local contact or mixing of water with jet material. If such a local mixing zone could be formed, rapid vaporization and pressure buildup would disperse and fragment the entire jet material, leading to coherent interactions. It is not known experimentally whether the water temperature exceeds its spontaneous nucleation temperature, but this is possible if a certain amount of water is entrapped by the melt. Obviously a physical mechanism of vapor film collapse cannot be explained by the static thermodynamic treatment in this study. A dynamic film collapse and mixing process is likely to be driven by a high-velocity vapor flow generating turbulence on the jet and water surfaces. The above argument, however, well explains the differences among FCI modes, at least phenomenologically.

In contrast to mode B, mode C interactions exhibit no coherent FCI behavior. The vapor film collapse is prevented along the entire jet length. With higher jet temperature in this case, the film boiling is very stable and the jet temperature cannot be cooled below the MFBT condition. The jet still breaks up at its maximum penetration length which is likely to be induced by a hydrodynamic mechanism. Thus the boundary between modes B and C should be actually determined by the relationship between the jet cooling and the MFBT criterion. We suppose that the mode C behaviors appear when the transient cooling of the molten jet through the vapor film is insufficient and the film collapse is achieved after breakup of jet column. Under these conditions, the interactions initiated by the collapse of vapor film on the fragmented droplets no longer break down the above existing jet column. The experimental data indicate (see Fig. 4) that this boundary appears to lie roughly where the initial interface temperature corresponds to water's critical temperature. Therefore it is simply plotted in Fig. 6 that the mode C interactions are initiated where the interface temperature exceeds the critical point of water; obviously this is not exact.

The above discussions have successfully explained reasons why different interaction behaviors were achieved in the jet FCI experiments. Especially we have narrowed down the initial thermal conditions necessary for energetic interactions in jet-type FCIs.

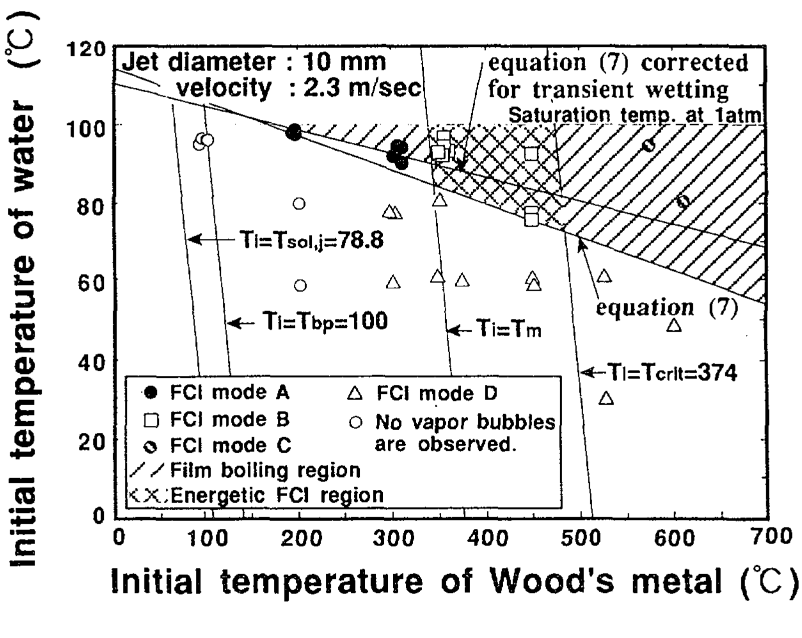

Fig. 6. Film boiling region predicted by the present MFBT model.

6. DISCUSSIONS

The most important conclusion of this study is that energetic interactions in a jet-type contact mode are possible only in a narrow range of initial thermal conditions. This is mode B interactions in which an entire jet mass undergoes interactions almost coherently. This mode exhibits typical FCI phenomena: quiet jet penetration with film boiling, local vapor film collapse triggering the breakup and dispersion of existing jet material and the resultant coherent interaction with the coolant. It is not believed, however, that the mode B interactions in our experiments are real "triggering and propagation" events if we strictly define the terminology, since the pressure pulses generated are relatively mild (0.2 MPa at most). It is also important to note that possible mechanical energy yields from this mode of interactions are only benign. As described in Section 3, mode B interactions consist of a series of intermittent FCI events. A melt mass participating in a single FCI event is limited to the mass of the jet up to its maximum penetration length.

This study alone cannot rule out all the other types of energetic FCIs, outsides the mode B region, which potentially occur especially when an external triggering event is postulated. Such triggering events might be possible if massive melt would impact a structure wall or a small mass of coolant would be entrapped by the melt and rapidly pressurized. This consideration is particularly important for much higher temperature jet-water interactions are concerned like during a light water reactor severe accident progression. Initial temperature conditions suggest that probable FCI modes should lie either in mode C region. This means that energetic interactions directly between the jet and the coolant (mode B) could be precluded. However a growing mass of melt would accumulate in the water pool beyond the jet breakup length, potentially forming a different geometry of pre-mixture. Therefore a question still remains as to whether such a pre-mixture undergoes explosive interactions. Unfortunately our experimental study with a low-temperature small-mass jet in a relatively large pool cannot address this point. It is still argued that the mode C interaction experiment indicates significant vapor formation as the jet penetrates and breaks up. Thus the jet tends to enter a highly voided (or water depleted) region, and this would prevent a large mass of melt from being mixed with the coolant.

The map of thermal conditions for different FCI modes, shown in Fig. 4 or 6, is only based on initial temperatures of the melt and the coolant. Possible modes of FCIs can be predicted from a combination of initial thermal conditions. This approach seems to be reasonable for our jet FCI experiments because the melt is continuously supplied at constant temperature into a relatively large water pool. However it is noted that the argument based only on the initial conditions is sometimes misleading. The effect of transient cooling is not negligible but can be essential as discussed in the mode B interactions in the previous section. Generally this approach cannot be applied directly to different configurations or contact modes where changes in thermal conditions with time have large influence on FCI behaviors.

7. EXTRAPOLATION TO REACTOR CONDITIONS

The experimental results obtained thus far are for low temperature simulants and hence they cannot be directly applied to a reactor situation. Nevertheless it might be very beneficial if the results are preliminarily extrapolated to the fuel and sodium system under LMFR accident conditions. Using the empirical constants of C =0.6 and δ_{min} =100μm, Eq. (6) was deduced and validated with sodium data by Farahat [20]. As shown in Fig. 7, fair agreement was obtained with these parameter values within large scatter of data points. We assumed the UO_2 jet with 10 cm-diameter (supposed against control rod guide tube) and obtained an MFBT criterion for LMFR accident conditions. Figure 8 depicts the temperature map for a UO_2-sodium system based on a similar approach to Fig. 6. The shaded region at the center reflects the conditions anticipated in an LMFR CDA. It is noted that the contact interface temperatures plotted are all below the melting point of UO_2, and should really be corrected for taking into account the latent heat of fusion. This is mainly attributed to the good thermal properties of sodium, and may suggest that a likely scenario be solidification of the fuel surface even at hypothetical high temperatures where the interface temperature exceeds sodium's critical point.

The criteria for the MFBT for sodium with and without transient wetting are also shown in Fig. 8, assuming a fuel-jet diameter of 10 cm with considering the radiation heat transfer this time. The effect of transient wetting is much more significant in this case, again because of good thermal conductivity of sodium. From analogy to Fig. 7, a region where the film boiling is anticipated is shaded in Fig. 8. The dark-shaded region at the upper-right corner represents where mode B energetic interactions are anticipated. The energetic FCI region lies far away from the LMFR accident conditions. It might be therefore concluded that the energetic jet-type FCIs are unlikely to occur in LMFRs. The main uncertainty that may challenge this conclusion is whether, and to what extent, the surface temperature of fuel is reduced by transient wetting. Unfortunately there are no experimental data addressing this point.

Although there are large uncertainties in extrapolating the small-scale experiments with water to a large-scale reactor environment with sodium, it is useful to predict preliminarily a likely FCI scenario in LMFRs. The molten fuel jet-coolant interactions under CDA conditions should exhibit either mode D behavior, with short penetration lengths, or solidification of the jet surface. These are interactions without significant mechanical energy generation. This mode of interactions is also favorable from the viewpoint of post-accident heat removal, because rapid and efficient molten fuel quenching can produce a coolable fuel debris bed.

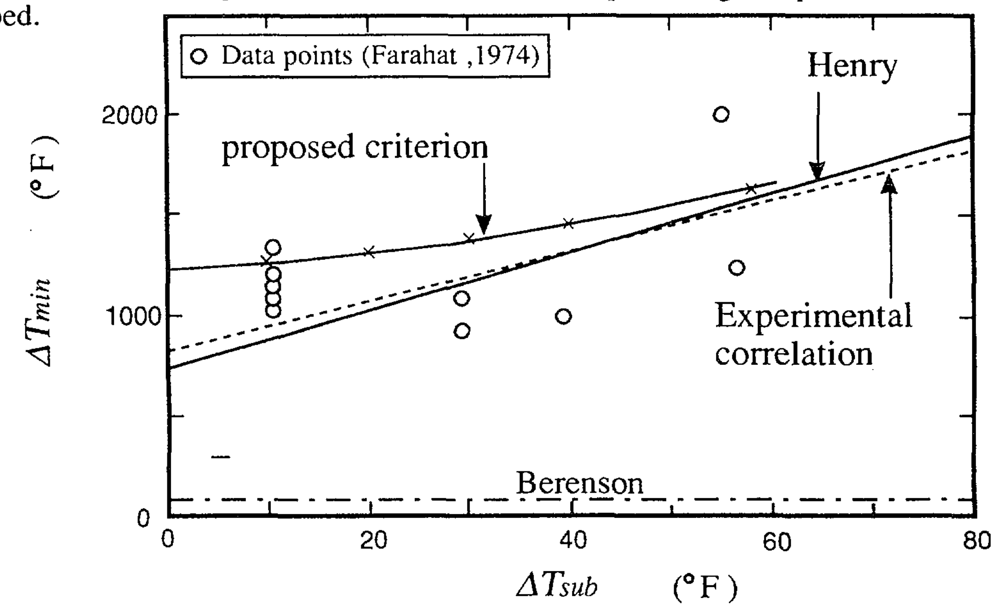

Fig. 7. Validation of MFBT criterion against sodium.

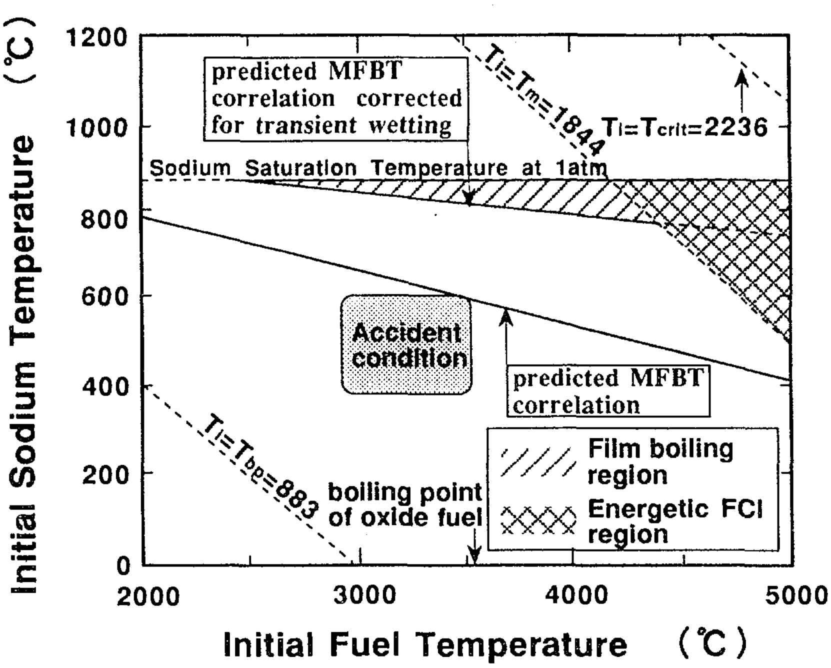

Fig. 8. Extrapolation of the results to the UO_2-sodium system under LMFR accident conditions.

8. CONCLUSIONS

From a series of Wood's metal jet-water experiments, four distinct modes of interaction behaviors were observed for various combinations of initial temperature conditions of the two fluids. A semi-empirical model for a minimum film boiling temperature criterion was developed and used to successfully explain the differences in these FCI modes. It was concluded that energetic jet-water interactions are only possible under relatively narrow initial thermal conditions. Also a mass of melt participating in this mode of interactions is limited to the mass of the jet up to its maximum penetration length.

Application of the present results to other materials has not been examined in detail, but the thermodynamic aspects underlying the jet FCI behavior with or without film boiling are essentially generic. However this study, investigating jet-mode FCIs, cannot address other contact modes or FCI environments. For example, even if energetic jet-mode FCIs are precluded from this study, an accumulating mass of melt beyond the jet breakup length might undergo energetic FCIs if an appropriate triggering event could be postulated. Preliminary extrapolation of the present results to a UO_2-sodium system suggests that mild interactions with short jet penetration lengths should be most likely in LMFRs.

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NOMENCLATURE

Fr	Froude number
L	maximum penetration length (m)
c	specific heat (J/kg °C)
C	an empirical constant
D	the diameter of a sphere / the diameter of a jet column (m)
k	thermal conductivity (W/m °C)
Nu_r	the radiative Nusselt number across the vapor film
Nu_c	the heat transfer Nusselt number in the coolant
T_i	instantaneous contact interface temperature (°C)
T_m	maximum superheat temperature of coolant
T_{crit}	critical temperature of the liquid (°C)
T_{sat}	saturation temperature of the coolant (°C)
T_{surf}	surface temperature of the hot material (°C)
ΔT_{min}	minimum temperature difference to be sustained across a vapor film ; $\Delta T_{min} = T_{surf} - T_{sat}$ (°C)
ΔT_s	the temperature difference across the vapor film (°C)
ΔT_{sub}	coolant subcooling (°C)

Greek symbols

γ	the ratio of liquid/vapor coolant thermal conductivities
δ	vapor film thickness,
δ_{min}	minimum vapor film thickness
ρ	density (kg/m^3)

Subscripts

c	cold fluids
h	hot fluids
j	jet

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