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AN APPROXIMATE MODEL FOR CALCULATING OVERALL HEAT TRANSFER  
BETWEEN OVERLYING IMMISCIBLE LIQUID LAYERS WITH  
BUBBLE-INDUCED LIQUID ENTRAINMENT

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**MASTER**1. Background

In the event a commercial power reactor is subjected to a class 9 accident resulting in gross core melting and reactor pressure vessel penetration, it has been shown that the containment integrity may subsequently be threatened by steam overpressurization, combustible gas reactions, and basemat penetration. A major contributor to these events would be the interaction of molten core debris with the structural concrete.

Modeling of core-concrete interactions involves many poorly understood and complicated heat transfer phenomena for which there exists a sparse data base. One of these phenomena, which has been shown to have significant impact upon code calculations of core-concrete interactions, is the rate of heat transfer between overlying immiscible layers of core oxides and molten metals whose interface is agitated by transverse gas flow. The only previous investigations applicable to this problem were the surface renewal modeling of interfacial heat transfer with gas bubbling by Szekeley and the interfacial heat transfer experiments by Werle.

Szekeley's heat transfer model is simply an application of transient conduction at a liquid-liquid interface due to periodic destruction of the temperature gradients by arrival of rising bubbles, having no provisions for entrainment. The form of the Szekeley model, including a modification by Blottner, for the heat transfer coefficient from the liquid to the interface is

$$h_{SZE} = 1.69 k \sqrt{j_q / \kappa r_b} \quad (1)$$

Experiments were performed by Werle at KFK with oil-water and oil-Wood's metal fluid pairs to measure the overall interfacial heat transfer coefficient as a function of the superficial gas velocity and the liquid density ratio. For the Wood's metal-oil case, no entrainment of the Wood's metal into the oil layer was reported, even at the highest gas velocities achieved. For the water-oil case, however, entrainment

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was observed, even at the lowest gas velocity, which resulted in a significantly greater interfacial heat transfer coefficient than for the Wood's metal-oil case.

It was found that the Wood's metal-oil data agreed reasonably well with the Szekeley surface renewal model, since no mass entrainment was found in the experiments, in accordance with the assumptions inherent in the model. However, the oil-water data exceeded the calculated heat transfer coefficient by several orders of magnitude due to severe mass entrainment effects not included in the Szekeley model. As a result of these findings, the experiments about to be described were undertaken.

## 2. Experiment

### 2.1 Apparatus

In order to measure the heat transfer between overlying liquid layers with gas agitation, an experimental apparatus was constructed (Greene 1981). It consisted of a rectangular lexan enclosure, open at the top, with a replaceable porous frit in the base for distribution of the gas flux. The lower half had opposing electrodes for resistance heating of one fluid layer. A traversable vertical thermocouple rake was installed. Liquid pairs employed were silicone oil, and copper sulfate (or zinc sulfate solutions) and mercury and water. The apparatus was insulated on the sides and base to insure one-dimensional heat transfer. The overall interfacial heat transfer coefficient was measured as a function of the superficial gas velocity. Two sets of data were taken. The entraining tests with zinc sulfate-silicone oil (Series 100) had a density ratio of 0.80 and the copper sulfate-silicone oil (Series 200) tests had a density ratio of 0.65. The second set of data which were taken were with a mercury-water fluid pair (Series 300) with a density ratio of approximately 13.5. These bubbling heat transfer data were characterized by the absence of entrainment. Instead, the interface experienced severe disturbance formation and wave propagation.

### 2.2 Experimental Results

Two sets of bubble-enhanced liquid-liquid heat transfer data with entrainment were developed by the authors; series 100 with  $ZnSO_4$ -silicone oil and series 200 with  $CuSO_4$ -silicone oil fluid pairs. These were compared to the existing water-oil heat transfer data of

Werle (1978) and are presented in Figure 1. These data sets are in close agreement with each other, however, they exceed the numerical predictions of the Szekeley model, similar to the modified Konsetov model (Blottner, 1979; Konsetov, 1966) which is used in the CORCON code (Muir, 1981) for the prediction of the interfacial heat transfer between molten metal and oxide layers with gas agitation by two to three orders of magnitude at modest superficial velocities on the order of only 1 cm/s. The impact of this heat transfer model upon the numerical results of CORCON calculations was found to be considerable.

The experimental data from the KFK Wood's metal-oil interfacial heat transfer experiments with bubble agitation (Werle, 1981) and the mercury-water data (Series 300, 400) from the present study were compared to the Szekeley model. Only the KFK data are presented in Figure 1.

All the water-oil data with bubbling converge asymptotically to the natural convection conducting-sheet model (Haberstroh, 1974) for the case of zero gas flux. The same behavior holds also for the Wood's metal-oil and mercury-water data when there is no gas flux. For low gas bubbling rates, the water-oil heat transfer data depart immediately from the Szekeley model. The disagreement between the data and model increases as the superficial velocity exceeds .5 cm/s and gross mixing is observed. However, the Wood's metal-oil and mercury-water data maintain agreement with the Szekeley surface renewal model over the same range of superficial velocity maintaining agreement with the model within approximately a factor of two to three.

### 2.3 Qualitative Observations

The evidence presented by these sets of experimental data tends to support the following description of the modes of heat transfer experienced over the range of gas velocity covered for interfacial liquid-liquid heat transfer with gas bubble agitation.

#### Natural Convection Regime

At zero gas flux, the liquid-liquid interface is not disturbed and the heat transfer is controlled by turbulent natural convection in each layer. The layers are observed to be nearly isothermal and the temperature gradients are restricted to the interface region. For both liquid pairs, water-oil and liquid metal-oil/water, the data are found to agree with the conducting-sheet model of Haberstroh (1974).

#### Surface Renewal Regime - Wood's Metal/Oil, Mercury/Water Data

When the gas flux is initiated, the interfacial heat transfer coef-

efficient is found to increase above the value characteristic of natural convection. For the liquid metal-oil/water case, no entrainment of the liquid metal is observed into the overlying oil/water layer. When the bubble breaks through the interface, a droplet forms behind the bubble from the metal film that previously surrounded it (Porter, 1966). For this liquid pair, the density difference between the liquids is great enough that the droplet remains at the interface while the bubble rises through the lighter fluid. Evidently, the static and dynamic forces exerted by the bubble are not sufficient to carry the drop of metal upward. For this case, the bubble acts to disrupt the temperature gradients at the interface. There is also considerable disturbance formation and wave propagation at the interface, which is not modeled in Szekeley's model and may account for the data exceeding the model calculations by a factor of two to three.

#### Droplet Entrainment Regime - Water/Oil Data

For the water-oil data, the density difference is not great enough to prevent droplet entrainment by the rising bubbles. A water droplet is observed to entrain behind the bubble as the bubble bursts through the interface (Porter, 1966). During the time the drop (hot) is suspended in the upper (cold) liquid, calculation of the droplet Biot and Fourier numbers indicates that most of the droplet's excess sensible heat can be transferred to the surrounding liquid by convection prior to return to the interface (Arpaci, 1966). The mass transfer enhanced heat transfer, absent in the case of liquid metal, offers an explanation for the immediate increase in the overall heat transfer coefficient above the surface renewal model for the water-oil data. The entrainment rate is an increasing function of the gas flux and this is demonstrated by the trend of increasing  $h$  with increasing superficial velocity. Currently modeling efforts are underway to describe the entrainment rate as a function of gas velocity. The data tend to indicate that there are several regimes of entrainment, as suggested by the obvious break in the slope of the data in the vicinity of 0.3 cm/s.

#### 4. Entrainment Heat Transfer Modeling

For the case of fluids which will exhibit mass transfer or entrainment when subjected to a transverse gas flux, the heat transfer rate is not well characterized by the Szekeley surface renewal model and, under these conditions, it and similar models should not be employed. As previously shown, for the same gas velocity as non-entraining fluids,

heat transfer with entrainment was found to be greater in magnitude by as much as two orders of magnitude or more. This effect certainly cannot be explained by modification to the surface renewal theory nor can it be ignored.

#### 4.1 Model Development

Current modeling of liquid-liquid entrainment due to gas bubbling is crude at best. Although we have been able to develop a model, based upon a static force balance, which appears to describe the conditions for the onset of entrainment, calculated entrainment rates have been greater than measured rates in single bubble entrainment tests by approximately a factor of ten. For the purposes of this discussion, therefore, the entrainment will be treated in a parametric fashion, subject to future refinement in the entrainment rate model.

For the entrainment heat transfer model, it is assumed that the heat transfer is composed of a component due to the interfacial agitation (surface renewal) and a component due to the mass entrainment itself. The Szekeley heat transfer coefficient is

$$h_{SZE} = 1.69 k(j_g/\kappa r_b)^{1/2} \quad (2)$$

where  $k$  is the fluid thermal conductivity,  $j_g$  is the gas superficial velocity,  $\kappa$  is the fluid thermal diffusivity, and  $r_b$  is the bubble radius. The interfacial heat transfer rate (surface renewal) is

$$q_{\text{interface}} = h_{SZE} A \Delta T_{12} \quad (3)$$

where  $A$  is the interfacial cross-sectional area and  $\Delta T_{12}$  is the temperature difference between the upper (1) and lower (2) layers.

The component of the heat transfer due to entrainment can be expressed as the product of the mass rate of entrainment times the excess enthalpy of the entrained phase (2) transferred to the continuous phase (1), that is

$$q_{\text{entrain}} = (\text{mass entrainment rate}) \times (\text{excess enthalpy transferred/unit mass})$$

or

$$q_{\text{entrain}} = (j_2 A \rho_2) (C_1 C_{p2} \Delta T_{12}) \quad (4)$$

where  $j_2$  is the superficial velocity of the entraining fluid,  $\rho_2$  is the density,  $C_{p2}$  is the specific heat, and  $C_1$  is the fraction of the excess enthalpy of fluid 2 that is transferred to fluid 1. It can

be easily shown by analysis of transient convective heat transfer around a sphere, under conditions of the entrainment heat transfer data, that  $C_1 \sim 1$  (Arpaci, 1966).

Combining Equations (3) and (4), we have

$$q_{\text{total}} = h_{\text{SZE}} A \Delta T_{12} + j_2 A \rho_2 C_{p2} \Delta T_{12} \quad (5)$$

If the effective heat transfer coefficient is defined as  $h_{\text{eff}} = q_{\text{total}}/A\Delta T_{12}$ , then this reduces to

$$h_{\text{eff}} = h_{\text{SZE}} + j_2 \rho_2 C_{p2} \quad (6)$$

Let  $j_2 = C_2 j_q$ , where  $C_2$  is the ratio of the volumetric entrainment rate of fluid 2 to the volumetric gas flux. Then Equation (6) becomes

$$h_{\text{eff}} = h_{\text{SZE}} + C_2 j_q \rho_2 C_{p2} \quad (7)$$

In the oil-water experiments, the component of the interfacial heat transfer resistance on the water side of the interface can be shown to be negligible with respect to that on the oil side of the interface. As a result the overall interface heat transfer coefficient from the Szekeley model is simply that calculated for the oil. In the general case, where both sides of the interface must be considered, the overall interfacial heat transfer coefficient due to interfacial disturbances (not entrainment) would be

$$\frac{1}{h_{\text{overall}}} = \frac{1}{h_{\text{SZE1}}} + \frac{1}{h_{\text{SZE2}}} \quad (8)$$

At present, the major uncertainty in applying Equation (7) to the case of heat transfer with entrainment is the determination of the coefficient  $C_2(j_q)$ . Comparison of Equation (7) to the available BNL and KFK entrainment heat transfer data suggests that the data are bracketed by the choice of  $C_2$  in the range (0.3, 1.0). Further work is underway to improve this aspect of the heat transfer model.

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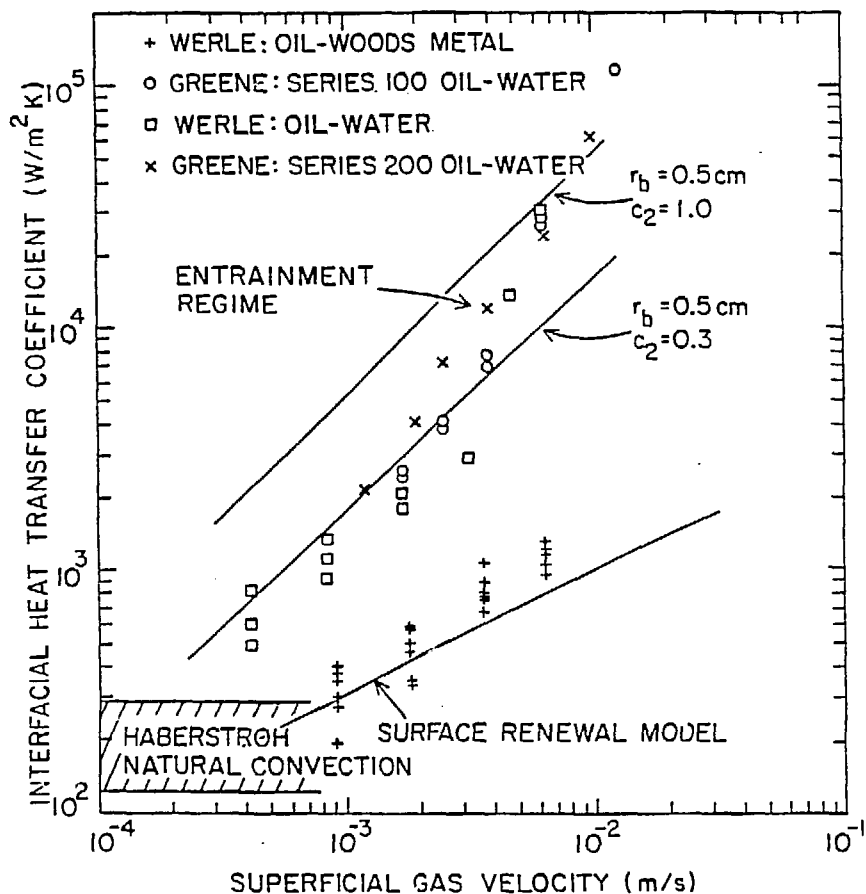


Fig. 1. Interfacial Heat Transfer with Transverse Bubble Agitation