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MODELING AOKI ET AL. EXPERIMENTS OF CONDENSATION OF FLOWING STEAM ONTO INJECTED WATER VIA K-FIX

by

Raymond C. Mjolsness and Bart J. Daly

ABSTRACT

The experiments and the 1-D theoretical calculations of Aoki et al. are reviewed. K-FIX calculations of these experiments are discussed and the modifications of the condensation model and the momentum-exchange model needed to secure agreement with experiments are presented. Calculations are presented for the cases of 30°C and 5°C subcooled water for a particular set of parameters for these models. Agreement with experiment is very good for the case of 30°C subcooled water and good for the case of 5°C subcooled water.

I. INTRODUCTION

The experiments of Aoki et al.[1] study the condensation of steam flowing in a rectangular channel into which subcooled water is injected through a rectangular inlet at the top of the channel and filling the width of the channel. The water forms a jet at the inlet, is bent strongly in the downstream direction by the flowing steam, and breaks up into drops 3-5 cm downstream of the inlet. The authors claim that there is a dead water region at the top of the channel downstream of the inlet. The experiments[1] measure the normalized pressure distribution, and, in the case of 50°C subcooled water, the absolute pressure distribution, at a number of points along the bottom of the channel. In addition, in the case of 50°C subcooled water, the mass flux of steam which has been condensed onto the water, i.e., the condensate-mass velocity, is measured at several locations downstream of the inlet.

The theoretical prediction of the results of the Aoki et al.[1] experiments is of interest because, if the physical processes occurring in these experiments can

be adequately modeled, and if the modeling is validated by successful prediction of the results, then the theoretical machinery can be used to predict very significant results that would occur in a hypothetical loss-of-coolant accident in a pressurized water nuclear reactor. Thus, the major value of theoretical predictions of the Aoki et al. experiments is very strongly tied to whether the models of the physical processes occurring in the atmospheric pressure, 100°C steam Aoki et al. experiments can be confidently extrapolated to the higher pressures and steam temperatures occurring in a pressurized water reactor.

II. THE AOKI ET AL. EXPERIMENTS

The presentation of the Aoki et al. data would suggest that experimental errors in the pressures are a small fraction of a millibar. This is not inconsistent with the best accuracy obtainable with modern instrumentation, but may be an optimistic estimate of the accuracy of their water manometers, which they state were used to obtain time-averaged pressures. Moreover, the shapes of the pressure-vs-distance-downstream-of-inlet curves of their Fig. 2 and Fig. 9 are significantly different in shape, or, equivalently, in absolute pressure measurement, although, of course, their general shapes are roughly similar. Accordingly, we have been unable to convince ourselves that the accuracy of the data is appreciably greater than a millibar. This point is of significance in judging the adequacy or inadequacy of calculations to be presented later in this report, in which average deviations between theory and experiment are less than a millibar and peak deviations are about two millibars. Should there be a one millibar uncertainty in the data, then the shape of the experimental data could be significantly altered from the shapes given here and taken from the Aoki et al. paper.[1]

The major qualitative features of the measured pressure profiles are that there is a pressure drop in the vicinity of the inlet followed, when the water subcooling is 20°C or more, by a region of pressure recovery, followed again by a pressure drop in which the pressure drop in the gas balances frictional forces at the wall and drag forces contributed by the water droplets. From the data, and especially from 1-D theoretical calculations, Aoki et al.[1] conclude that the pressure drop is largely independent of condensation and the pressure recovery is very heavily influenced by the condensation process. In the next section, we will explain why we think that the 1-D calculations[1] cannot be used even for qualitative purposes in establishing the physical mechanisms responsible for the qualitative shape of the pressure profiles. In the following section, we will

present rather different conclusions as to the major physical mechanisms responsible for the pressure profile, but will emphasize that there remains an irreducible uncertainty to our conclusions.

III. AOKI ET AL. 1-D CALCULATIONS

The Aoki et al.[1] experiments constitute a valuable data base for testing the reliability of calculational methods that might be used to predict the consequences of a hypothetical loss-of-coolant accident. Further, their 1-D calculations are a reasonable first attempt to utilize available means at hand to represent the complex phenomena and predict the observed pressure profile. However, the phenomena occurring in the experiments are too complex to fit well into the mathematical framework of their calculations, with the result that their predicted pressure profile is not very accurate.

We principally criticize these calculations because major aspects of the flow are 2-D phenomena which are necessarily misrepresented in a 1-D calculation. To illustrate the magnitude of the errors engendered we notice that (a) The 1-D calculations overpredict the pressure drop by a factor of 2.6 (260%). (In contrast, the 2-D calculations err by less than 10%.) (b) The 1-D calculations force the pressure recovery to occur in a small fraction of a centimeter. (In contrast, the experimental pressure recovery occurs in 20 cm.) (c) The 1-D calculations incorrectly state that the pressure recovers to a value higher than the value 5 cm upstream of the inlet. (In fact, this false elevated pressure elevation is over 40% of the total experimental pressure drop.) These qualitative and quantitative errors of prediction suggest that the dominant physical processes are being modeled so poorly that there would be some danger even to infer from the calculations what physical processes <u>are</u> the dominant ones in any given flow region.

In addition, there are difficulties of detail in the manner in which the 1-D calculations were carried out. Both the 1-D and the to-be-reported 2-D calculations show that the results are sensitive to droplet size. But the 1-D calculations use a single droplet size throughout the flow field, while the 2-D calculations suggest that the droplet size varies by 1 1/2 to 2 orders of magnitude in the various regions of the flow. The single droplet size of the 1-D calculations will necessarily misestimate the momentum drag force even in order of magnitude over much of the flow. Also the Aoki et al.[1] 1-D calculations appear to attribute the entire gas pressure drop of the Chisholm-Laird[2] correlation to friction-

al wall drag. If they actually do this, they surely significantly overestimate the wall drag, since the steam also is subject to appreciable momentum drag from the droplets.

IV. K-FIX CALCULATIONS OF 2-D TWO-PHASE FLOW

We have undertaken a series of 2-D calculations of the Aoki et al.[1] experiments with the transient two-phase flow code K-FIX.[3] The code employs the standard formulation of two-field flow, in which two freely penetrating fluids interact via mass exchange, momentum exchange, and energy exchange, and are, in addition, subject to frictional drag at the channel walls. In the initial stages of these calculations, the various exchange processes were modeled via a standard droplet model. Specifically, water is presumed to break up into droplets immediately upon entering the channel. The size of the droplets is taken from a Weber number criterion which is presumed to hold throughout the downstream flow region. Condensation of the steam is described by a composite condensation model which gives some representation of the complex, turbulent, forced convection that occurs in the vicinity of a droplet during violent condensation processes as well as the quivering motions of the water jet and the condensation onto the jet prior to its breakup into droplets.

In the early phases of this project, rather poor agreement with the experimental results was obtained. The major problems were that the condensation model used was inaccurate and that the complex physical processes occurring in the vicinity of the jet, and also downstream from the inlet, invalidated the spherical droplet model used for the momentum-exchange coefficient KDRAG. However, it was not clear initially how much of the problem encountered was due to the boundary conditions employed or to other facets of the modeling of the exchange coefficients. Accordingly, an extensive program of checking out the boundary conditions and the exchange coefficient was undertaken. The results went very far toward establishing that correct calculations are being produced by the boundary conditions and that any problems with the exchange coefficients result from our having to model very complex physical processes with simple mathematical models which occasionally oversimplify the physics. The good agreement with the data which we have subsequently obtained, and will discuss below, suggests strongly that we are now well on the way toward adequately modeling the exchange processes.

It was not possible to produce theoretical pressure profiles that had any close relation to the experimental pressure profiles if the droplet model for

the momentum-exchange rate KDRAG between the species was used throughout the computing mesh. Extensive numer al experiments established that corrections to the droplet KDRAG were required not only locally, in the vicinity of the water jet near the inlet, but nonlocally in a wide number of cells in the computing mesh if good agreement with experimental pressure profiles is to be obtained. The simplest rule we found which would dramatically improve the quality of the agreement between theory and experiment is to say that we have a basic problem with the droplet model whenever we have an appreciable amount of water, i.e., whenever the steam volume fraction θ is less than some critical value θ_{crit}, and to provisionally set KDRAG equal to some constant value K_o when that occurs. We thus make a composite adjustment for several physical processes, each of which causes deviations from the droplet model. Near the jet the steam sees a wall of water and large K_o. Downstream, it seems plausible that large Reynolds number effects cause ellipsoidal, that is, flattened oblate-spherioidal-shaped, droplets and small K_o. Presumably, the value of K_o selected is an average representation of all these effects, and it is, in fact, an intermediate value in the range of KDRAG values occurring over the computing mesh. Specifically we take

$$\text{KDRAG} = K_o \text{ if } \theta < \theta_{crit} \quad , \tag{1}$$

and we test for values of K_o and θ_{crit} that best represent the data. When θ is greater than θ_{crit}, we compute KDRAG from the droplet model.

The physics we are trying to approximate in an average sense with the model of Eq. (1) is fairly complex. Near the inlet the water is in the form of a jet, its surface-to-volume ratio is very different from that of a droplet, and its surface is unstable and pulsating prior to breakup into droplets. As mentioned previously, in the vicinity of the jet, K_o would be large. The droplets have radii mostly between 0.01 cm and 0.5 cm, corresponding to high Reynolds numbers for the droplets. Under these conditions, droplets will depart significantly from spherical shape, causing changes in KDRAG. The high Reynolds number effects, of ellipsoidal droplets rather than spherical ones, will drive down K_o in the downstream region. Finally, when θ is small, droplets will amalgamate via collisional processes with further changes in KDRAG. Droplet amalgamation enhances the Reynolds number and hence reduces K_o. Our model is a very provisional way of representing this physics, chosen for its simplicity and its effectiveness.

Finally, we introduce two further parameters, JC and COEFJET, to specify the composite condensation model referred to previously. Specifically, the condensation rate CRATE is presumed to be given by

$$\text{CRATE} = (1.0 - \text{CINTERP}) \times 0.3 \times 0.1 \times \text{JC}/540 + \text{CINTERP}*\text{COEFJET}*\theta(1 - \theta)(T_s - T_\ell)/0.25 \times (\text{HJET})^{\frac{1}{2}} \quad , \qquad (2)$$

where

$$\text{CINTERP} = 1.0 \quad \text{if HJET} < 3.0 \text{ cm}$$

$$\text{CINTERP} = 0.9/[\text{HJET} - 2.0]^{\frac{1}{2}} \quad \text{if HJET} \geq 3.0 \text{ cm}$$

and

$$\text{HJET} = \left[(y - y_{\text{inlet}})^2 + (x - x_{\text{inlet}})^2\right]^{\frac{1}{2}} \quad .$$

In Eq. (2), the first term represents droplet condensation while the second term represents condensation onto a water jet. In the above expression 0.3 is an assumed proportionality constant between the average turbulent velocity and the relative velocity between the two species, 0.1 (cm) is a turbulent length scale, and 540 is the ratio of the latent heat to the liquid specific heat. Nominal values for the parameters are

$$\text{JC} = 2.0 \times 10^{-4}$$

and

$$\text{COEFJET} = 6.0 \times 10^{-6} \quad ,$$

but we choose values to give best agreement with the pressure profiles.

We present the calculated (solid line) and the experimental (dashed line) pressure profiles for the case of 30°C subcooled water in Fig. 1. Values taken for the parameters are

$$K_o = 0.5 \times 10^{-4}$$

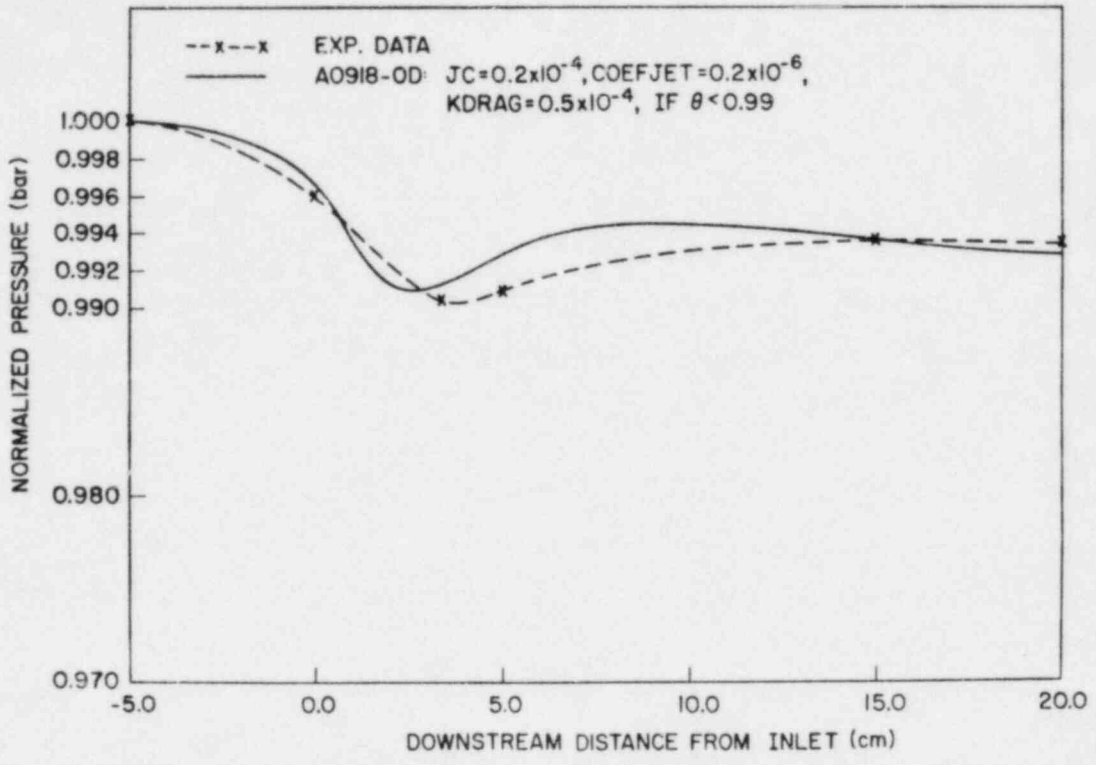

Fig. 1. Normalized theoretical (curve) and experimental (dashed curve) pressure profiles for Aoki et al. experiment with 30°C subcooled water. Theoretical curve obtained with JC = 0.2 × 10^{-4}, COEFJET = 0.2 × 10^{-6}, θ_{crit} = 0.99, and K_o = 0.5 × 10^{-4}.

$$\theta_{crit} = 0.99$$

$$JC = 0.2 \times 10^{-4}$$

and

$$COEFJET = 0.2 \times 10^{-6} \quad .$$

This calculation is judged to be a fairly successful simulation of the experimental pressure profile. It is a dramatic improvement upon the results obtainable in the early stages of this calculational program. The improvement is largely due to the improved condensation model and to the use of an averaged representation of KDRAG, rather than the droplet model for KDRAG, when there is a substantial amount of water present, i.e., when $\theta < \theta_{crit}$. The average deviation between theory and experiment is less than one millibar, while the peak deviation

is about 2 millibars. The calculations reproduce the experimental pressure drop very accurately and agree well with the total value for the pressure recovery. The distance for total pressure recovery is somewhat underestimated. The calculated value for the pressure drop depends very strongly on the parameters chosen for the condensation model. This is at variance with the findings of Aoki et al.,[1] who conclude that the pressure drop is essentially independent of condensation. The amount of pressure recovery is influenced by condensation parameters but is largely controlled by the values taken for K_o and θ_{crit}, specifying the deviations from the droplet model for KDRAG. This, too, is in some variance with the findings of Aoki et al.,[1] who conclude that the pressure recovery is largely determined by condensation processes. We find that 56% of the energetically possible steam condensation occurs by 20 cm downstream of the inlet, which is not an unreasonable value; however, there are no direct measurements of this quantity for the 30°C subcooled case.

In Fig. 2 we give the theoretical (solid curve) and experimental (× data points) pressure profiles for the 5°C subcooled case for the same values of parameters as used in the 30°C subcooled calculations. It is seen that the calculation reproduces the experimental pressure drop near the inlet but underpredicts the total pressure drop. Better agreement between theory and experiment may be obtained in several ways, the simplest being to keep the condensation parameters and θ_{crit} constant but to increase K_o. We do not do this at present because the study of the consistency or the systematic variation of parameters upon flow conditions is best undertaken when calculations are also made for the 50°C subcooled cases, which will be the next phase of our calculational program.

V. COMPLETION OF COMPARISONS WITH AOKI ET AL.

The fairly successful agreement between theory and experiment in the 30°C subcooled case and the 5°C subcooled case suggests strongly that we are now well on the way to modeling adequately the dominant physical processes in the Aoki et al.[1] experiments. The obvious next step to test this hypothesis is to calculate the 50°C subcooled case, for which there are data at three separate liquid mass fluxes, 110, 220, and 330 kg/m^2s, which are well away from the threshold for fluid-steam flow instability, as well as data on the fraction of energetically possible steam condensation that occurs by 20 cm downstream of the inlet. The overall level of agreement with this full set of data and the consistency of the

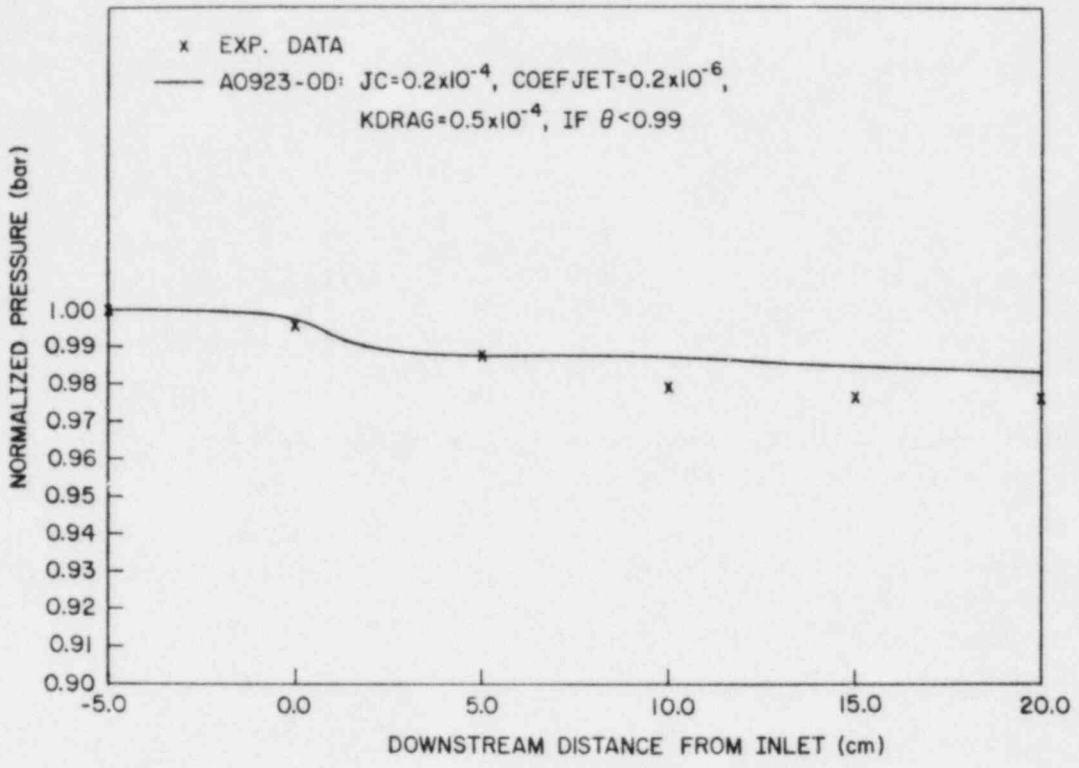

Fig. 2. Normalized theoretical (solid curves) and experimental (× denotes data) pressure profiles for Aoki et al. experiment with 5°C subcooled water. Theoretical curve obtained with JC = 0.2 × 10^{-4}, COEFJET = 0.2 × 10^{-6}, θ_{crit} = 0.99, and K_o = 0.5 × 10^{-4}.

systematic variation of parameters in fitting the several cases would then determine the confidence one would have in applying the resulting model to the extrapolated conditions occurring in a hypothetical loss-of-coolant accident. Of course, some residual uncertainty will necessarily remain for such extrapolations, until the present mathematical models for the averaged effects of the momentum-exchange processes and the condensation processes are replaced by physical models for the separate dynamical processes occurring in the vicinity of the jet and in the downstream region. The latter level of modeling has maximal chance for successful extrapolation to hypothetical loss-of-coolant accidents, and it represents the final stage of our modeling of the Aoki et al. experiments. At present it is possible to be moderately optimistic about the outcome of such work.

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