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A reinterpretation of measurements in developing annular two-phase flow

Carl Adamsson*, Henryk Anglart

Royal Institute of Technology, AlbaNova University Center, SE 106 91 Stockholm, Sweden

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ABSTRACT

Measurements of developing films in adiabatic high pressure steam-water flow in annular geometry have been reanalyzed and compared to a linearized film-flow model. The development rate of the outer film could be determined with good accuracy in four cases. In one case it was also possible to conclude that the inner film develops faster than the outer one. When compared to the linearized model, these observations show that the deposition rate has to be almost independent of the drop concentration at the investigated conditions. Furthermore, any significant deposition by direct impaction of drops can be excluded as it would couple the development of the two films. These conclusions are quite general and do not depend on the use of any particular correlation for the deposition or entrainment rates. Finally, a rough estimate of the deposition rate was possible, confirming that deposition rates are considerably lower at high pressure steam-water flows than in air-water flows.

1. Introduction

Annular two-phase flows appear in various boiling systems, many of which have considerable technical importance. The development of film-flow models to analyze such flows has been an active research field for at least four decades. The research has been driven primarily by the desire to predict the onset of dryout in boiling water nuclear reactors. Over the last 10 years or so, computer codes based on such models have developed from pure research projects into tools that are starting to take the step to standardized engineering tools. Even though these models are often called "mechanistic", and indeed are much more mechanistic than traditional empirical dryout correlations, they still rely on some empirical correlations. Essentially it is the rate of deposition of drops to the liquid wall film and the rate of entrainment of this film into drops that are correlated. The correlations are based on dedicated measurements in annular two-phase flow, usually measurements of film-flow rate or film thickness. Such measurements are relatively abundant at various conditions, but have mostly been performed in round pipe geometry. When applied by engineers, however, these models often have to cope with geometric configurations that differ considerably from round pipes. For example, a nuclear fuel assembly consists of a large number of cylindrical rods, arranged in a square lattice. The accuracy of the round pipe correlations may be questioned in such cases, in particular in the highly asymmetrical corners of a fuel lattice.

In fact, measurements in annular geometry prove the existence of geometry effects that are not captured by state-of-the-art film models. It is well known (Becker, 1975) that dryout, i.e. the complete disappearance of the liquid film on a heated wall, occurs on the inner wall of an annulus at a much lower heat flux than what is required at the outer wall. There have been several attempts to explain this effect as a result of weaker deposition rate (Doerffer et al., 1997; Su et al., 2003) as well as higher entrainment rate (Saito et al., 1978) on the inner surface.

Moeck (1970) carried out an interesting series of measurements, which emphasize the lack of understanding of these flow conditions. Moeck measured the film-flow rate at both the inner and the outer wall at several axial locations in a developing, adiabatic, annular steam-water flow in an annular test section. The data were subsequently analyzed by Andersen (1972), who drew two main conclusions from the data. First, the inner film developed towards a thinner film (less mass flow per wall perimeter) than the outer film. This is consistent with previously cited dryout measurements in annular geometry. Andersen's second conclusion is more surprising. Both films developed roughly exponentially towards equilibrium, but the inner film developed about twice as fast as the outer one. This is surprising mainly because the development of the two films is coupled by the deposition of drops from the common gas core and hence the development rate, at least asymptotically, should be the same. Andersen had no explanation for his result, but does not seem to have fully realized the role of the coupling, most likely because film-flow models were not as developed at the time.

Moeck's measurements are interesting for one other reason, namely that they offer a possibility to estimate the deposition coefficient in high pressure adiabatic steam-water flows, whereas most

* Corresponding author.
E-mail addresses: carlad@kth.se (C. Adamsson), henryk@kth.se (H. Anglart).

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Nomenclature

d	diameter
C	drop concentration
D	rate of deposition
E	rate of entrainment
f	normalized film flow rate
k_D	deposition coefficient
$\mathbf{M}$	coefficient matrix
n_D	exponent in deposition correlation
n_E	exponent in entrainment correlation
P	perimeter
U^*	deposition reference velocity
$\mathbf{V}$	eigenvector
W	mass flow rate
z	axial coordinate

Greek

λ_1	smaller eigenvalue
λ_2	larger eigenvalue
λ^*	estimate of eigenvalue
ρ	density

Indices

d	drops
f	film
g	gas
i	inner wall
o	outer wall

accurate measurements of the deposition rate (e.g. Jepson et al., 1989; Okawa et al., 2005), deal with air-water or similar conditions. High pressure steam-water, however, is exactly the condition that is of interest for nuclear reactor applications. Moreover, the measurements of deposition rates that are available in steam-water flows (e.g. Bennett et al., 1966; Hewitt et al., 1969; Lee and Obertelli, 1963), show that that the deposition rate is very much reduced compared to air-water flows. In fact, the deposition coefficient is about an order of magnitude lower for steam-water (Saito et al., 1978). This effect is captured by most empirical deposition correlations that are used at these conditions, but there is, to the authors' knowledge, as yet no mechanistic explanation for this large difference. It could even be possible that the reduced deposition rate is an effect of the wall heating that was applied in all the steam-water experiments cited above.

Moeck's measurements did not include a direct measurement of the deposition rate. The present analysis does, however, offer a method to, at least roughly, estimate the deposition coefficient based on the measurements. Even though this estimate is not very accurate, it still provides an independent verification of deposition measurements performed in boiling flows, thus reducing the risk that these measurements are biased by the presence of wall heating and the specific measurement technique that was used.

This paper sets out to reanalyze Moeck's experiments and Andersen's conclusions in the light of modern film-flow theory. It should be emphasized, though, that we do not rely on any particular deposition or entrainment correlation. On the contrary, we are well aware that most such correlations would treat the two walls equally and thus fail to capture the asymmetries that are present in the data. Instead, the analysis is based on the fact that Andersen found that, when plotted on a logarithmic scale, the measurements fall on straight lines, thus indicating that the development is exponential. This suggests that linear theory is sufficient to describe these experiments. Thus the starting point is to linearize the theory around the equilibrium conditions. In the next section it is shown that, when these conditions are known, the resulting equations contain very few unknown parameters with a minimum of assumptions.

2. Model

Most models for film-flow analysis that are implemented in various codes (Glück, 2007; Sugawara and Miyamoto, 1990; Hoyer, 1998) are based on the same basic principle. The axial development of the film is modeled as a balance between deposition of drops to the film, entrainment of the film and evaporation of film. Since the present paper considers only adiabatic flows, the evaporation term is zero and the mass balance equation for the liquid film can be written as:

$$\frac{1}{P}\frac{dW_f}{dz} = D - E, \tag{1}$$

where P is the wall perimeter, W_f is the liquid film flow rate, and D and E are the deposition and entrainment rates, respectively. The axial elevation is denoted by z. There should be no controversy about the use of this mass balance as the base of a film-flow model. The variations between such models are instead found in the formulation of the correlations for the deposition and entrainment rates. The deposition correlations usually take the following general form:

$$D \propto C^{n_D} U^* \tag{2}$$

where C is the effective drop density in the gas core, U^* is a reference velocity and n_D is an empirical parameter. The definitions of these quantities differ between different correlations. For example Hewitt and Govan (1990), define the drop concentration as

$$C = \frac{W_d}{(W_d/\rho_l) + (W_g/\rho_g)}, \tag{3}$$

where W_d, W_g, ρ_l and ρ_g denote mass flow rate of drops and gas, and liquid and gas densities, respectively. In Kataoka et al. (2000) and Okawa et al. (2004), the simpler expression

$$C = \frac{W_d}{W_g}\rho_g \tag{4}$$

is used. Note that Eq. (3) reduces to Eq. (4) if $W_d/\rho_l << W_g/\rho_g$, which is usually the case. Thus, Eq. (4) will be used in this work. Many options for the reference velocity, U^*, have been proposed, but this is of little importance for the present work.

In the case of the entrainment rate, E, the diversity of correlations is even larger. There is, however, a general agreement that, at least for adiabatic flow, the entrainment process is caused by the shear stress at the liquid film interface and that the entrainment rate increases with the film thickness. In this paper it is mainly the dependence on the film thickness that is of importance. The relation between the film thickness and the film mass flow rate, W_f, is, however, not simple. Since the mass balance is based on the latter quantity, the following basic form for the entrainment correlation is adopted:

$$E \propto \left(\frac{W_f}{P}\right)^{n_E} \tag{5}$$

This simplified expression turns out to be, at least locally, consistent with successful entrainment correlations, such as Okawa et al. (2004) and Hewitt and Govan (1990).

In order to model the annular geometry, with two separate liquid films, two mass balance equations of the form (1) are needed.