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Experimental investigation on dominant waves in upward air-water two-phase flow in churn and annular regime

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ABSTRACT

This paper describes new measurements on the characteristics of waves in churn and annular flow. The measurements were for air-water flow in an 11 mm diameter vertical tube, a diameter close to the equivalent diameter of nuclear reactor channels. These measurements extend the parameter space of previous publications into the low and gas and liquid mass flow rates important for nuclear reactor fault studies. Detailed measurements of the flow characteristics are reported, including the identification of a new regime we designate 'pre-annular flow', in which the liquid film between the waves appears to be stationary. The results of these measurements at low mass fluxes are compared with predictions in this low mass flux region using the principal literature correlations, all of which were actually obtained from elsewhere in the parameter space. Reassuringly, the broad conclusion is that despite this, these correlations obtained from elsewhere are safe to continue to be used in this low mass flux region. A new interpretation of the criteria for onset of entrainment was also obtained from the study.

1. Introduction

Annular flows occur in many industrial applications; boiler and evaporator tubes, heat exchangers, Boiling Water Reactors (BWRs) and so on. This flow regime is characterised by the presence of a thin wall-adhering liquid film and a central gas core. Depending on the gas and liquid velocities, the gas core may or may not entrain liquid droplets. The liquid film surface is normally wavy, the most important waves being intermittent large waves known as disturbance waves. In upward annular flow, the waves on the interface are travelling upwards. Another important regime (occurring at somewhat lower gas velocities than annular flow) is churn flow. As was seen by Hewitt et al. [1], the churn flow regime is also characterised by a liquid film at the wall and droplet entrainment in the core of the flow. However, churn flow differs from annular flow in that the liquid film reverses direction and flows downwards between the upwards-travelling large waves. Prediction of the liquid entrainment fraction and the rates of entrainment and deposition in churn and annular flow are important for mass transfer and phase change studies, and such predictions are used widely in predicting dryout (i.e. the condition in which the film flow rate becomes zero as a result of entrainment and evaporation (Hewitt and Govan [2]).

The behaviour of waves is one of the most important characteristics in churn and annular flow. Studies of the formation and behaviour of waves in churn flow are reported by Govan et al. [3], Barbosa et al. [4] and Wang et al. [5]. Such waves are crucial in determining entrainment at the onset of annular flow. There is relatively greater number of studies on disturbance waves in annular flows. These waves affect the entrainment, and possibly deposition, rates. Traditionally, most of the efforts towards prediction of entrainment and deposition are purely observational in nature, but the thrust of much current work is for these empirical approaches to become more mechanistic, informed by an (at least) qualitative understanding of the flow.

Such phenomenological modelling depends on good experimental data; on measurements of quantities such as entrainment rates and deposition rates, and on observations of 'intermediate' quantities such as the frequencies and form of disturbance waves.

There is a wide parameter space of interest, ranging from the high pressures and flows associated with normal operation in a BWR, to the low pressures and low flows important in studying various fault conditions.

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A major motivation of this paper was to augment the rather sparse availability of experimental data for nuclear-relevant small tubes, in particular by extending it into the low liquid and gas flow region, of particular interest for fault studies. This had two main objectives:

(1) The first objective was to allow the validity of existing correlations to be investigated for this region, as these are largely based on measurements outside this region, or for which the experimental range cannot be ascertained. Demonstration that correlations used in safety analyses are truly valid for the parameter space in which they are applied is naturally necessary to satisfy regulators.
(2) Secondly, by measuring the fullest possible set of parameters, in particular wavelength, frequency and wave speed, we hoped to provide additional insights into the flow characteristics that would aid those attempting to build semi-empirical phenomenological models of the dryout process. Disturbance waves, being large amplitude waves, have been identified as the major source of entrainment [6,7]. This fact is also highlighted by Sawant et al. [8] who have indicated the importance of disturbance wave studies for the evaluation of entrained fraction. In the literature are reports of attempts to model the rate of entrainment through simplified representations of the wave [9]. Such models require various wave characteristics such as wavelength and speed, which can only be determined experimentally.

The role of disturbance waves in influencing deposition has been less considered. Since disturbance waves change markedly the flow area available to the high-speed vapour core (e.g. Han et al. [10]), especially in small diameter channels, the core velocity will be modified by the waves, and one might expect that the rate of deposition might consequently be modified. In Fig. 1 is shown a typical disturbance wave, and an idealized sketch, with postulated vapour streamlines.

Droplets already entrained upstream of the wave, especially inertial droplets, might be deposited directly into the upstream face of the wave, if they are unable to follow the rapid radially-inwards acceleration of the vapour. The rapid radial expansion of the gas flow, and possible recirculation, downstream of the wave might similarly increase deposition rates. Since the waves themselves are believed to be a major entrainment source, it could indeed be that a large fraction of drops are born directly into this high-deposition environment. This effect of the waves on deposition rate does not feature explicitly in any of the deposition rate correlations. This might be due to the fact that normally experimental determination of deposition rate involves measuring deposition after completely removing the film and thus no waves exist when the deposition rate is measured. Thus, 'by construction', our models and correlations for deposition rate do not admit any influence of waves. On the other hand, predictions of film flow rate as a function of quality not taking direct account of the influence of waves on deposition do rather well [2]. Part of this second motivation was to provide data for a subsequent investigation into the role of disturbance waves in the deposition process.

With reference to Fig. 1, the velocity of the disturbance waves relative to the gas, as well as their size and other characteristics, all seem likely to affect the radial velocities generated. Thus disturbance wave velocity, amplitude, wavelength and time period, along with the vapour flow rate, are all important quantities that are required to be known to investigate this further. Determining these was part of our second motivation.

In Section 2 we review and discuss the relevant literature, setting the scene for our own measurements. Section 3 summarizes where the data generated in the present work lies in the parameter space. In Section 4 we describe our experimental arrangements, discussing both the quantitative and the 'qualitative observations. In Section 5 we report our measurements, and relate them as appropriate to earlier literature values. In Section 6 we investigate the accuracy with which earlier correlations, predominantly based on higher flow rate conditions, predict behaviour at the low liquid and low gas flows measured. Conclusions are drawn in Section 7.

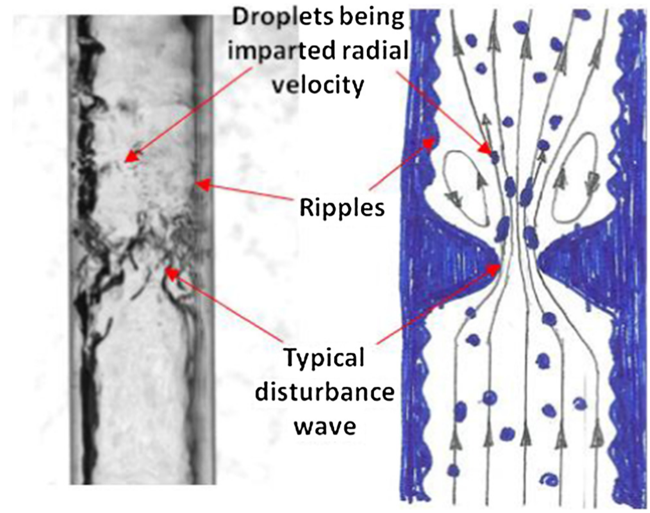

Fig. 1. Typical disturbance wave, its simplified representation, and postulated flow field.

2. Literature review

Based on the mechanism of formation, in the literature large waves in annular flow are called *disturbance waves* and those in the churn flow regime are called *flooding waves*. There have been many measurements reported for disturbance waves, and only what are possibly the most relevant ones for the present work are summarized here. There are far fewer studies on flooding waves. Most of these measurements have been carried out using air and water, primarily because of the ease of experimentation.

2.1. Previous measurements on disturbance waves in annular flow regime

In the literature, pioneering and very informative work on study of disturbance wave characteristics has been done by Nedderman and Shearer [11] and Hall-Taylor et al. [12] who used cine films to determine wave characteristics in annular flow. Hall-Taylor et al. [12] used in addition conductance probes to measure the liquid film thickness, but they found that such probes tend to give spurious signals for large ripples. They found the wave velocity to be a function of both air and liquid flow rates, although the dependence on air flow rate was dominant. In both these works, wave frequency was found to be a function of both air and water flow rates. However at higher water flow rates, dependence on water flow rate was not observed [11]. The tube diameter used in these experiments was 31.8 mm, which is much larger than the ~10 mm hydraulic diameters of nuclear reactor rod bundles. Nevertheless, these experiments gave a good insight into the characteristics of disturbance waves.

Azzopardi [13] and Thwaites et al. [14] conducted similar studies on the same 31.8 mm diameter pipe, and their observations were mostly in accord with previous works. Thwaites et al. [14] found that below a particular gas flow rate the wave frequency was independent of gas flow rate, whilst above this value there was approximately linear increase with gas flow rate.