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Entrained liquid fraction prediction in adiabatic and evaporating annular two-phase flow

Andrea Cioncolini[1], John R. Thome*

Heat and Mass Transfer Laboratory, Swiss Federal Institute of Technology-EPFL, EPFL-STI-IGM-LTCM, Station 9, 1015 Lausanne, Switzerland

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ABSTRACT

A new method to predict the entrained liquid fraction in annular two-phase flow is presented. The underlying experimental database contains 2460 data points collected from 38 different literature studies for 8 different gas–liquid or vapor–liquid combinations (R12, R113, water–steam, water–air, genklene–air, ethanol–air, water–helium, silicon–air), tube diameters from 5.0 mm to 95.3 mm, pressures from 0.1 to 20.0 MPa and covers both adiabatic and evaporating flow conditions, circular and non-circular channels and vertical upflow, vertical downflow and horizontal flow conditions. Annular flows are regarded here as a special form of a liquid atomization process, where a high velocity confined spray, composed by the gas phase and entrained liquid droplets, flows in the center of the channel dragging and atomizing the annular liquid film that streams along the channel wall. Correspondingly, the liquid film flow is assumed to be shear-driven and the energy required to drive the liquid atomization is assumed to be provided in the form of kinetic energy of the droplet-laden gas core flow, so that the liquid film–gas core aerodynamic interaction is ultimately assumed to control the liquid disintegration process. As such, the new prediction method is based on the core flow Weber number, representing the ratio of the disrupting aerodynamic force to the surface tension retaining force, a single and physically plausible dimensionless group. The new prediction method is explicit, fully stand-alone and reproduces the available data better than existing empirical correlations, including in particular measurements carried out in evaporating flow conditions of relevance for boiling water nuclear reactor cooling.

1. Introduction

Annular two-phase flow is one of the most frequently observed flow regimes in practical applications involving gas–liquid and vapor–liquid two-phase flows, such as steam generators, refrigeration and air conditioning systems, nuclear reactors and chemical processing plants. In annular flows, a part of the liquid phase flows as a continuous film that streams along the channel wall, while the rest of the liquid phase is transported in the gas core as entrained droplets. Annular flows have been extensively investigated in the last decades, particularly in connection with nuclear reactor cooling applications. Nonetheless, this topic is currently experiencing a renewed interest, driven in particular by nuclear reactor power uprates and nuclear reactor fuel optimization, applications where more accurate and reliable prediction methods for system computer codes are required. Sound prediction methods for annular flows are as well required for the design of micro evaporators and micro heat sinks for the thermal management of microelectronic components, computer chips, laser diodes and high energy physics particle detectors, while also for refrigeration, air-conditioning and petrochemical piping and processes.

A crucial parameter for predicting and modeling annular flows is the entrained liquid fraction e, defined as the ratio of the entrained liquid droplets mass flow rate to the total liquid mass flow rate. The entrained liquid fraction is a flow parameter bounded between 0 and 1, with values close to 0 being characteristic of annular flows with an almost perfect segregation between liquid and vapor and most of the liquid concentrated in the film, while values close to 1 are typical of annular flows close to the transition to dispersed mist flow where most of the liquid is in the form of entrained droplets. The accurate prediction of the entrained liquid droplets mass flow rate is of paramount importance since this is liquid not flowing in the annular film, and hence has an important influence both on the gas/vapor core and annular film flows. As a matter of fact, an accurate knowledge of the entrained liquid fraction is required in most thermal–hydraulics predictions, such as the onset of dryout in boiling channels, post-dryout heat transfer and the effectiveness of nuclear reactor core cooling, particularly during transient and accident scenarios.

* Corresponding author. Tel.: +41 21 693 5981; fax: +41 21 693 5960.
E-mail addresses: andrea.cioncolini@epfl.ch (A. Cioncolini), john.thome@epfl.ch (J.R. Thome).
[1] Tel.: +41 21 693 5984; fax: +41 21 693 5960.

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Nomenclature

a_g	gas sonic velocity (m s^{-1})
a_{tpf}	two-phase flow sonic velocity (m s^{-1})
A_{flow}	channel cross section flow area (m^2)
d	tube diameter (m)
d_c	core flow diameter (m)
e	entrained liquid fraction (–)
g	acceleration of gravity (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
M	Mach number (–)
P_{wet}	channel wetted perimeter (m)
J_g	superficial gas velocity (m s^{-1})
J_l	superficial liquid velocity (m s^{-1})
V_c	core flow velocity (m s^{-1})
V_g	gas velocity (m s^{-1})
V_{tpf}	average two-phase flow velocity (m s^{-1})
We_c	core flow Weber number (–)
x	vapor quality (–)
ε	cross sectional void fraction (–)
ρ_c	core density (kg m^{-3})
ρ_g	vapor density (kg m^{-3})
ρ_l	liquid density (kg m^{-3})
σ	surface tension (kg s^{-2})

Recently, Cioncolini and Thome (2010) proposed a prediction method for the entrained liquid fraction based on the assumption that annular flows can be regarded as a special form of a liquid atomization process, where a high velocity confined spray, composed by the gas phase and entrained liquid droplets, flows in the center of the channel dragging and atomizing the annular liquid film that streams along the channel wall. In particular, the liquid film flow was assumed to be shear-driven and the energy required to drive the liquid atomization was assumed to be provided in the form of kinetic energy of the droplet-laden gas core flow, so that the liquid film–gas core aerodynamic interaction was ultimately assumed to control the liquid disintegration process. Accordingly, the dimensionless group used by the authors to fit entrained liquid fraction data is a core flow Weber number We_c, representing the ratio of the disrupting aerodynamic force to the surface tension retaining force and defined as:

$$We_c = \frac{\rho_c V_c^2 d_c}{\sigma} \tag{1}$$

If the slip between the carrier gas phase and the entrained liquid droplets is neglected so that gas and droplets are assumed to travel at the same speed, then the droplet-laden gas core density ρ_c, the core flow velocity V_c and equivalent diameter d_c are as follows:

$$\rho_c = \frac{x + e(1-x)}{(x/\rho_g) + (e(1-x)/\rho_l)}; \qquad V_c = \frac{xG}{\varepsilon \rho_g};$$

$$d_c = d\sqrt{\varepsilon \frac{x\rho_l + e(1-x)\rho_g}{x\rho_l}} \tag{2}$$

where x is vapor quality, ρ_l and ρ_g are the liquid and vapor densities, G is the mass flux, ε is the cross-sectional void fraction of the channel and d the tube diameter. The measured entrained liquid fraction values from Cioncolini and Thome (2010) are displayed in Fig. 1 versus the core flow Weber number defined in Eq. (1), together with the proposed correlating equation:

$$e = (1 + 13.18 \quad We_c^{-0.655})^{-10.77} \tag{3}$$

Besides outperforming existing prediction methods, as discussed by the authors, a significant advantage of Eq. (3) with respect to other empirical correlations is that it is based on a single and physically plausible dimensionless number, which is also a controlling group in determining the wall shear stress and associated frictional pressure gradient of annular flows (Cioncolini et al., 2009b). The experimental database used to derive Eq. (3) contained 1504 measurements of the entrained liquid fraction and covered 8 gas–liquid or vapor–liquid combinations (R12, R113, water–steam, water–air, genklene–air, ethanol–air, water–helium, silicon–air) and 19 different values of the tube diameter from 5.0 mm to 57.1 mm. Although this experimental database was quite large, it is essentially limited to adiabatic annular flows, as it contains only 16 points obtained in diabatic flow conditions. As such, the application of Eq. (3) to evaporation in channels is not straightforward and requires some extrapolation. Besides, as can be seen in Eq. (2), the core flow density ρ_c depends on the entrained liquid fraction e, so that Eq. (3) has to be used iteratively, a complication that might limit its applicability into existing simulation tools. Finally, this prediction method is not completely stand-alone, since the void fraction ε is required as input in Eq. (2) to calculate the core flow velocity V_c and equivalent diameter d_c. As such, an additional empirical correlation is actually required to provide the void fraction.

The purpose of the present study is to improve the prediction method for the entrained liquid fraction proposed in Cioncolini and Thome (2010). In particular, the method is here extended to cover evaporating flow conditions and non-circular channels. Moreover, the method is also simplified and made explicit and fully stand-alone. The underlying experimental databank has been significantly expanded from the 1504 data points initially used by

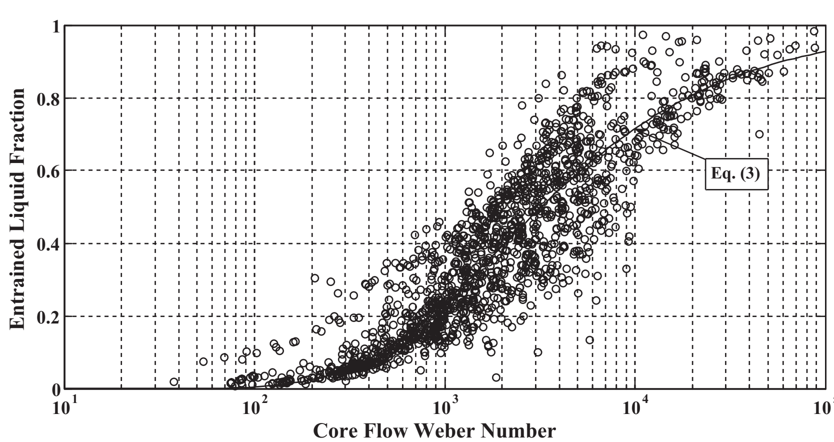

Fig. 1. Entrained liquid fraction vs. core flow Weber number as defined in Eq. (1), from Cioncolini and Thome (2010).