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Review of droplet entrainment in annular flow: Characterization of the entrained droplets

C. Berna [a, *], A. Escrivá [a, 1], J.L. Muñoz-Cobo [a, 1], L.E. Herranz [b, 2]

[a] Instituto de Ingeniería Energética, Universitat Politècnica de València (UPV), Camino de Vera 14, 46022 Valencia, Spain
[b] Unit of Nuclear Safety Research, Division of Nuclear Fission, CIEMAT, Avda. Complutense 22, 28040 Madrid, Spain

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ABSTRACT

Annular flow is characterized by a thin liquid film flowing on the pipe wall and a high velocity gas core flowing in its center, which normally carries liquid droplets. This review presents and analyzes most of the extensive literature existing on the annular two-phase flow, focusing specifically on the analysis of the main phenomena that are involved. In particular, the paper focuses on the study of the liquid droplets that are entrained by the gas stream from the gas–liquid interface, due to the strong influence that these droplets exert in many important parameters of both, flow and heat transfer processes. Consequently, it is important to be able to know the maximum amount of information about them, in order to characterize droplets' size and velocity, and to determine the amount of them that are entrained into the gas stream and, finally, apply this knowledge in all processes in which annular flow is involved.

This review analyzes most of the extensive literature on droplets, specifically analyzes its main characteristics once they have been formed, such as its sizes, speeds and total amount. A vast amount of data has been found in the open literature and collected here. Their analysis leads to two major observations: their huge scattering and the existence of remaining knowledge gaps. Some of the experimental data have been also used to derive new correlations on variables as important as amount and size of entrained droplets.

1. Introduction

The study of two phase flows, and annular flow in particular, is important due to its relevance in many industrial processes; for instance, channel flow during steam generation processes, nuclear reactors and other power plants, heating and refrigeration equipment, such as, heat exchangers and condensers, gas–liquid mixers and gas–liquid separators, transportation of natural gas and crude oil, etcetera.

The annular flow, in both horizontal and vertical pipes, has been the subject of many theoretical studies. When describing the annular flow, one may split the scenario in three major features: the existence of a series of waves at the gas–liquid interface; the droplet entrainment into the gas core from the interface; and the subsequent deposition of a fraction of entrained droplets onto the gas–liquid interface. Recently, a first part of this work, with the main emphasis on interfacial waves and onset of entrainment, was published (Berna et al., 2014). To close-up the study of two-phase annular flow, this paper is focused on the key parameters associated with the entrained droplets i.e., size, velocity and total amount. These parameters are studied in steady state conditions, that is, when entrainment and deposition processes reach the equilibrium.

A huge number of papers have been published previously on the matter tackled with in this paper. Given the review nature of this one, those papers with a major impact on the area will be referenced properly in next sections.

The present paper is structured as follows: Sections 2 and 3 deal with equations characterizing droplet sizes and velocities; Section 4 reviews the existing expressions for estimating the total amount of droplets entrained; Section 5 analyzes the data and sets comparisons with preceding equations and other new ones derived in this paper; Section 6 wraps up the whole paper with a number of conclusions.

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* Corresponding author. Tel.: +34 963879245.
E-mail addresses: ceberes@iie.upv.es (C. Berna), aescriva@iqn.upv.es (A. Escrivá), jlcobos@iqn.upv.es (J.L. Muñoz-Cobo), luisen.herranz@ciemat.es (L.E. Herranz).
[1] Tel.: +34 963879245.
[2] Tel.: +34·913466219; fax: +34·913466233.

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2. Droplet sizes

The determination of droplets sizes is one of the key parameters in order to describe the entrained process in annular flow, for this purpose an open literature search was carried out. When estimating the droplet size distribution should be noted that the aerodynamic breakup is an important mechanism for the description of two-phase flows associated with droplets suddenly exposed to a high speed gas stream. Detailed developments of the droplets breakup phenomenon can be found in several works, for instance, accurate descriptions are shown in Crowe (2006), Kolev (2007) and Azzopardi (1997).

The initial droplet sizes are determined by the mechanism from which have been generated, such as shearing off of roll-wave crests in the case of annular flow, or primary atomization in the case of sprays formation from a liquid jet or sheet. But, in addition to the formation mechanisms, when these droplets are surrounded by a continuous phase which is moving at a high relative velocity, the aerodynamic forces will cause the deformation and fragmentation of these droplets. Then the droplets with a diameter larger than the maximum stable size begin to oscillate, which finally results in the rupture of the droplet. Consequently, a distribution of smaller droplets is produced by the generation mechanisms (Appendix I).

The droplet breakup mechanisms can be expressed as a balance of forces between external stress forces and surface forces. External stress forces, which attempt to disrupt the droplet and surface tension forces, which try to avoid droplet deformation. Consequently, the Weber number, which is the ratio between these two forces, has to be considered. A larger value of Weber number indicates that there is a higher tendency toward breakup. In this sense, equations estimating droplet sizes may be classified in two groups: those that are based on a critical Weber number (the one corresponding to the maximum stable droplet diameter) and correlations depending directly on fluid properties and dimensionless numbers. The basic model of the We group is the critical Weber number criterion, which sets $\mathrm{We}_{\mathrm{crit}}$ to 12 (although experimental values range from 5 to 20 in low viscosity fluids, like water); other models just add a correction factor usually based on the viscosity effect on shear stresses on droplets. The second group expressions are diverse as for the target variable, some give the maximum stable diameter, while others correlate the mean or the Sauter diameter.

2.1. *The critical Weber number*

Based on experimental data it has been observed that water droplets break-up whenever Weber dimensionless number (the ratio between inertia and surface tension forces) exceeds a certain value ($\mathrm{We}_{\mathrm{crit}}$). In low viscosity liquids, $\mathrm{We}_{\mathrm{crit}}$ ranges from 5 to 20 (Kolev, 2007), a complete summary of the experiments carried out to determine the critical Weber number is shown in Wierzba's paper (Wierzba, 1990).

2.1.1. *The critical Weber number criterion*

The most widely used criterion to estimate the size of the droplets is related to an empirical value of the Weber number:

$$\mathrm{We}_{\mathrm{crit}} = \frac{\rho_g u_g^2 \phi_{d,\max}}{\sigma} = \mathrm{CONSTANT}(6 \text{ or } 12) \tag*{1)}$$

This equation implies that the droplets diameter varies as the inversed square of the gas velocity, $\phi_d \propto \frac{1}{u_g^2}$.

2.1.2. *Droplet break-up*

Suspended particles undergoing significant local stresses may break-up into two or more particles. The instabilities caused may be driven by density differences (Rayleigh-Taylor) and/or velocity differences (Kelvin-Helmholtz) (Loth, 2010).

If a fluid particle submitted to high accelerations has a density quite different from that of the continuous-phase, the interface become unstable. These instabilities are likely to take place when the deformations due to dynamic pressure become so severe that surface tension is insufficient to maintain the particle's surface integrity. Under these conditions, the Rayleigh-Taylor instabilities are considered to be dominant. Then, the suggested value of the critical Weber number is:

$$\mathrm{We}_{\mathrm{crit},R-T} = \frac{\rho_g u_g^2 \phi_{\mathrm{crit},R-T}}{\sigma} \approx 8 \tag*{2)}$$

The Kelvin-Helmholtz (KH) instability is mainly associated with flows which have tangential variation in the velocity field, i.e. for high relative velocity between the gas and the droplet. This instability is caused by the hydrodynamic amplification of perturbations that arise at the gas–liquid interface with a discontinuity in the velocity field. A critical Weber number related to the fluid's densities can be defined, while experiments may be used to determine the proportionality constant, the final proposed expression is:

$$\mathrm{We}_{\mathrm{crit},K-H} = \frac{\rho_g \left|u_g - u_d\right|^2 \phi_{\mathrm{crit},K-H}}{\sigma} \approx 12 \frac{(\rho_l + \rho_g)}{\rho_l} \tag*{3)}$$

For the condition of $\rho_d \gg \rho_g$ (droplets in a gas), this corresponds to $\mathrm{We}_{\mathrm{crit},K-H} \approx 12$.

A similar expression applicable to the Kelvin-Helmholtz instability analysis is presented by Kolev (2007). That expression is useful if the entrained particle in this process has a size approximately equal to the height of the most unstable wavelength, $\phi_d = \Delta h_{w,\,K-H}$, Fig. 1. In order to estimate the wave amplitude, is taken into account the Kelvin-Helmholtz instability, which is caused by the relative motion of two continuous phases (Chandrasekhar, 1981). For that instability, the most unstable wave amplitude is (for gas as a continuous phase):

$$\Delta h_{w,K-H} = 3\pi \frac{\left(1 + \frac{\rho_g}{\rho_l}\right)\sigma}{\rho_g \left(u_g - u_d\right)^2} \tag*{4)}$$

then, the critical Weber number would be

$$\mathrm{We}_{\mathrm{crit}} = \frac{\rho_g \left|u_g - u_d\right|^2 \phi_d}{\sigma} \approx 3\pi \left(1 + \frac{\rho_g}{\rho_l}\right) \tag*{5)}$$

Note that for water droplets in a gas stream $\mathrm{We}_{\mathrm{crit}} \approx 9.5$.

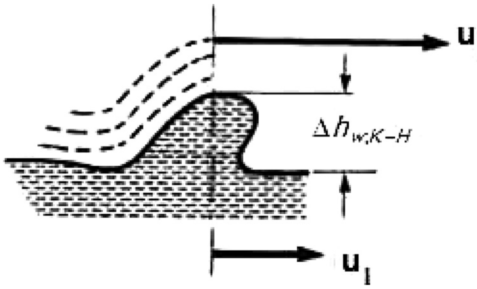

Fig. 1. Most unstable wavelength during relative motion of two continuous phases.