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Numerical modeling of a horizontal annular flow experiment using a droplet entrainment model

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ABSTRACT

One limitation in current simulating horizontal annular flows is the lack of treatment of droplet formation mechanisms. For self-generating annular flows in horizontal pipes, the interfacial momentum exchange and the turbulence parameters have to be modelled correctly. Furthermore the understanding of the mechanism of droplet entrainment in annular flow regimes for heat and mass transfer processes is of great importance in the chemical and nuclear industry.

A new entrainment model is proposed. It assumes that due to liquid turbulence the interface gets rough and wavy and forms droplets. The new approach is validated with HZDR annular flow experiments. Important phenomena like the pressure drop, the wave pumping effect, the droplet entrainment, the liquid film formation and the transient flow behavior could be calculated, analyzed and some of the phenomena compared with the measurement.

1. Introduction

Annular flow occurs in many industrial processes, and is characterized by high gas flow at the center of the pipe and liquid film flow around the pipe wall. Due to the high gas velocity, large shear velocities are induced that result in high interfacial shear stress causing continuous entrainment of liquid droplets into the gas core from the liquid film. When the liquid fraction is small in horizontal annular flow, it is possible to cause an extremely important problem that relates to the damage of heat exchanger tubes, because the drainage of liquid due to gravity, as well as the evaporation, leads to the dry-out of thin liquid film near the top of the tube. Therefore, it is important to accurately predict the circumferential distribution of film thickness in horizontal annular flow. Furthermore the thin water film at the cold wall plays a major role for the heat transfer resistance of the condensation process. For better understanding of condensation heat transfer the film formation mechanism and the film distribution need to be known.

Since many years, measurements of the wave structure of the liquid film have been made for both, vertical and horizontal annular flows. These measurements included local time variation of film thickness, wave velocity, and frequency, as well as spectral properties of film thickness time records. In these studies, resistance probes (Jayanti et al., 1990 and Paras and Karabelas, 1991) and optical methods were employed (Shedd and Newell, 1998). More recently, Kopplin (2004) obtained partial success with particle image velocimetry (PIV) and particle tracking techniques to estimate velocity field in the film.

Today's theories to explain the annular flow mechanism are wave spreading, wave pumping, secondary gas flow and entrainment of droplets into the waves.

The *Wave Spreading* mechanism (Fig. 1) was described by Butterworth and Pulling (1972) and Fukano and Ousaka (1989). They assume that disturbance waves travels faster along the bottom than along the top, creating a plowing or wedge effect that pushes the liquid film upwards in front of the wave and keeps the liquid film on top.

A *Wave Pumping* Mechanism was proposed by Fukano and Ousaka (1989) and first shown by Darling and McManus (1968). Later, also Paras and Karabelas (1991) did analyze the Wave Pumping Mechanism. They found out that waves travel upward due to circumferential pressure gradients and liquid drains by gravity after the passage of each wave. The authors further suggests that the circumferential pressure gradient is caused by stagnation of gas in front of the disturbance wave and the separation behind it, which is higher on the bottom part than on top.

The *Secondary Gas Flow* (Fig. 2) was first proposed by Pletcher and McManus (1965) and shown by Darling and McManus (1968). Later, also Paras and Karabelas (1991) observed this gas flow structure. The motion is caused by interfacial roughness circumferential gradient. According to Flores et al. (1995), secondary

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Nomenclature

A	interfacial area density (1/m)
a	surface roughness (m)
α	volume fraction (–)
C	constant (–)
C_D	drag coefficient (–)
d	local deposition rate (m/s)
d	diameter (m)
D	droplet formation rate per unit volume and time (1/s)
f	blending function (–)
f	frequency (Hz)
Φ	interface layer (m)
g	constant of gravity acceleration (m/s^2)
k	turbulent kinetic energy (m^2/s^2)
$\mathbf{n}$	normal vector of the interface (–)
P	pressure (Pa)
t	time (s)
u	velocity (m/s)
U	characteristic velocity (m/s)
$\dot{V}$	volumetric flow rate (m^3/s)
x	distance (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	shear stress (Pa)

Subscript

B	bubble
D	drop
FS	free surface
G	gas
i	phase index
L	liquid

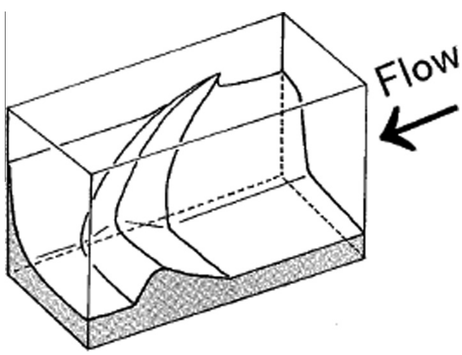

Fig. 1. Wave Spreading mechanism (Fukano and Ousaka, 1989).

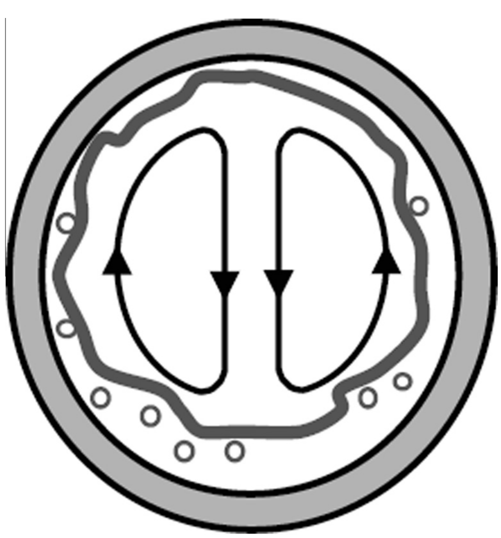

Fig. 2. Secondary Gas Flow (Kopplin, 2004).

flow velocity is about 4% of axial velocity. Westende et al. (2007) compared the behavior of the droplets (dispersed phase) with and without secondary flow, using LES. It was shown that the presence of secondary flow increases the droplet concentration in the core of the pipe and the droplet deposition-rate at the top of the pipe.

Droplet entrainment/deposition: Azzopardi and Whalley (1980) found that droplets in annular core come predominantly from the surface of disturbance waves. Stevanovic and Studovic (1995) presented a derivation for droplet entrainment in vertical annular flow, it is extensively used for all configurations. Kopplin (2004) suggests that this mechanism becomes more important as the flow goes further into the annular regime. Entrainment fraction results from a dynamic equilibrium between the rate of deposition of drops from the gas core to the liquid film and the rate of droplet formation (also called atomization) at the gas–liquid interface from waves occurring on the film surface. Its prediction is important for the estimation of pressure drop, flow rate, liquid holdup, dry-out in annular flow as well as for designing and optimizing separation facilities. It should be noted that the phenomenon of dry-out, also known as Critical Heat Flux (CHF), corresponds to the point where a continuous liquid contact cannot be maintained at the surface. This has importance in the nuclear industry since droplet entrainment and deposition rates need to be known to predict dry-out. According to Kataoka and Ishii (1982), the entrainment fraction is a more stable parameter to measure and correlate as this represents the integral effects of deposition and entrainment rate of the droplets.

In general, the conditions leading to entrainment of a liquid surface film by a gas flow is of considerable practical importance for heat and mass transfer processes in two-phase flow systems. The mechanisms of mass, momentum, and energy transfer is significantly altered by the inception of entrainment (Ishii and Grolmes, 1975). A wavy liquid surface can be entrained into a gas flow in different ways. Hydrodynamic and surface forces govern the motion and deformation of the wave crests. Under certain conditions, these forces lead to an extreme deformation of the interface which results in breakup of a portion of a wave into several droplets. The forces acting on the wave crests depend on the flow pattern around them as well as on the shape of the interface. Ishii et al. explained in his paper five basic types of entrainment mechanisms, while four of them are relevant in segregated horizontal flow regimes which are shown in Fig. 3. In the first type the tops of large amplitude roll waves are sheared off from the wave crests by the turbulent gas flow (Hewitt and Hall-Taylor, 1970). The drag force acting on the wave tops deforms the interface against the retaining force of the liquid surface tension. The