5 Entrainment in annular two-phase flow

5.1 Introduction

Entrainment is a process defined as mechanical mass transfer from the continuous liquid velocity field into the droplet field. Therefore, entrainment is only possible if there is a wall in the flow, that is in channel flow (see Fig. 5.1) or from the surfaces in pool flows. The surface instability on the film caused by the film-gas relative velocity is the reason for droplet formation and their entrainment.

Fig. 5.1 Annular flow: 1 gas, 2 film, 3 droplets

The entrainment is quantitatively described by models for the following characteristics:

(1) Identification of the conditions when entrainment starts;
(2) The mass leaving the film per unit time and unit interfacial area, \((\rho_w)_23\), or the mass leaving the film and entering the droplet field per unit time and unit mixture volume, \(\mu_{23}\)

\[
\mu_{23} = a_{12} (\rho_w)_{23}
\]  \hspace{1cm} (5.1)

where \(a_{12}\) is the interfacial area density, that is the surface area between gas and film per unit mixture volume;
(3) Size of the entrained droplets.
Note that there is no general correlation for entrainment and deposition up to now. In what follows we summarize some results presented in the literature for quantitative modeling of these processes.

### 5.2 Some basics

Taylor, see Batchelor (1958) or Taylor (1963), obtained the remarkable result for the interface-averaged entrainment velocity

$$u_{23} = \text{const} \left( \frac{\rho_1}{\rho_2} \right)^{1/2} \Delta V_{12} \lambda_m^* f_m^*$$  \hspace{1cm} (5.2)

where $\lambda_m^*$, defined by

$$2\pi \lambda_m^* = \lambda_m \rho_1 \Delta V_{12}^2 / \sigma,$$ \hspace{1cm} (5.3)

and $f_m^*$, defined by

$$2f_m^* = f_m \left[ \left( \frac{\rho_1}{\rho_2} \right)^{1/2} \rho_1 \Delta V_{12}^3 / \sigma \right],$$ \hspace{1cm} (5.4)

are the dimensionless wavelength and the frequency of the fastest growing of the unstable surface perturbation waves which are complicated functions of the Taylor number based on relative velocity,

$$Ta_{12} = \left( \frac{\rho_2}{\rho_1} \right) \left[ \frac{\sigma}{(\eta_2 \Delta V_{12})} \right]^2,$$ \hspace{1cm} (5.5)

where $f_m^* \leq \sqrt{3}/9$ and $0.04 \leq \lambda_m^* f_m^* \leq \sqrt{3}/6$ for $10^{-5} \leq Ta_{12} \leq 10^4$ and $\lambda_m^* f_m^* = \sqrt{3}/6$ for $Ta_{12} > 10^4$. Comparison with experimental data for engine spray where $\Delta V_{12} = V_2$, indicates that $\frac{1}{2} \left( \text{const} \lambda_m^* f_m^* \right)$ is of the order of 7, see Bracco (1985). This means

$$u_{23} \approx 14 \left( \frac{\rho_1}{\rho_2} \right)^{1/2} \Delta V_{12}.$$ \hspace{1cm} (5.6)

Following Schneider et al. (1992) and assuming that (a) the surface entrainment velocity is equal to the liquid side surface friction velocity,

$$u_{23} = u_2^{1*} = \left( \frac{\tau_2^{1*}}{\rho_2} \right)^{1/2},$$ \hspace{1cm} (5.7)

and (b) the liquid side surface shear stress is equal to the vapor side shear stress due to the gas flow

$$\tau_2^{1*} = \frac{1}{2} \rho_1 \Delta V_{12}^2,$$ \hspace{1cm} (5.8)