The influence of liquid properties on flooding phenomena in small diameter tubes

A.A. Mouza, M.N. Pantzali, S.V. Paras and A.J. Karabelas
Department of Chemical Engineering, Aristotle University of Thessaloniki
and Chemical Process Engineering Research Institute
Univ.Box 455, GR 54124 Thessaloniki, GREECE

1. INTRODUCTION

The phenomenon of flooding in narrow flow passages is of great importance as a limiting factor in the operation of novel compact process equipment such as reflux condensers. In this type of equipment made of corrugated plates, flow passages are characterized by equivalent diameters less than 10mm. Consequently, the study of flooding in small diameter tubes, which may be regarded as an essential element of the complicated flow field of a compact reflux condenser, is expected to contribute towards improved design and operation of this type of equipment. Bankoff & Lee [1] and Hewitt [2] have reviewed and summarized the work done in this area, most of which is based on experiments in pipes with i.d. much larger than the sizes considered here. It appears that there is a lack of reliable predictive tools of general validity, even for large diameter pipes, probably due to the complexity of the flooding mechanism resulting from the multitude of parameters, such as the dimensions of the conduit, its inclination angle, the type of liquid and gas entries and the fluid properties.

Studies on the influence of small tube diameter and inclination angle on falling film and flooding phenomena have been conducted in this Laboratory [3,4]. The data collected suggest that the small tube i.d. plays a significant role in wave evolution and film development; thus the falling film characteristics seem to essentially determine the flooding behavior of small diameter tubes. It appears that the small tube diameter promotes wave interaction and damping, and that the dominating flooding mechanism is wave levitation and upward transport. Motivated by these results, the present work is focused on the effect of the *liquid phase properties* on flooding mechanisms.

2. EXPERIMENTAL SETUP AND PROCEDURES

The flooding experiments have been carried out in small i.d. tubes (7 and 9mm), using smooth inlet and outlet conditions. In order to study the influence of liquid properties on flooding phenomena several liquids have been used (i.e. water, kerosene, ethylene glycol, as well as sec-octanol and glycerine solutions) with a wide range of viscosity (1.0×10^{-3} - 17.0×10^{-3} kg/m·s) and surface tension (0.028 - 0.072 kg/sec^2) (***Table 1***). The gas phase (air) enters at the bottom through a small tube, while the liquid phase is introduced uniformly from the top, through a specially machined porous wall segment. Fast-video recordings are employed to elucidate the various flooding mechanisms, which depend on the liquid Reynolds number, Re_L, defined as $4\Gamma/\nu_L$, where Γ is the liquid flow rate per unit length and ν_L is the liquid kinematic viscosity. A detailed description of the experimental setup used and procedures followed for carrying out flooding experiments are described elsewhere [3,4].

3. RESULTS

In ***Figure 1*** the data are plotted in terms of superficial gas velocity, U_{GS}, at incipient flooding, versus the corresponding liquid Reynolds number, Re_L. At low Re_L, the flooding velocity is nearly *inversely proportional* to Re_L and this trend can be clearly identified in all the data sets. For the 7mm tube (***Figure 1a***) there is a second region at higher Re_L, where the flooding velocity tends to be *proportional* to Re_L. The extent of this region is reduced when the tube diameter increases and almost disappears for the 9mm tube (***Figure 1b***). Finally, in all the data sets, there appears to be another region, where the flooding velocity tends to be independent of the liquid flow rate. This constant flooding gas velocity exhibits a rather strong dependence on tube **diameter,** and it is generally greater for the smaller diameter tubes as shown in ***Figure 1***.

The fast video recordings clearly show that wave levitation and upward transport is the main flooding mechanism for the first two regions in small diameter tubes. Indeed, the observed sequence of events suggests that flooding is initiated when the drag forces exerted by the gas flow on a standing wave near the tube exit become large enough to carry it upwards, overcoming gravitational forces [3]. The small tube diameter strongly influences the flooding mechanism because it affects film flow development by promoting wave interaction and damping [2,3]. In the third region, flooding is initiated just after the liquid entrance, where a local disturbance wave tends to grow and block the tube, leading to flow reversal.

Table 1. Physical properties of the liquids used

	ρ_L kg/m^3	σ_L 10^{-3} kg/sec^2	μ_L 10^{-3} kg/m.s	$Ka = \sigma_L \left(\frac{\rho_L}{g\ \mu_L^4} \right)^{1/3}$
water	1000	72	1.00	3354
sec-octanol (0.02% w/w)	996	60	1.10	2470
kerosene	800	28	1.40	775
glycerine (33% w/w)	1095	70	3.49	637
ethylene glycol	1150	50	17.70	52

Surface tension as well as *viscosity* influences the wave formation [5], its size and shape, thus playing a significant role on the drag forces developed due to the gas flow. A lower surface tension promotes the formation of relatively larger amplitude waves, a higher viscosity results in greater substrate thickness, while the density affects gravity forces. The *Kapitsa* number (***Ka***), which includes these variables, is considered to be an appropriate dimensionless group to correlate the flooding data with various liquids tested. The use of Kapitsa number for correlating flooding data is also supported by the stability analysis of Cetinbudaklar & Jameson [6].

As shown in ***Figure 1***, the flooding curves for the various liquids are sorted according to their Kapitsa number; i.e. a higher Kapitsa number corresponds to higher flooding velocities. Furthermore, the dependence of critical flooding velocity on Re_L appears to be influenced by *Ka*; i.e. liquids with similar *Ka* (e.g. kerosene and glycerine solution or water and sec-octanol solution) exhibit similar trends.

4. CONCLUDING REMARKS

Visual observations based on fast-video recordings of flow characteristics leading to flooding are used to elucidate the various mechanisms which are strongly influenced by liquid flow rate and liquid properties. The new data are helpful in current efforts to formulate a generalized expression for predicting the transition between different flooding mechanisms and would be applicable to counter-current gas/liquid flow equipment design.

5. REFERENCES

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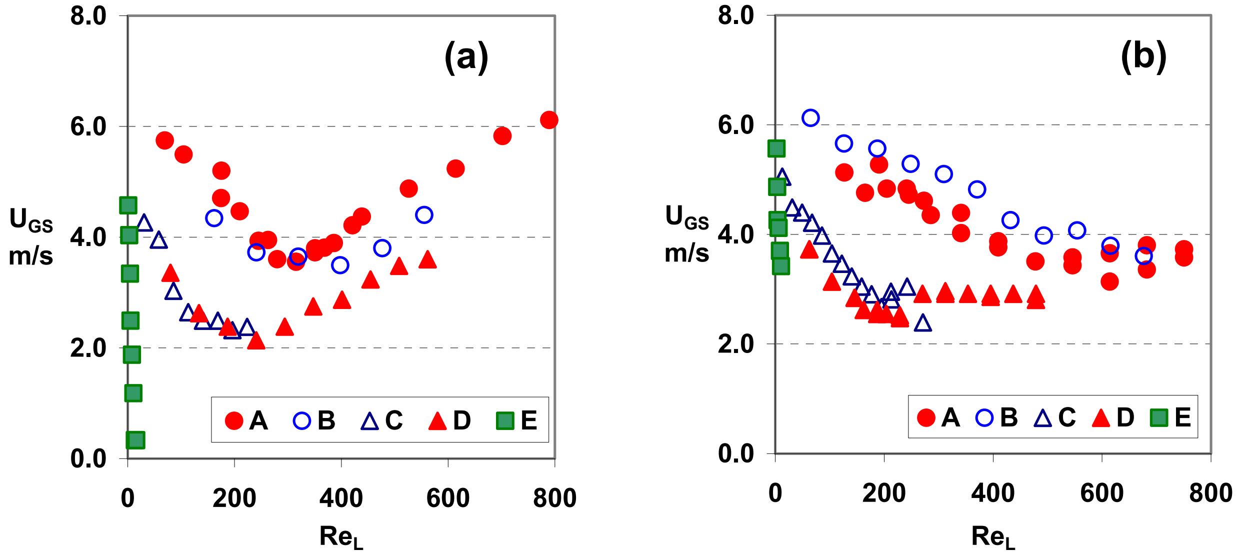

Figure 1: The superficial gas flooding velocity versus the corresponding liquid Reynolds number. Effect of the fluid properties on the form of flooding curve; a) i.d.=7mm, b) i.d.=9mm. (where *A*=water; *B*=sec-octanol solution; *C*=glycerine solution; *D*=kerosene; *E*=ethylene glycol)