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Countercurrent gas–liquid flow in inclined and vertical ducts — II: The validity of the Froude–Ohnesorge number correlation for flooding

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Abstract

A number of flooding correlations have been proposed in the past. These correlations often succeed in predicting the researcher's own data but fail to correlate data of other investigations, limiting the use of the correlations. The validity of the correlation method proposed in part I is discussed in part II in the context of data generated in previous investigations by other researchers. The correlation method consisting of a combination of the phase Froude numbers and the Ohnesorge number succeeds in correlating the data of two previous investigations. A critical discussion of other dimensionless groups used in the past for the purpose of correlating flooding data is presented. The well known Kutateladze-type equation appears not to be valid for flooding in vertical tubes of diameters in the region of 30 mm.

Keywords: Gas–liquid flow; Counterflow; Flooding; Fluid properties; Tubes; Rectangular ducts

1. Introduction

In part I of this publication that addresses the effect of the duct geometry and fluid properties on flooding, it has been demonstrated that the densimetric gas and liquid Froude numbers

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$$Fr_{HG} = \frac{\rho_G V_G^2}{gH(\rho_L - \rho_G)} \tag{1}$$

and

$$Fr_{DL} = \frac{\rho_L V_L^2}{gD_e(\rho_L - \rho_G)} \tag{2}$$

and the Ohnesorge number (Ohnesorge, 1936), defined as

$$Oh_L = \sqrt{\frac{\eta_L^2}{\rho_L D_e \sigma}} \tag{3}$$

form a simple but effective correlating equation for flooding in tubes and rectangular ducts. V_G and V_L are the gas and liquid superficial velocities and ρ_L and ρ_G the phase densities. η_L is the liquid viscosity while σ is the surface tension.

In the case of rectangular ducts, the duct height H is the characteristic dimension in Fr_{HG}, while the required length dimension D_e in the liquid Froude number and the Ohnesorge number is the hydraulic diameter. For tubes, the length dimension required in both the gas and liquid Froude number, as well as the Ohnesorge number, is the diameter of the tube. In other words the duct height H in the gas Froude number is represented by the diameter in the case of tubes.

In the past a number of researchers proposed various dimensionless groups for the purpose of correlating flooding data. Often those groups succeeded in the case of their own data, but failed to correlate data generated by other researchers. The aim of part II of the present flooding investigation is to assess the general validity of the dimensionless groups defined by Eqs. (1)–(3) in the context of data by previous other investigations and at the same time to critically comment on other dimensionless groups that have been proposed in the past. Finally some general comments on the correlation method proposed in part I are given.

Before discussing the flooding data of previous investigations and other dimensionless groups that have been proposed in the past, a brief description of how the Froude–Ohnesorge number correlation was originally arrived at, is presented. The process that led to the Froude–Ohnesorge number correlation is quite unique and deserves some attention.

2. Original data/process that led to the Froude–Ohnesorge number correlation

During a systematic experimental program Zapke and Kröger (1996) investigated the effect of the liquid properties on the gas flooding velocity in a vertical tube. By varying the alcohol content in an aqueous methanol solution, the viscosity, density and surface tension were varied. Five different solutions/liquids were tested, i.e. pure water, 8% methanol, 15% methanol, 28% methanol and pure methanol. Air was used as the working gas.

The flooding data are shown in Fig. 1. In Fig. 1 it can be seen the highest flooding gas Froude numbers were measured for pure water and pure methanol. As the percentage

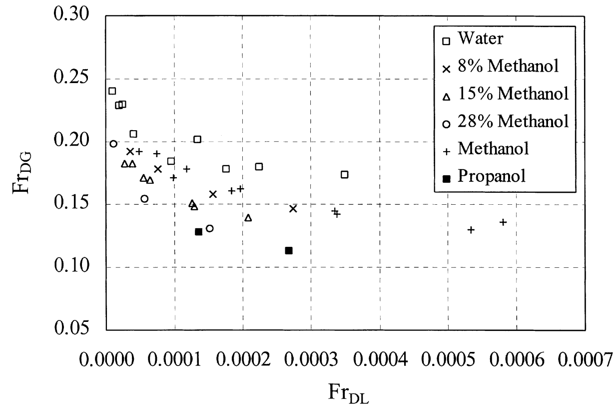

Fig. 1. Flooding data by Zapke and Kröger (1996) plotted in terms of the densimetric phase Froude numbers for gas–liquid flow in a 30 mm i.d. vertical tube with a square-edged gas inlet. The percentage methanol indicates the percentage alcohol by volume of an aqueous methanol solution.

methanol increases, the gas Froude numbers decrease, reach a minimum and increase, for the pure methanol data to be approximately equal to the water data.

A dimensionless group that exhibits such trend is the inverse of the Ohnesorge number defined by Eq. (3). It is plotted in Fig. 2 for aqueous methanol solutions, against the percentage of methanol in the solution. Note the initial decrease, the minimum approximately midway and the subsequent increase as the percentage methanol varies from 0% to 100%, similar to the gas Froude number trend depicted in Fig. 2.

Figs. 1 and 2 imply that the gas Froude number at flooding is some function of the liquid Froude number and the Ohnesorge number, i.e.

$$Fr_{DG} = f(Fr_{DL}, Oh_L) \tag{4}$$

where the terms in parentheses form the independent parameter. Through a method of

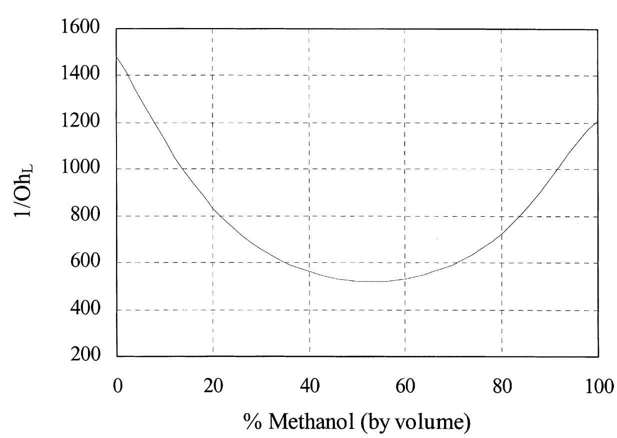

Fig. 2. The inverse of the Ohnesorge number plotted for aqueous methanol solutions. The Oh_L number is defined by Eq. (3). The length dimension required is the diameter $D = 30$ mm.

empirical correlation, it was found that the gas Froude number at flooding, is a function of the product $Fr_{DL}^{0.2}Oh_{L}^{0.3}$ in the case of vertical ducts and tubes. This independent parameter is introduced on the abscissa in Fig. 3 to illustrate the functional relationship proposed by Eq. (4).

Note that the "minimum" exhibited in Fig. 1 does not mean that the flooding gas Froude number for a specific liquid (constant Ohnesorge number) goes to a minimum as the liquid Froude number increases. The trend under consideration is the variation of the Fr_{DG} for a constant Fr_{DL} as the Ohnesorge number is varied. In other words, Fr_{DG} for water (smallest Oh_{L}) is the highest, whilst Fr_{DG} for the 28% methanol solution (largest Oh_{L}) is lowest.

Also shown in Figs. 1 and 3 are two data points obtained with propanol. The two data points serve as an independent verification of the trend observed with the aqueous methanol solutions. Note the scaling effect that the Ohnesorge number has on the data of Fig. 1: the liquids with the highest Ohnesorge numbers flood at lower gas velocities. By introducing the Ohnesorge number the lowest flooding data are shifted to the right relative to the higher flooding gas Froude numbers, in order to achieve correlation.

3. Dimensionless groups previously used for correlating flooding data

Comprehensive information on empirical and theoretical flooding correlations has been published by McQuillan and Whalley (1985) and Bankoff and Lee (1986). Dimensionless groups appearing in these publications other than those defined by Eqs. (1) and (2) are listed in Table 1.

Zapke and Kröger (1996) have previously demonstrated in detail that flooding in vertical tubes is not related to the gas Reynolds number. It further implies that gas viscosity has no effect on the flooding fluid flow rates.

With reference to Table 1, the gas Reynolds number, the mass flux ratio and the viscosity ratio should therefore not be employed for the purpose of correlating flooding data.

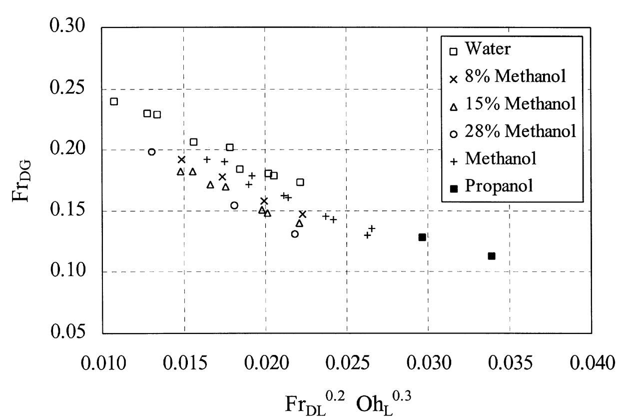

Fig. 3. The flooding data of Fig. 1 plotted against the independent parameter $Fr_{DL}^{0.2}Oh_{L}^{0.3}$.

The density ratio which has been used in the past for correlating flooding effectively forms part of the gas Froude number and is therefore eliminated as an independent parameter.

A widely known correlation for flooding is the Kutateladze-type correlation by Chung et al. (1980):

$$Ku_G^{1/2} + mKu_L^{1/2} = c_1 \tanh\left[c_2\left(Bo^{1/8}\right)\right] \tag{5}$$

Ku_G and Ku_L are the gas and liquid Kutateladze numbers, i.e.

$$Ku_G = \frac{\rho_G^{1/2} V_G}{\left[g\sigma(\rho_L - \rho_G)\right]^{1/4}} \tag{6}$$

$$Ku_L = \frac{\rho_L^{1/2} V_L}{\left[g\sigma(\rho_L - \rho_G)\right]^{1/4}} \tag{7}$$

Bo is the Bond number and is defined as

$$Bo = \frac{D^2 g(\rho_L - \rho_G)}{\sigma} \tag{8}$$

c_1 and c_2 are empirical constants whose values are determined by the tube end geometry. Eq. (6) can be rearranged as follows:

$$\frac{Ku_G^{1/2}}{\tanh\left[c_2\left(Bo^{1/8}\right)\right]} + m\frac{Ku_L^{1/2}}{\tanh\left[c_2\left(Bo^{1/8}\right)\right]} = c_1. \tag{9}$$

The flooding data shown in Fig. 1 are plotted in terms of the dimensionless parameters defined

Table 1
Dimensionless groups other than those defined by Eqs. (1) and (2), previously used to correlate flooding data, l represents a length dimension

Name	Symbol	Definition
Gas Reynolds number	Re_G	$\rho V_G l/\eta_G$
Liquid Reynolds number	Re_L	$\rho V_L l/\eta_L$
Gas Kutateladze number	Ku_G	$\rho_G^{1/2} V_G/[g\sigma(\rho_L - \rho_G)]^{1/4}$
Liquid Kutateladze number	Ku_L	$\rho_L^{1/2} V_L/[g\sigma(\rho_L - \rho_G)]^{1/4}$
Bond number	Bo	$l[g(\rho_L - \rho_G)/\sigma]^{1/2}$
Inverse viscosity parameter	N	$[gl^3\rho_L(\rho_L - \rho_G)/\eta_L^2]^{1/2}$
Mass flux rate	–	$\rho_G V_G/\rho_L V_L$
Dimensionless film thickness	–	δ/l
Density ratio	–	ρ_G/ρ_L
Viscosity ratio	–	η_G/η_L
Reference viscosity ratio	–	$\eta_{reference}/\eta_L$

by Eq. (9) in Fig. 4. The data do not correlate. This implies that the Kutateladze-type correlation is not applicable for tube diameters close to 30 mm.

The dimensionless liquid volume rate, which is a combination of the Kutateladze number and the Bond number, also fails to correlate the data under consideration.

The Kutateladze-type correlation originally proposed by Chung et al. (1980) is based on a Kelvin–Helmholtz instability analysis by Tien et al. (1980). Subsequently Faghri et al. (1989, 1995) proposed exactly the same type of Kutateladze correlation. Their correlation is, however, based on an empirical model that assumes that the Wallis- and the Kutateladze-type correlations are simultaneously valid for predicting flooding. Existing flooding data indicate that this assumption may not be invalid. There is furthermore a trend to differentiate between the two types of models, where the Wallis correlation is applied for conditions when the duct dimensions affect flooding while the Kutateladze correlation is applied when the duct dimensions do not play a significant role.

Faghri et al. (1989, 1995) had to introduce a density correction into the Kutateladze-type correlation developed by Tien et al. (1979) to correlate flooding data for liquids other than water. The reason for this may be explained by trends observed in Fig. 4, i.e. the Kutateladze-type correlation may not have been valid for the range of data used by Faghri et al. and for this reason a density correction factor was introduced to achieve better correlation.

The reference viscosity ratio has no real physical meaning and should not be considered for correlating purposes.

The dimensionless groups remaining in Table 1 are the film thickness ratio δ/l, the inverse viscosity parameter N and the liquid Reynolds number Re_L.

The film thickness ratio is related to the liquid Reynolds number and the inverse viscosity parameter through laminar film flow analysis, i.e. $\delta/l = f(N, Re_L)$. Attempts by the present authors to correlate the flooding gas Froude number as a dependent parameter in terms of the film thickness ratio failed. It implies that a combination of N and Re_L cannot serve as an independent parameter for correlating the flooding gas Froude number.

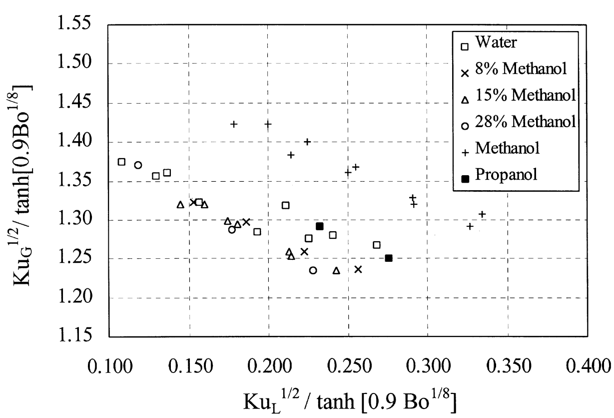

Fig. 4. The flooding data of Fig. 1 plotted in terms of the Kutateladze-type dimensionless parameters of Eq. (9). The value for c_2 that is applicable for a square-edged gas inlet is 0.9.

The only successful independent parameter was found to be the combination of the liquid densimetric Froude number Fr_{DL} and the Ohnesorge number Oh_L.

4. Evaluation of the validity of the Froude–Ohnesorge number correlation with reference to previous experimental investigations

4.1. Data by Clift et al. (1966)

Clift et al. (1996) investigated the effect of the liquid viscosity on flooding in a vertical tube of diameter $D = 31.8$ mm. Water and aqueous glycerol solutions were used as working fluids. The properties of the solutions tested are given in Table 2. Liquid was injected through a porous section and air entered the tube at the bottom through a bell-mouth inlet.

The flooding data by Clift et al. (1996) are shown in Fig. 5 in terms of the measured phase superficial velocities. The data are replotted in Fig. 6 in terms of the Froude–Ohnesorge parameters. Excellent correlation is achieved.

4.2. Data by Chung et al. (1980)

Chung et al. (1980) conducted experiments with pure water, water treated with surfactants and silicon oil to establish the role of the surface tension during flooding. The properties of the liquids tested are shown in Table 3. Air was used as the working gas. The test section consisted of a plexiglas tube with an inner diameter of 31.8 mm, clamped between an upper and a lower plenum. The liquid was introduced into the vertical tube by spilling it from the upper plenum over into the tube under the action of gravity.

In another set of experiments Chung et al. (1980) made use of three different types of oils to investigate the effect of the liquid viscosity on the flooding gas velocity. The properties of the oils are given in Table 4.

The measured flooding velocities are shown in Fig. 7. The oils flood at low air flow rates as the result of their high viscosities. The data are shown in Fig. 8 in terms of the Froude-Ohnesorge dimensionless groups. Note how well the transition from the higher flooding gas

Table 2
Properties of the aqueous glycerol solutions tested by Clift et al. (1966)

% Glycerol	Liquid viscosity (kg/ms × 10^3)	Liquid density (kg/m^3)	Surface tension (N/m × 10^3)
0% (Water)	1.32	1000	72.0
25%	2.18	1060	70.2
59%	10.4	1150	68.0
70%	23.4	1180	66.4
77%	46.0	1200	65.8
82%	82.5	1210	65.0

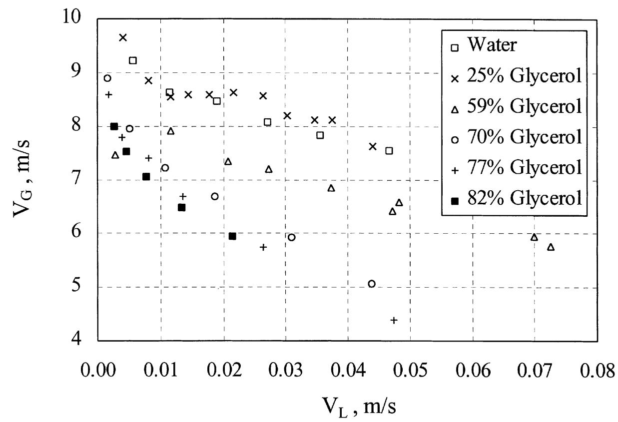

Fig. 5. Flooding data by Clift et al. (1966) plotted in terms of the phase superficial velocities. The corresponding fluid properties are given in Table 2.

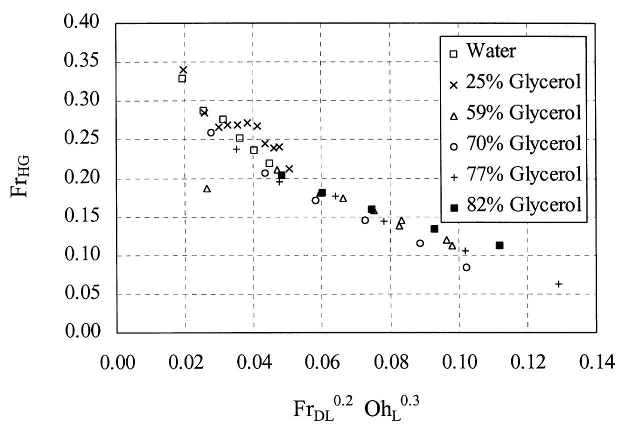

Fig. 6. The flooding data by Clift et al. (1966), shown in Fig. 5, replotted in terms of the Froude–Ohnesorge parameters proposed in part I of this publication.

Table 3
Liquids tested by Chung et al. (1980) to investigate the effect of the surface tension. The corresponding flooding superficial velocities are shown Fig. 7

Liquid	Liquid viscosity (kg/ms × 10^3)	Liquid density (kg/m^3)	Surface tension (N/m × 10^3)
Water; 22°C	1.00	1000	72.7
Water with Surfynol SE 0.1% by weight; 20°C	1.00	1000	35.0
Water with Surfynol TG 0.1% by weight; 20°C	1.00	1000	28.0
Silicon oil; 20°C	0.82	820	17.4

Table 4
Oils tested by Chung et al. (1980) to investigate the effect of the liquid viscosity. The flooding superficial velocities are shown in Fig. 7

Type of oil	Liquid viscosity (kg/ms × 10^3)	Liquid density (kg/m^3)	Surface tension (N/m × 10^3)
Chevron white oil 3; 20°C	3.85	844.3	31.0
Chevron white oil 5; 20°C	5.25	850.8	35.0
Chevron white oil 9; 20°C	10.60	863.6	36.0

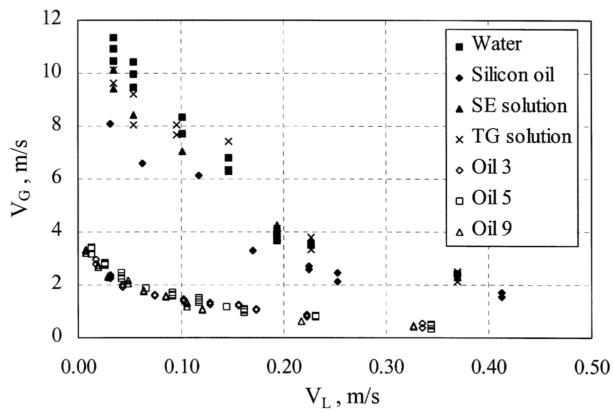

Fig. 7. Flooding data by Chung et al. (1980) plotted in terms of the superficial phase velocities. The corresponding fluid properties are given in Tables 3 and 4; D = 31.8 mm.

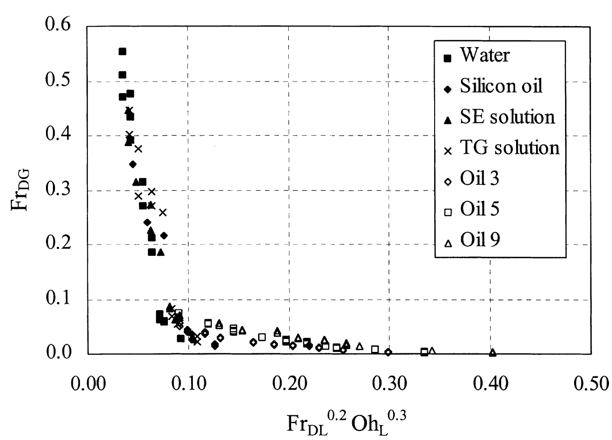

Fig. 8. The flooding data by Chung et al. (1980) shown in Fig. 7, plotted in terms of the Froude-Ohnesorge parameters proposed in part I of this publication.

velocities (data obtained with solutions) to the lower velocities (data obtained with oils) is correlated by the proposed dimensionless groups.

5. Comments on the newly proposed correlation method

Flooding data taken from two previous investigations were expressed in terms of the phase Froude numbers and the Ohnesorge number to evaluate the general validity of the dimensionless groups. Note that each set of data was treated individually and it was not attempted to present all the data on a single graph. The reason for presenting the data separately is the strong effect that the test section geometry has on the flooding process. Flooding data generated in different test sections can be expected to differ and should therefore not be compared directly for correlating purposes.

According to a theoretical analysis by Cetinbudaklar and Jameson (1969) a liquid film tends to become more unstable with an increase in the liquid viscosity. For a given liquid flow rate the film becomes thicker with an increase in viscosity. Cetinbudaklar and Jameson (1969) argued that the effect of viscous damping at the wall becomes less as the film thickness increases and therefore the film becomes more unstable as the film thickness increases. Because an increase in viscosity implies an increase in the film thickness, an increase in viscosity causes the film to become more unstable. It therefore appears that the Ohnesorge number is an indication of the stability of the liquid film draining down the duct wall. With an increase in the Ohnesorge number (i.e. increase in liquid viscosity) the liquid film becomes more unstable and flooding occurs at lower gas velocities. Apart from the effect of the liquid viscosity represented in the Ohnesorge number, the stabilising effect of the surface tension forces is also accounted for by the Ohnesorge number.

In the past the researchers often made use of the hydraulic diameter to correlate flooding data for geometries other than round. In Fig. 7(a) and 7(b) of part I it is demonstrated that the height of a rectangular duct is the required length dimension in the gas Froude number and not the hydraulic diameter. The definition for the height and width of a rectangular duct is illustrated in Fig. 9(a).

The flooding data for rectangular ducts of different height shown in Fig. 7(a) of part I, fail to correlate when employing the hydraulic diameter as the characteristic dimension in Fr_{HG}, where the hydraulic diameter is defined as

$$D_{\mathrm{e}} = \frac{4 \times \text{Cross-sectional flow area}}{\text{perimeter}}. \tag{9}$$

In the case of tubes the diameter represents the effective height, as illustrated in Fig. 9(b). The diameter is therefore employed as the height H required in Fr_{HG}. In other words, the role of the diameter is that it is representing the physical height and not that of an equivalent dimension such as defined by Eq. (10).

Lee and Bankoff (1983) conducted flooding tests with an inclined duct of 380 mm width. Two heights of 38 and 76 mm respectively were investigated. Similar to the present investigation, the flooding gas velocity was found to increase with an increase in the height. Lee and Bankoff (1983) did however present their data in terms of a modified Wallis parameter

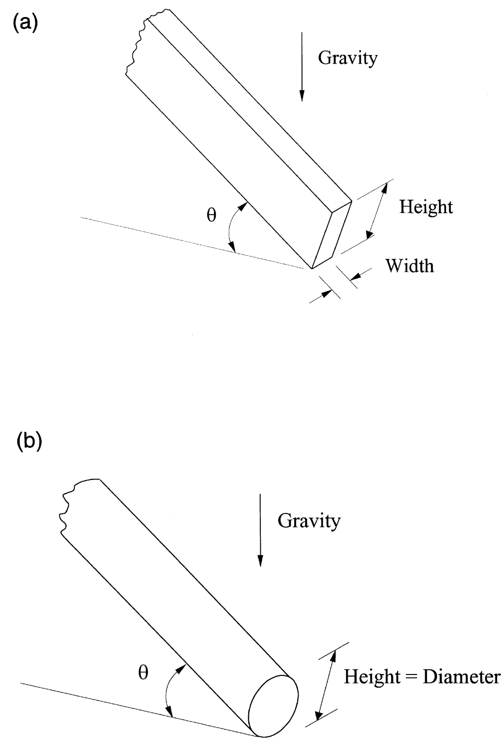

Fig. 9. (a) Definition of the height and the width of a duct. (b) Equivalent height of a tube.

$$V_G^* = \frac{\rho_G^{1/2} V_G}{\left[2Hg\sin(\theta)(\rho_L - \rho_G)\right]^{1/2}}. \tag{10}$$

In the definition of V_G^* the term $2H$ represents the hydraulic diameter of the channel. θ is the duct inclination. The experimental results of the present investigation have however revealed that the hydraulic diameter is not the characteristic dimension in the gas Froude number, as explained in the previous paragraph and H should have been used by Lee and Bankoff (1983) for correlating purposes rather than $2H$.

Lastly it should be noted that in the case of rectangular ducts the characteristic dimension for the gas and the liquid Froude number differ, i.e. the height is used for gas Froude number while the hydraulic diameter represents the length dimension in the liquid Froude number. Existing correlations like the well known Wallis (1969) equation usually employ the same characteristic for both the gas and the liquid Froude number.

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