ON INSTABILITIES IN HORIZONTAL TWO-PHASE FLOW

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Two regions of instabilities in horizontal two-phase flow were detected. The first was found in the transition from slug to annular flow, the second between stratified and slug flow. The existence of oscillations between the slug and annular flows can explain the differences in the limitation of the slug flow in flow regime maps proposed by different authors. Coexistence of these two regimes is similar to bistable behaviour of some differential equation solutions.

Two-phase horizontal gas–liquid flow is a frequently occurring flow situation in many problem areas of practical importance. In most cases, the gas–liquid flow in tubes represents a much more complicated flow phenomenon than the single-phase flow. A large number of investigations have been performed in the field of intermittent flow (for review see e.g.[1–4]). Despite this, many inconsistencies can be found in the literature concerning both the classification of flow regimes and transitions among them.

Some authors consider only two basic flow regimes (Fig. 1):
a) segregated flows and
b) intermittent flows,
other propose a more detailed distinction of various subregimes[5]:

a) in segregated flows:	stratified smooth flow (SS)
	stratified wavy flow (SW)
	annular wawy flow (AW)
b) in intermittent flows:	bubble flow (B)
	plug flow (PL)
	slug flow (SL)
	annular mist flow (AM).

The characteristic features of the basic regimes within intermittent flow and the transitions among them were defined quantitatively by Drahos et al.[6].

Development as well as design of experimental the two-phase gas–liquid flow devices need knowledge of parameters such as pressure drop, flow distribution and stability of different flow regimes[7,8].

The problem of flow pattern recognition and prediction is therefore of great importance. A large amount of experimental two-phase flow data have been accumulated for developing the flow regime maps with various description coordinates (for review see Spedding and Nguen[9] and Barnea and Taitel[10]). Most of these data are based on visual observations completed with high speed photography. In several studies, the time records from special sensors were combined with the visual observations to obtain more reliable results[11,12].

The present work is a continuation of the series of articles published in last ten years[13–16]. It is concerned with two regions of instabilities which were found in the region of stratified-smooth flow, plug flow and slug flow and in the region of slug flow and annular flow. The study of such instabilities is only at the beginning.

EXPERIMENTAL

The experiments were performed in horizontal tubes made of Perspex (inner diameter 50 mm and different lengths) with the system tap water–air at atmospheric pressure and room temperature. Dimensions and experimental conditions are given in Table I, a scheme of the experimental set up is shown in Fig. 2.

The horizontal tube units were composed of a simple tee mixing device at the inlet, a flow stabilizing section, a test section, a terminal section and a separation part. The test section was located some definite length L_1 downstream to realize the measurements in a fully developed stabilized two-

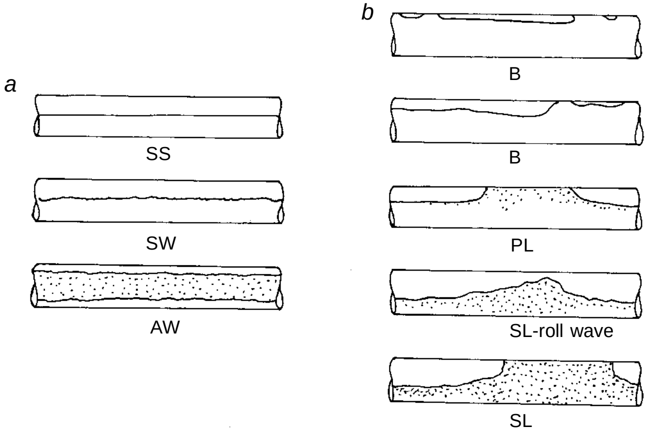

FIG. 1

Basic types of flow regimes: *a* in segregated flows: SS stratified smooth flow, SW stratified wavy flow, AW annular wavy flow; *b* in intermittent flows: B bubble flow, PL plug flow, SL slug flow (AM annular mist flow not shown) phase flow. The L_1/D ratios are given in Table I. The test section was 1.01 m long for tube A of 5 m length and 0.5 m long for tube B of 10 m length; it consisted of two strain-gauge pressure transducers P3, P4 mounted at the bottom of the tube to measure the wall pressure fluctuations and two pairs of wire conductance electrodes E1, E2, located 2.4 mm above the bottom of the tube. The location of points P1, P2 for the static pressure drop measurement with sensor GH 610 08391-90 GRW Teltow is shown in Fig. 2. The lengths of pressure drop test sections $L_{\Delta p}$ are given in Table I.

The experimental technique was similar to those described by Drahos et al.[15]. Time series of 164 s sampled at 50 Hz with the upper cut-off frequency f_{cut} = 25 Hz were registred from the strain-gauge transducers. These signals and signals from both conductance electrodes were monitored in a four-channel mode by means of a computer. These primery signals from the pressure and conductivity sensors were used in this work to illustrate the instabilities in the horizontal two-phase flow.

TABLE I
Tube dimensions and experimental conditions

Tube	D, mm	L, m	T, °C	L_1/D	$L_{\Delta p}$, m	w_L, m s^{-1}	w_G, m s^{-1}
A	50	5.0	20 ± 3	58	1.91	0.1 – 2.0	0.1 – 25
B	50	10.0	20 ± 3	80	7.00	0.1 – 0.8	0.2 – 10

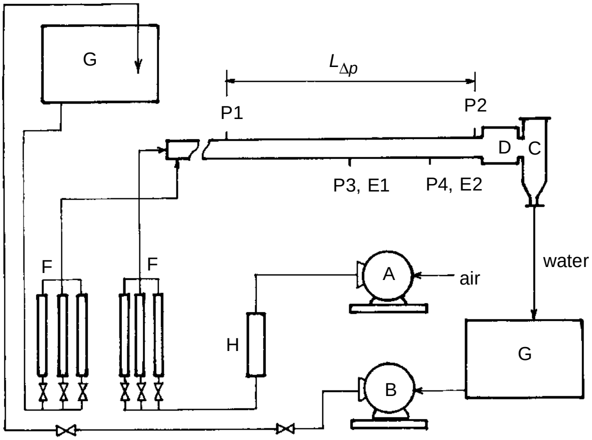

FIG. 2
Experimental set up: A air blower, B water pump, C cyclone, D separator, E1, E2 conductance electrodes, F flow meters, G storage tanks, H air filter, P1, P2, P3, P4 pressure transducers

RESULTS AND DISCUSSION

Instability in the Region Stratified Smooth Flow, Plug Flow and Slug Flow

A transient region at small velocities of gas and liquid in the regimes of stratified-smooth flow, plug flow and slug flow was found in literature[17] (for tube B – see Table I). The range of instabilities for superficial liquid velocity $w_L = 0.23 \text{ m s}^{-1}$ for the air–tap water system is schematically shown in Fig. 3. The conductivity–time and pressure–time traces in this region are shown in Fig. 4. Stable flow pattern I (stratified smooth flow–slug flow (SS–SL) or "pseudo-slug" flow) exists for lower gas velocities. With the increase in gas flow-rate to the critical value $w_{G,\text{crit }2} = 1.25 \text{ m s}^{-1}$, flow pattern II appears (Fig. 4*a*). Flow pattern II is a real slug (SL) flow. With the decrease in gas flow-rate, this area of coexistence of both regimes reaches the critical value $w_{G,\text{crit }1} = 0.60 - 0.61 \text{ m s}^{-1}$, where again flow pattern I appears (see Figs 3 and 4*b*). In the region between the two critical boundary values, both flow patterns can exist. Exceeding these boundary values results in the change of the flow regime in any case. This area of irregular form (see the \\\\ hatched area in Fig. 5) is the second discovered transition area in the two-phase horizontal flow. The first one exists in the slug–annular region[15] (see the //// hatched area in Fig. 5). The newly discovered transition area occurs at the transition between stratified and intermittent flows and is limited by superficial velocities

$$0.20 \text{ m s}^{-1} < w_L < 0.25 \text{ m s}^{-1} \qquad (1)$$

and

$$0.20 \text{ m s}^{-1} < w_G < 1.25 \text{ m s}^{-1} \quad . \qquad (2)$$

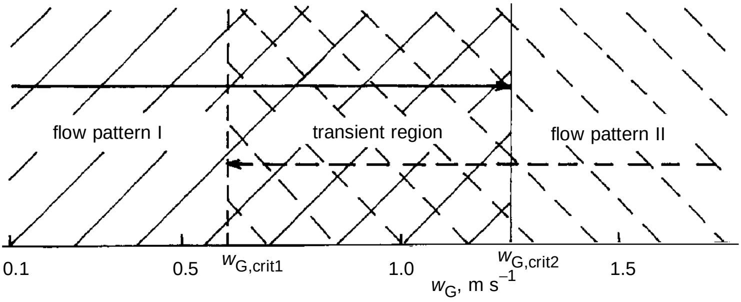

FIG. 3
Scheme of the transient behaviour for superficial liquid velocity $w_L = 0.23 \text{ m s}^{-1}$

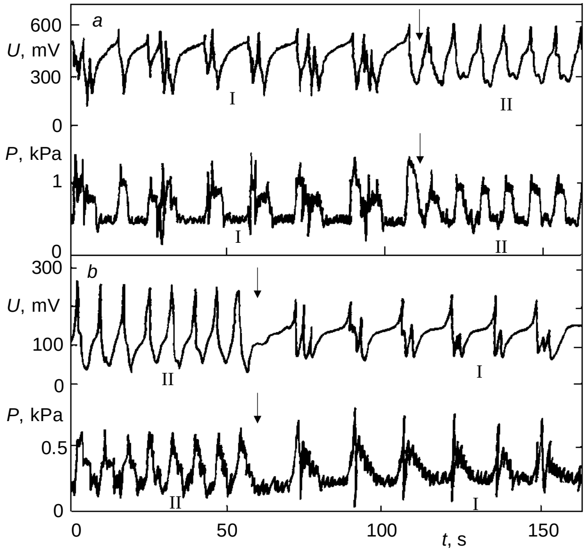

FIG. 4

Conductivity–time (U, mV) and pressure–time (P, kPa) traces at $w_L = 0.23$ m s^{-1} for tap water. I flow pattern I, II flow pattern II: *a* changing flow pattern I to flow pattern II at $w_{G,crit\ 2} = 1.25$ m s $^{-1}$ (increasing w_G); *b* changing flow pattern II to flow pattern I for $w_{G,crit\ 1} = 0.60 – 0.61$ m s^{-1} (decreasing w_G). Changing flow pattern is marked with arrows

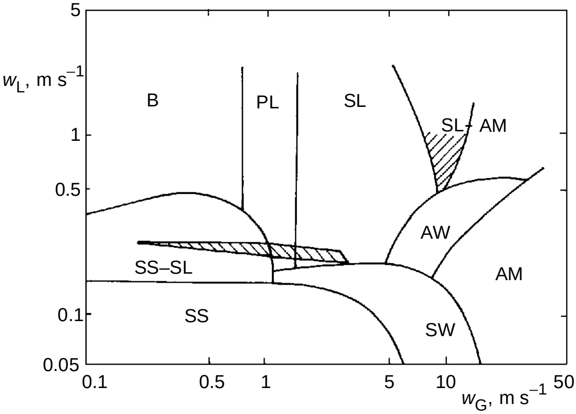

FIG. 5

Position of transient areas in flow regime map by Ebner et al.[14,16]. //// hatched area: bifurcation area in transition from slug flow to annular flow[15]; \\\\ hatched area: newly discovered transient area in regimes of stratified smooth flow, plug flow and slug flow. Abbreviations in Fig. 1

Instability in the Region of Slug Flow and Annular Flow

Long-term flow pattern oscilations observed in the slug–annular region were first described in ref.[15] by former investigation on tube A (see Table I).

The wide-spread area of the coexistence of slug and annular flow regimes (//// hatched area in Fig. 5) was in this work observed and analyzed in detail. Oscillations between both limiting regimes, slug flow and annular flow, were found in the area limited by superficial velocities

$$0.6 \text{ m s}^{-1} < w_L < 1.0 \text{ m s}^{-1} \qquad (3)$$

and

$$6.0 \text{ m s}^{-1} < w_G < 15.0 \text{ m s}^{-1} \quad . \qquad (4)$$

Such a large transient area between both stable limiting regimes should be carefully investigated. Comparing the flow regime maps proposed by Mandhane et al.[18], Weisman et al.[11] and Taitel and Dukler[19] in this area, see Fig. 6, considerable deviations from the individual transition limits can be noticed. Our investigations show that the line proposed by Weisman limits the genuine slug flow area towards the transition area. On the other hand, the transition to the annular flow in Mandhane's map limits the mixed slug–annular regime. However, Mandhane did not distinguish further details inside the area of intermittent flow that extended from bubble flow to annular flow. In this region the Taitel and Dukler's[19] prediction corresponds well to the higher (right) limit. Therefore, it is possible to interpret the transition lines given by Weisman et al.[11]

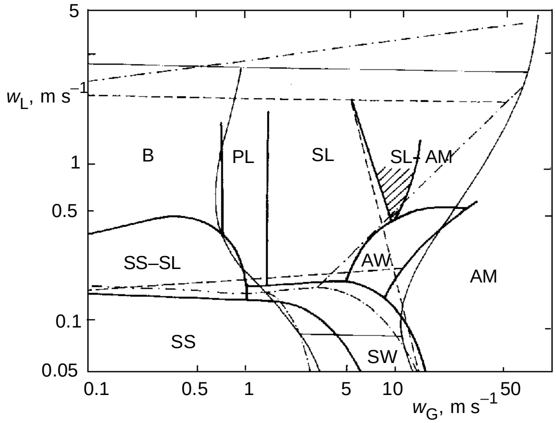

FIG. 6
Comparison of flow regime maps: ——— Mandhane et al.[18], – – – – Weisman et al.[11] – · – · – · Taitel and Dukler[19], ━━━ Ebner et al.[14,16]. Abbreviations in Fig. 1

(left line) as well as by Taitel and Dukler[19] (right line) in the first approximation as limits of the oscillating area of slug and annular flow (//// hatched area in Fig. 5). Time traces from pressure and conductivity sensors (Fig. 7) illustrate the flow behaviour in this region.

The observed oscillation time of a cycle changed in dependence on superficial velocities of gas and liquid between 40 and 80 s. The observed coexistence of both regimes is similar to bistability of the stationary state solutions of some nonlinear ordinary differential equations, where the interval of bistable behaviour is bounded by bifurcation values of parameter. For both stable states (slug flow and annular flow), Bernoulli's equation should be valid.

The coexistence of two switching regimes can explain oscillations from slug to annular flow and vice versa:

Transition from slug flow to annular flow. The pressure drop increases (Fig. 8) from Δp_1 for slug flow to Δp_2 for annular flow. The dashed straight lines represent this pressure drop increase to a value which corresponds to the annular flow with higher superficial velocity of gas. Bernoulli's equation is not valid in this case. Therefore, the regime becomes instable and the gas breaks through the "liquid bridge" (slug) and annular flow appears.

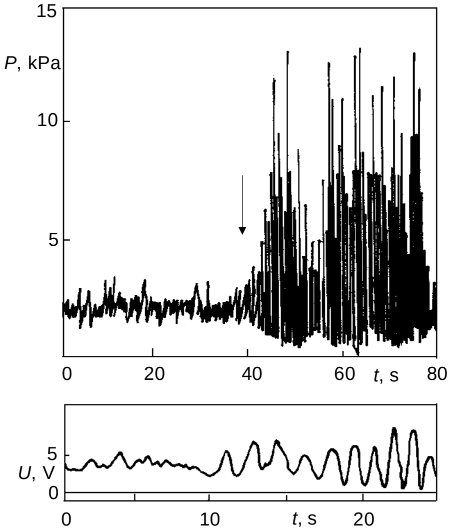

FIG. 7

Pressure–time[15] (P, kPa) and conductivity–time (U, V) traces for transition regime between slug and annular flow at $w_L = 0.8$ m s^{-1} and $w_G = 15$ m s^{-1}. Transition is marked with arrows

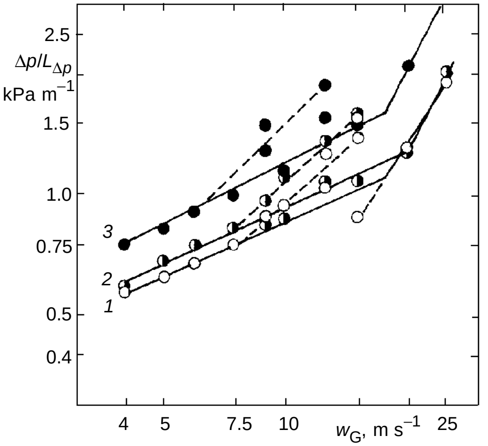

FIG. 8

Dependence of two-phase flow pressure drop $\Delta p_i/L_{\Delta p}$ on superficial gas velocity w_G in slug–annular transition region: *1* $w_L = 0.75$ m s^{-1}, *2* $w_L = 0.80$ m s^{-1}, *3* $w_L = 1.00$ m s^{-1}; —— Δp_1 for slug flow, – – – – Δp_2 for annular flow

Transition from annular flow to slug flow. The pressure drop decreases simultaneously after the occurrence of annular flow from Δp_2 (Fig. 8) to Δp_1. Bernoulli's equation is not fulfilled for the annular flow. Therefore, this regime becomes instable. Small changes in parameters Δp or w, e.g. by wall friction of the liquid, or influence of gravity, which normally can be neglected, lead in this case to the collapse of the liquid film.

The Magnus effect[20] could be also of importance for the transition from annular to slug flow. Mayinger[8] mentioned that in addition to shear stresses (τ_{gas} and τ_{wall}), the turbulence behind the minimal diameter of the liquid rings and the roughness of liquid surface are of importance for the decrease in liquid velocity. The turbulence at the waves can be depicted as rotating and moving cylinders. In this case, predictions based on Magnus effect can contribute to the explanation of the collapse of liquid film.

CONCLUSIONS

Two areas of instabilities in horizontal two-phase flow were found, located between two basic flow regimes, the segregated and intermittent flow. One transient region exists between slug and annular flow and the other one between stratified and slug flow. Annular flow can be considered as a special type of segregated flow[21], with a layer of liquid around the tube wall and gas in the core. The surface interaction of both layers is comparable to normal stratified flow. The existence of oscillations between slug and annular flow can explain the differences in the limitation of the slug flow in the flow regime maps proposed by different authors. Weismann et al.[11] determined the lower limiting line and Taitel and Dukler[19] the upper one (see Fig. 6). Coexistence of these two regimes is similar to bistable behaviour of some differential equation solutions.

SYMBOLS

D	tube diameter, mm
f_{cut}	cut-off frequency, Hz
L	reactor length, m
L_1	length of inlet section of reactor before test section, m
$L_{\Delta p}$	length of pressure drop measuring section, m
P	pressure (from pressure–time traces measuring), kPa
t	time, s
T	temperature, °C
U	voltage (from conductivity–time traces measuring), V
w	average velocity of gas and liquid, m s^{-1}
w_G	superficial gas velocity, m s^{-1}
$w_{G,crit}$	critical value of superficial gas velocity, m s^{-1}
w_L	superficial liquid velocity, m s^{-1}
Δp	pressure difference, kPa
τ	shear stress, kPa

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