# HYDRODYNAMICS OF PLATE COLUMNS. X.*

# ANALYSIS OF OPERATION OF SIEVE PLATES WITHOUT DOWNCOMERS

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Received December 8th, 1972

Qualitative analysis is presented of hydrodynamic regimes on sieve plates without downcomers.

It is generally known that changes of flow rates of phases through the internals of plate columns result in considerable changes of behaviour of gas–liquid mixtures. Hydrodynamics greatly affects mass transfer mechanism and thus a hydrodynamic analysis of individual regimes is of considerable importance.

In the earlier published papers[1,2] regions with different hydrodynamic behaviour were differentiated on basis of changes of the character of hydrodynamic quantities (mostly overall pressure drop) on flow rates. They were described according to the visually observed typical phenomena in the gas–liquid mixture on the plate. Recently[3], attention has been paid to changes in structure of the gas–liquid mixture for which more exact experimental methods have been used (photographic, absorption of $\gamma$-rays, light absorption). The usually observed types of two-phase systems are the bubble flow (barbothage) region, region of cellular foam, region of froth (movable foam) and spray regime. Regions are given in the order they may be encountered at increasing gas flow rates at constant liquid flow rate.

The approach presented here is close to the studies published earlier as the structure of the gas–liquid mixture has been studied only visually but simultaneous measurements of a great number of hydrodynamic quantities supplied some new information on phenomena taking place on plates on which basis they can be described from the point of view of macroscopic motion of the gas–liquid mixture on the plate. This description leads to consideration on scaling-up in hydrodynamic studies of columns with plate internals.

## EXPERIMENTAL

Measurements were made in a one-plate hydraulic model of plate column with the water–air system at 20°C. Fourteen different sieve plates without downcomers were studied. Plates were

* Part IX: This Journal *38*, VII, (1973).

made of brass 2 mm thick with the hole diameter and free plate area as variable parameters. Holes were drilled, burrs removed so that the edges were sharp. Geometrical parameters are summarized in Table I. The experimental unit is schematically given in Fig. 1. It consists of the liquid loop, gas loop and the own column. The column is formed by glass cylinders of inside diameter 288 mm. A single plate is situated in a frame held by flanges of both cylinders. The over-all height of the column is 2400 mm, the distance of the plate from the upper edge is 1300 mm. Gas is supplied by a gas blower and is led through a cooler, control valve and flap valve into the gas distributor situated in the lower part of the column. The gas is flowing from the column into the separator of liquid entrainment. In the inlet piping to the blower is situated the gas orifice and the control valve. The gas flow rate is determined according to the DIN standards with the accuracy $\pm 1{\cdot}5\%$ at gas velocities in the column higher than 0·2 m/s. The maximum possible gas velocity in the column is 2·5 m/s. Liquid is pumped from the liquid supply tank by a centrifugal pump through a filter into the overflow vessel. The excess liquid is returned into the supply tank through a heat exchanger by which the temperature is controlled. Liquid inlet into the column has three parallel branches. In two of them are situated orifices, in one a rotameter. Each one is equipped with a stop cock and in the main is a control valve. Liquid enters the plate from below through three pipes welded into the holes of the plate. These pipes are situated approximatelly in the centre of gravity of the sectors of circle of the plate with the apex angle 120° and are situated in the plate plane. Liquid weeping through the plate is collected in the lower part of the column and is returned through a liquid seal into the supply tank. Orifices and the rotameter have been calibrated by weighing the collected water. The accuracy, with which the flow rate is set, is $\pm 3\%$. Range of measurable flow rates is $0{\cdot}1 - 6$ kg/s m$^2$.

*Liquid holdup.* Arrangement for measurement of liquid holdup is given in Fig. 2. Both valves situated on the liquid inlet and outlet could have been closed by one lever. After stopping the gas flow, liquid holdup of the gas–liquid mixture on the plate is weeping through the plate holes and is collected in the lower part of the column. From there it is drained and weighed. This holdup included also the dead holdup *i.e.* the liquid present in the column outside the gas–liquid mixture on the plate which must be subtracted. We have assumed that the dead holdup in the space above the plate is negligible. In the space below the plate it is formed by liquid weeping through the plate and falling down in the form of drops or flowing down the walls and also by liquid present on the column bottom forming the pressure gradient necessary for flow from the column.

TABLE I

Geometrical Parameters of Plates Used

| Plate No | Hole diameter mm | Relative free area | Plate No | Hole diameter mm | Relative free area |
|---|---|---|---|---|---|
| 1 | 10 | 0·0506 | 8 | 6 | 0·1865 |
| 2 | 10 | 0·1012 | 10 | 4 | 0·0982 |
| 3 | 10 | 0·1494 | 11 | 4 | 0·1465 |
| 4 | 10 | 0·2000 | 12 | 4 | 0·1955 |
| 5 | 6 | 0·0495 | 14 | 2·5 | 0·0978 |
| 6 | 6 | 0·0994 | 15 | 2·5 | 0·1468 |
| 7 | 6 | 0·1483 | 16 | 2·5 | 0·1951 |

It is necessary that the dead holdup be as small as possible and reproducible. Above the flat bottom column is situated a truncated cone with the gas inlet and the distributor in its centre. To eliminate the effect of pressure in the space below the plate the end of the outlet pipe is situated in the part of the liquid seal connected with the space below the plate. The dead holdup is determined experimentally. The plate is removed and liquid inlet pipes are situated instead. Part of the column below the position of the plate is wetted by liquid and gas is supplied. The liquid holdup in the column is determined in the above described manner and is considered to be the dead holdup. The dead holdup is found dependent on the liquid flow rate and in the range of the experimental accuracy is independent on the gas flow rate. For the actual liquid holdup is considered the difference between the over-all holdup and the dead holdup at the corresponding liquid flow rate. The accuracy of repeated experiments is in the range of $\pm 2{\cdot}5\%$.

*Over-all pressure* drop is measured by taps situated 150 below and 550 mm above the plate. The absolute accuracy of measurement of the pressure difference is 5 $N/m^2$. The accuracy of the measured quantity is, due to fluctuations of the measured quantity, in the range of about $\pm 2\%$.

*Pressure drop across the gas–liquid mixture* is the difference of the pressure in the upper plate plane and in the space above the gas–liquid mixture. The tap for the pressure above the gas–liquid mixture is the same as for measurement of the over-all pressure drop. Pressure in the upper plate plane is measured by 7 taps situated at the distance 0, 50, 80, 100, 120, 130 and 139 mm from the plate centre with hoses connected to manometers filled with water. In the connecting hoses are situated glass taps by which the motion of the liquid surface in the manometer tubes could

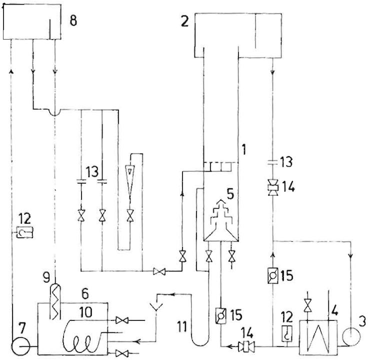


FIG. 1

Experimental Unit

**1** Column with plate, **2** separator of entrainment, **3** blower, **4** gas cooler, **5** gas distributor, **6** liquid supply tank, **7** pump, **8** overflow vessel, **9** liquid heater, **10** liquid cooler, **11** liquid seal, **12** contact thermometer, **13** orifice, **14** valve, **15** cock.

have been limited. The accuracy is dependent on the size of pressure pulsations and varied from 5 to 30 $N/m^2$.

*Visual observation* covered the structure and motion of the gas–liquid mixture on the plate, the way the liquid is passing through the plate and measurement of the gas–liquid height. This height is determined by a ruler as the distance between the plate and the middle position of the gas–liquid surface.

The dependence of hydraulic quantities on gas flow rate at constant liquid flow rate is measured for several selected liquid flow rates per each plate. At some changes of the hydraulic regime the hysteresis effect has been observed due to which the value of hydraulic quantities dependens not only on flow rates of both phases but on the way how the flow rates are fixed as well. Thus at all measurements the liquid flow rate has been fixed at first and then the gas flow rate is increased to the required value. After reaching the steady state the visual observations are made, over-all pressure drop, local pressure drop across the gas–liquid mixture, and the liquid holdup are measured.

## RESULTS

Under conditions which could have been materialized in the described experimental unit on different plates, existence of seven different hydraulic regimes have been determined. The first two are, as concerns mass transfer, of little importance as they exist before formation of the gas–liquid mixture and we are discussing them only for the sake of completeness. The same applies to the last regime when liquid is not passing any more through the plate and the countercurrent flow of both phases stops.

Individual regimes determined in the same sequence as they can exist at the given liquid flow rate and at successively increasing gas flow rates are:

*I*. Separate flow of liquid and gas through the plate, *II*. Uniform pulsations, *III*. Bubbling, *V*. Homogeneous foam, *V*. Circulation, *VI*. Wave and *VII*. Fluidization regimes. At first their characteristics are given, secondly is summarized the region of their appearance. Limited informations in this respect are given by Fig. 3 where the dependence of the liquid holdup on flow rates of both phases for the plate No 7 is demonstrated.

*For the separate flow of gas and liquid through the plate* (I) is typical that liquid and gas are passing through different holes and the holes occupied by liquid or gas are not changing with time. The liquid holdup is practically immeasurable and the over-all pressure drop is increasing with the second power of the gas velocity similarly as with the dry plate.

*For uniform pulsations* (II) the following operation takes place: At a certain moment all holes of the plate are covered with liquid and the pressure below the plate increases. After reaching sufficient pressure drop the liquid film bursts in majority of the holes, gas is for a short period of time flowing through the plate and the over-all pressure drop across the plate decreases. Liquid then covers all free holes, it flows partially through the plate and all the holes are again covered with liquid. The described cyclic operation is uniformly repeated. Frequency increases with the gas velocity. Liquid holdup is relatively small ($15-40\ N/m^2$) and it practically does not change with the gas velocity.

*For bubbling* (III), relatively large liquid holdups form on the plate ($100-300\ N/m^2$). Through part of the plate flows the gas, through a small plate area flows the liquid and majority of holes is blocked by liquid. Gas is usually entering the liquid on the plate in the form of individual bubbles. Above the part of the plate through which the gas flows is the foam, above the remaining part is a bed of clear liquid. At higher gas velocities the liquid bed is covered by a foam consisting of large cells of 10–30 mm diameter. With increasing gas flow rate the part of plate through which the gas flows enlarges, liquid holdup is about constant or increases slowly (Fig. 3).

*The homogeneous foam* (IV). A narrow bed of liquid usually exists above the plate and on this bed there is a layer of foam consisting of cells the diameter of which

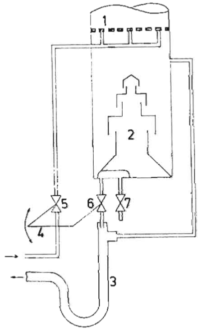


FIG. 2

Measurement of Liquid Holdup

1 Sieve plate, 2 gas distributor, 3 liquid seal, 4 lever for valves 5 and 6, 5 valve at the liquid inlet into the column, 6 valve at the liquid outlet from the column, 7 discharge valve.

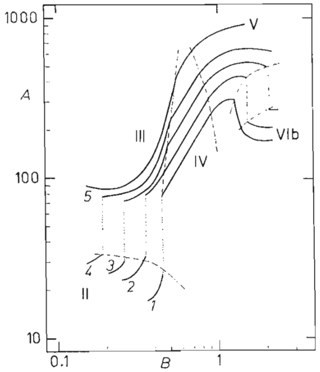


FIG. 3

Dependence of Liquid Holdup on Gas Velocity for Plate No 7

*A* Liquid holdup ($N/m^2$), *B* gas velocity (m/s); *1* liquid flow rate 0·4, *2* 0·7, *3* 1·2, *4* 2·0, *5* 4·0 ($kg/s\ m^2$).

increases with increasing distance from the plate. At greater gas velocities the differences in cell sizes are not observable. The instant local changes of the height of the gas–liquid mixture are in the range of 5–10% around the mean value. Liquid is accidentally but in average uniformly weeping through the whole plate area. The dependence of liquid holdup on gas velocity is about of power type (Fig. 3). Pressure drop across the gas–liquid mixture on the whole plate area is practically constant (Fig. 4*a*).

*Circulation* (V) is characterized by an intensive mixing of the gas–liquid mixture. At the walls can be observed frequent motion of the foam from the bed surface to the plate. The foam height varies in the range of 10–20% in respect to the mean value. Liquid is weeping nearly exclusively in the annulus in vicinity of the column walls. Liquid holdup usually slightly increases with increasing gas velocity up to the maximum and then slightly decreases (Fig. 3). Pressure drop across the foam bed is in the region of weeping, for about 50% greater than in the central part of the plate (Fig. 4*b*).

Measurements of pressure drop across the foam made possible distinguishing of *two types of wave regimes* (VI): *a*) regime of waves between the plate centre and the walls. The operation takes place so that the gas–liquid mixture in the plate centre rises considerably with a simultaneous decrease of the bed at the walls. In the following stage the bed in the central part of the plate decreases with simultaneous rise of the gas–liquid mixture at the wall. Weeping takes place mostly in the plate centre. Pressure drop across the gas–liquid mixture becomes relatively greater in the plate centre and at the walls (Fig. 4*c*). Visually this regime is not very conspicuous. It has been observed only at very low liquid holdups (up to about 150 $N/m^2$). *b*) Regime of waves between the oposite sections of the column walls is characterized by a rocking motion of the gas–liquid mixture over the plate. Simultaneously with the rise of the foam at some place at the wall decreases the gas–liquid mixture at the wall on the opposite part of the column. In the next stage the rise is succeeded by a rapid decrease and a rise takes place at the oposite side. The frequency of this operation is about 0·8 to 0·9 $s^{-1}$. Weeping is encountered nearly exclusively at the column walls. The gas–liquid mixture height is varying for more than 30% around the mean value. Pressure drop across the gas–liquid mixture at the wall makes up to a multiple of that in the central part of the plate (Fig. 4*d*).

With both types of the wave regimes the decrease of the gas–liquid mixture is accompanied by weeping and the rise with an intensive spraying of droplets. In vicinity of the plate the continuous phase in the gas–liquid mixture is formed by liquid (froth) while in the upper part the continuous phase is gas (spray). With increasing gas velocity that part, in which gas is the continuous phase, is expanded at the expense of the lower part.

*In the fluidized regime* (VII) the held liquid is fluidized in the space above the plate in the form of droplets of various sizes. All the liquid brought to the plate is carried away as entrainment.

Regions of existence of individual regimes are summarized in Table II. Data given in this table are based on experimental dependences of liquid holdup on gas velocity, on pressure drop across the gas–liquid mixture at various distances from the plate centre and on results of experimental observations of operations on the plate. Individual regimes are in the head of this table given by Roman numerals. Below a given numeral is given the gas velocity from which the regime was observed on. In some other column of the same line are given gas velocities at which the following regime begins to appear which may be cosnidered as the termination of the foregoing regime. The regime with the initial gas velocity given as the last in the line has been observed up to the highest gas velocity used.

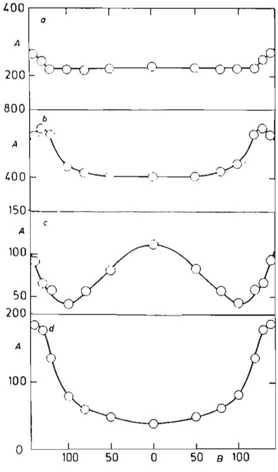


FIG. 4

Dependence of Pressure Drop Across the Gas–Liquid Mixture on Distance from the Plate Centre

*a IV*, *b V*, *c VIa*, *d VIb*. *A* Pressure drop across the gas-liquid mixture (N/m ), *B* distance from the the plate centre (mm).

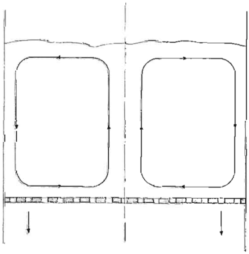

FIG. 5

Block Diagram of Motion of the Gas–Liquid Mixture and of Weeping for Regime V

TABLE II
Experimentally Determined Regions of Existence of Hydrodynamic Regimes

| No | Liquid flow rate kg/sm² | Range of gas velocities m/s | The regime exists from the gas velocity (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *I* | *II* | *III* | *IV* | *V* | *VIa* | *VIb* | *VII* |
| 2 | 0·1 | 0·229—2·30 | 0·229 | — | — | 0·547 | — | — | 0·746[a] | 2·30 |
| 2 | 0·2 | 0·187—2·36 | 0·187 | — | — | 0·479 | 0·70 | — | 1·00 | 2·36 |
| 2 | 0·4 | 0·204—2·32 | 0·204 | — | — | 0·446 | 0·64 | — | 2·10 | — |
| 2 | 0·7 | 0·123—2·12 | 0·123 | — | — | 0·380 | 0·59 | — | — | — |
| 2 | 2·0 | 0·112—1·67 | 0·112 | 0·153 | 0·208 | 0·28 | 0·39 | — | — | — |
| 3 | 0·2 | 0·217—2·18 | 0·217 | — | — | 0·700 | — | — | 0·87[a] | — |
| 3 | 0·4 | 0·463—2·16 | 0·463 | — | — | 0·687 | — | — | 0·88[a] | — |
| 3 | 0·7 | 0·288—2·15 | 0·288 | — | — | 0·582 | — | — | 0·88[a] | — |
| 3 | 1·2 | 0·322—2·18 | 0·322 | — | 0·435 | 0·47 | 0·90 | — | 1·29 | — |
| 3 | 2·0 | 0·236—2·20 | 0·236 | 0·322 | 0·384 | 0·52 | 0·90 | — | — | — |
| 3 | 4·0 | 0·166—2·00 | — | 0·166 | 0·264 | 0·64 | 0·80 | — | — | — |
| 4 | 0·4 | 0·426—2·19 | 0·426 | — | — | 0·879 | — | 1·05 | — | — |
| 4 | 0·7 | 0·309—2·34 | 0·309 | — | — | 0·736 | — | — | 1·15[a] | — |
| 4 | 1·2 | 0·285—2·20 | 0·285 | — | 0·660 | 0·71 | — | — | 1·20[a] | — |
| 4 | 2·0 | 0·247—2·21 | 0·247 | — | 0·588 | 0·76 | — | — | 1·19[a] | — |
| 4 | 4·0 | 0·208—2·20 | — | 0·208 | 0·345 | 0·83 | 1·20 | — | — | — |
| 4 | 6·0 | 0·141—2·16 | — | 0.141 | 0·356 | 0·90 | 1·12 | — | — | — |
| 5 | 0·1 | 0·111—0·69 | 0·111 | 0·179 | — | 0·233 | 0·31 | — | — | — |
| 5 | 0·2 | 0·083—0·59 | 0·083 | 0·153 | — | 0·203 | 0·26 | — | — | — |
| 5 | 0·4 | 0·054—0·40 | 0·054 | 0·141 | — | 0·172 | 0·21 | — | — | — |
| 6 | 0·1 | 0·134—2·19 | 0·134 | 0·382 | — | 0·426 | 0·71 | — | 1·20 | 2·00 |
| 6 | 0·2 | 0·116—2·10 | 0·116 | 0·371 | — | 0·442 | 0·69 | — | 1·60 | — |
| 6 | 0·4 | 0·107—2·09 | 0·107 | 0·345 | — | 0·371 | 0·67 | — | — | — |
| 6 | 0·7 | 0·129—1·57 | 0·129 | 0·233 | — | 0·283 | 0·58 | — | — | — |
| 6 | 1·2 | 0·041—1·35 | 0·041 | 0·111 | 0·181 | 0·27 | 0·44 | — | — | — |
| 7 | 0·4 | 0·259—2·16 | — | 0·259 | — | 0·475 | 0·92 | — | 1·32 | — |
| 7 | 0·7 | 0·254—2·00 | — | 0·254 | 0·363 | 0·46 | 0·88 | — | 1·52 | — |
| 7 | 1·2 | 0·245—2·20 | — | 0·245 | 0·275 | 0·48 | 0·86 | — | 2·10 | — |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 2·0 | 0·171—2·03 | — | 0·171 | 0·210 | 0·51 | 0·79 | — | — | — |
| 7 | 4·0 | 0·145—1·46 | — | — | 0·145 | 0·60 | 0·72 | — | — | — |
| 8 | 0·4 | 0·338—2·18 | — | 0·338 | 0·483 | 0·62 | — | 0·95 | 1·70 | — |
| 8 | 0·7 | 0·302—2·02 | — | 0·302 | 0·429 | 0·66 | — | — | 1·25[a] | — |
| 8 | 1·2 | 0·241—2·02 | — | 0·241 | 0·330 | 0·73 | — | — | 1·35[a] | — |
| 8 | 2·0 | 0·225—2·04 | — | 0·225 | 0·272 | 0·76 | 1·35 | — | 2·00 | — |
| 8 | 4·0 | 0·204—2·02 | — | — | 0·204 | 0·87 | 1·30 | — | — | — |
| 8 | 6·0 | 0·583—2·03 | — | — | 0·583 | 0·90 | 1·19 | — | — | — |
| 10 | 0·1 | 0·355—2·00 | — | 0·355 | — | 0·380 | 0·74 | — | 1·41 | — |
| 10 | 0·2 | 0·322—2·01 | — | 0·322 | — | 0·344 | 0·65 | — | 1·76 | — |
| 11 | 0·2 | 0·320—2·04 | — | 0·320 | 0·376 | 0·47 | — | — | 0·97[a] | — |
| 11 | 0·4 | 0·294—2·00 | — | 0·294 | 0·311 | 0·52 | 0·98 | — | 1·29 | — |
| 11 | 0·7 | 0·240—2·00 | — | 0·240 | 0·261 | 0·55 | 0·96 | — | 1·65 | — |
| 11 | 1·2 | 0·152—1·98 | — | 0·152 | 0·183 | 0·59 | 0·94 | — | — | — |
| 11 | 2·0 | 0·160—2·00 | — | 0·160 | 0·167 | 0·65 | 0·88 | — | — | — |
| 12 | 0·4 | 0·299—1·99 | — | 0·299 | 0·390 | 0·64 | — | 1·05 | — | — |
| 12 | 1·2 | 0·164—2·01 | — | 0·164 | 0·217 | 0·79 | — | — | 1·30[a] | — |
| 12 | 2·0 | 0·219—2·01 | — | — | 0·219 | 0·84 | 1·30 | — | — | — |
| 12 | 4·0 | 0·308—2·00 | — | — | 0·308 | 0·88 | 1·15 | — | — | — |
| 14 | 0·1 | 0·224—1·98 | — | 0·224 | — | 0·313 | 0·47 | — | 1·52 | — |
| 14 | 0·2 | 0·236—2·00 | — | 0·236 | — | 0·282 | 0·46 | — | 1·93 | — |
| 14 | 0·4 | 0·161—1·93 | — | 0·161 | 0·217 | 0·31 | 0·46 | — | — | — |
| 14 | 0·7 | 0·120—1·66 | — | 0·120 | 0·152 | 0·35 | 0·42 | — | — | — |
| 15 | 0·2 | 0·246—1·99 | — | 0·246 | 0·331 | 0·56 | 0·77 | — | 1·40 | — |
| 15 | 0·4 | 0·227—2·00 | — | — | 0·227 | 0·59 | 0·67 | — | 1·50 | — |
| 15 | 0·7 | 0·440—2·00 | — | — | 0·440 | — | 0·54 | — | 1·75 | — |
| 15 | 1·2 | 0·247—2·02 | — | — | 0·247 | — | 0·48 | — | — | — |
| 15 | 2·0 | 0·247—1·98 | — | — | 0·247 | — | 0·45 | — | — | — |
| 16 | 0·4 | 0·587—1·98 | — | — | — | 0·587 | — | — | 1·05 | — |
| 16 | 0·7 | 0·278—1·94 | — | — | 0·278 | — | — | — | 1·12 | — |
| 16 | 1·2 | 0·475—2·00 | — | — | 0·475 | — | 0·92 | — | — | — |
| 16 | 2·0 | 0·317—2·02 | — | — | 0·317 | — | 0·85 | — | — | — |
| 16 | 4·0 | 0·185—1·97 | — | — | 0·185 | — | 0·72 | — | — | — |

[a] Begin of the gradual change of the regime *IV* to regime *VI b*.

It is obvious from this Table that on a plate having a certain hole size and free area at a given liquid flow rate only some of the described regimes were observed.

Regime *I* existed with plates having larger hole sizes (10 and 6 mm). It was not observed in the used range of gas velocities with plates having smaller hole sizes (2·5 and 4 mm). Regime *II* was not observed with plates having hole diameters 10 mm, but it was quite usual with plates having small hole sizes. At increasing the gas velocity the region of existence of regimes *I* and *II* was ending at the holding point which was manifested in the dependence of liquid holdup on gas velocity by a step change (Fig. 3). As long as the holding point appears at low gas velocity (small hole sizes, greater liquid flow rates) the regime *III* appears on the plate. The regime *IV* appears on plates with large hole sizes and low liquid flow rates at the loading point.

A change of regime *III* to regime *IV* takes place at increasing gas velocity and is accompanied with homogenisation of conditions of hydraulic regimes in the plane parallel to the plate. The slope of the curve representing the dependence of liquid holdup on gas velocity is changing considerably at the transition from regime *III* to regime *IV*. (Regime *IV* has not been observed with plates having the hole diameter 2·5 mm and the free plate area 15 and 20% at greater liquid flow rates when transition from regime *III* to regime *V* took place). In accordance with the liquid holdup the regime *IV* is changing into the regime *V* or *VIb*. The change into the regime *V* takes place if the liquid holdup exceeds 300 to 350 $N/m^2$. The change of liquid holdup in dependence on the gas velocity is not instant. Visually this transition takes place so that the weeping moves toward the plate edge and at the walls motion of foam bubbles is observed more frequently in the direction toward the plate. In the case of large liquid holdups above 500–600 $N/m^2$ the regime *V* was stable up to the greatest gas velocities; at lower liquid holdups transition of regime *V* to regime *VIb* takes place. This change is accompanied by a decrease of liquid holdup for about 50% (Fig. 3). As long as the liquid holdup at regime *IV* is less than 300–350 $N/m^2$, a transition to the regime *VIb* takes place. The change is slow and observations made with the regimes *V* and *VIa* apply here as well. Transition of regime *VIb* to *VII* has been observed only with plates having the free area 10% at high gas velocities and at low liquid flow rates. It is accompanied by a sudden decrease of the over-all pressure drop across the plate.

For transition between the regimes accompanied by a sudden change of liquid holdup (*I*, *II*–*III*, *IV*, *V*–*VIb*, *VIb*–*VII*) hysteresis has been observed. At decreasing gas velocity the change of regimes in the reversed direction took place at lower gas velocities than corresponded to the velocity determined at the increasing gas velocities. Hysteresis did not appear at transitions with a continuous change of the dependence of liquid holdup on the gas velocity.

## DISCUSSION

The presented description concerns the operations determined in the described apparatus and it cannot be excluded that the existence of some observed operations is related to the design of the experimental unit and with its dimensions. So the existence of regime *II* has probably been enabled by the uniform gas inlet into the relatively large space below one plate and the regime *VII* could appear in a column with more plates only transitionally as through the plate no liquid flows downward. Nevertheless, we expect that from the obtained experimental data some general conclusions can be made which could contribute to the qualitative explanation of operations taking place on the plate. The simultaneous countercurrent flow of both phases across the plate without downcomers is possible only if the pressure in the given instant is not on the whole plate area constant. Gas flows through those parts of the plate above which the pressure is lower and liquid through those above which the pressure is higher. Pressure changes are originated by the wave formation which is completely determining the operation on the plate[4]. The simplified mechanism of formation of these waves can be explained as follows: Gas enters the gas–liquid mixture in the place of low pressure in the plate plane, is increasing its porosity, transfers to it its kinetic energy and is responsible for motion of the gas–liquid mixture in the upward direction. Simultaneously the gas–liquid mixture is sucked from the neighbouring part of the plate. The gas–liquid mixture disintegrates at its surface and gas ontinues in its motion upward. The liquid separated from the gas–liquid mixture is increasing the static pressure above the considered place of the plate and also moves into the neighbouring parts of the plate. By removal of the liquid from some parts of the plate in some place of the plate a considerable decrease of pressure appears and in this way forms a new passage for gas flow. Above the initial place the freed liquid is moving toward the plate in the form of the gas–liquid mixture with lower porosity. At the plate its kinetic energy is changed into the pressure energy with simultaneous weeping and liquid motion to places with lower pressure. In this way pressure is decreasing and thus a new passage for gas forms. On the plate such liquid holdup and motion of the gas–liquid mixture are established at a certain gas flow rate so that the liquid inlet and weeping are in dynamic equilibrium.

In the regime *IV* locations of the rise and fall of the gas–liquid mixture are randomly altered. The uniform weeping and constant value of the in-time averaged pressure drop across the gas–liquid mixture on the whole plate confirm that this operation is purely accidental. The minute values of pressure in the plate plane measured at a certain place have the normal distribution (this is not true in the case of other regimes[5]).

Increasing of the gas flow rate is causing increase of the velocity gradient between the places of motion of the gas–liquid mixture in the upward or downward direction and consequently increase of their distance. If the distance is increased so much that it becomes comparable with the dimensions of the column, a certain uniformity begins to appear in the accidental operation of the plate.

If the height of the gas–liquid mixture is large (*i.e.* the path of motion from the plate to the surface is relatively long) the slow motion of the gas–liquid mixture with lower porosity toward the plate starts to prevail at the column wall, as the result of action of friction forces in respect to the fast rise of the gas–liquid mixture with greater porosity from the plate upward. Regime *IV* is transferred to the regime *V* at which prevails the circulation motion schematically given in Fig. 5. In vicinity of the plate a change in direction of motion of the gas–liquid mixture takes place (from the vertical direction toward the plate to the radial one toward the plate centre) which is accompanied by increase of pressure on the plate in vicinity of the walls (Fig. 4*b*) and by transfer of weeping toward the walls of the column.

If the bed of the foam on the plate is low, the effect of friction with the column walls is not sufficient for formation of the circulation motion. But the maximum distance of centres of liquid flow and gas flow through the plate is limited by the dimensions of the unit and cannot be further increased. Thus with increasing gas flow rate the amplitude and velocity of motion of the gas–liquid mixture on the plate moves and more and more uniform wave regime forms. In the case of very low liquid holdups the regime *VIa*, in other cases the regime *VIb* have stabilized.

The change of regime *IV* to the regimes observed at higher gas velocities represents a change of the accidental motion to a systematic one and obviously is related to the dimensions of the unit. In columns of larger dimensions this change should take place at higher gas velocities than in small columns. In literature, only one pair of directly comparable experiments made in columns of different dimensions has been found[2]. While in a column of diameter 114 mm change of the regime *IV* (determined according to the step change of the over-all pressure drop on the gas velocity) has taken place at the velocity of about 0·78 m/s, a similar change in a column of diameter 400 mm has been observed at the velocity of about 1·15 m/s.

Considerations on scaling up should be verified experimentally but on basis of the discussed results they may be considered as reasonable.

As concerns the mass transfer, the regime of homogeneous foam seems to be of the greatest importance (*IV*) due to a good contact of both phases in the whole cross-sectional area of the column. With large plates, where the ratio of the foam height to the column diameter is smaller, it may be expected that the region of homogeneous foam will be wider in the direction of higher gas velocities in agreement with the above discussed example.

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Translated by M.Rylek.