AN EQUIPMENT FOR MASS AND HEAT TRANSFER TO A FILM OF LIQUID FLOWING DOWN A PLANE SURFACE. I.
DESIGN AND BASIC HYDRODYNAMIC DATA

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The paper deals with the design and basic hydrodynamic parameters of the new type of equipment for mass (or heat) transfer to a film of liquid flowing down a plane surface.

The main aim in design of equipment for mass (or heat) transfer between two fluid phases in chemical technology is to form the maximum possible interfacial area and suitable hydrodynamic conditions diminishing the concentration (or temperature) gradients in both phases toward the interphase at the minimum possible consumption of energy. The common types of packed and plate columns satisfy these requirements only partially. The main drawback of the packed columns is that only a part[1] (5—50%) of the surface of the packing is utilized for transport phenomena and the pressure drop is relatively high. A majority of types of plates displays considerable energy consumption of which only a part is used to form the gas-liquid mixture and the rest is uselessly dissipated at the passage of the phase through the plate. This lead to an effort in the past to construct various packings and plates free as much as possible of these disadvantages. One of these arrangements consisted of a set of vertical sheets. Although these arrangements did have a low pressure drop, the available types of distributors[2,3] did not permit to achieve a continuous film covering the whole surface of the sheets in a wide range of liquid flow rates. This was the main reason why this equipment did not find a more extensive utilization despite its low pressure drop.

The difficulties of forming a film on vertical surfaces are overcome in a wide range of liquid loads[4] by the arrangement shown in Fig. 1. From the figure it is seen that the packing consists of vertical sheets *4* (fabric, net *etc.*) provided with a liquid distributor. The distributor, in principle, is a vessel *1* whose bottom is formed alternatively by the tops of the packing *4* and spacers *5* of suitable height provided with ribs (or other suitable spacers) to form slots bringing the liquid onto the packing. The advantage of this arrangement is that it enables a large interfacial surface to be formed (the distance of the sheets is not limited and depends on operating conditions). Furthermore, the slot facilitates formation of a continuous film of liquid by the surface tension forces over the whole width of the sheet which persists on the packing. An obvious condition for a good function of the slot is the wettability of the material of the packing and that of the spacers. The aim of our study, the results of which will be gradually published, is to find out the efficiency of the equipment for various operations and systems of chemical technology. Nevertheless we thought it necessary to obtain first basic information regarding the hydrodynamic behaviour enabling us to operate the equipment effectively and to compare it with other types. For such basic data we took the flow rate of liquid through the slot in dependence on its geometrical parameters and physical properties of liquid, the pressure drop and liquid holdup at countercurrent flow of gas.

EXPERIMENTAL

Apparatus. The diagram of experimental set-up is shown in Fig. 2. It contained only one sheet of the packing irrigated on one face only. The sheet was from stainless steel 300 mm wide and 1000 mm long. The liquid was pumped from a stainless steel tank *1* placed on a balance arm *2* by a pump *3* through a temperature control *4* into an overflow tank *5*. From the tank *via* thermometer *6*, regulation valve *7* into a distributor *8* through openings located in the level of the bottom of the distributor. The bottom of the distributor consists of the top of the sheet of packing *9* and a spacer *10* provided on the side adjacent to the sheet with ridges to leave a slit between the sheet and the spacer of the following width: 0·29; 0·38; 0·60; 0·75; 0·85; 0·95 and 1·05 mm. The height of liquid in the perspex distributor was read on a scale *11* mounted on the wall of the distributor. The liquid leaving the packing was collected in a stainless steel tank *12* and returned *via* stopcock *13* into the storage tank *1*. The pressure drop and liquid holdup were measured in a simple methyl methacrylate 105 . 15 mm square column housing various plane packings (stainless steel sheet and expanded metal) 100 . 750 mm in size.

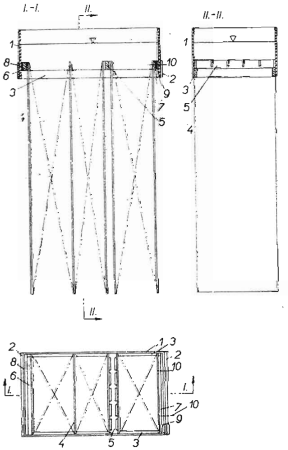

FIG. 1

Principle of the Distributor

1 Box of the distributor, *2* wall reinforcement, *3* bars for fastening the packing and the spacers, *4* plane packing, *5* spacers, *6, 7* end spacers (one-sided), *8,9* gaskets, *10* thrust screws.

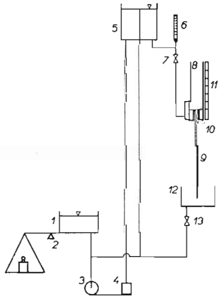

FIG. 2

Diagram of Experimental Equipment

1 Storage tank, *2* balance, *3* pump, *4* thermostat, *5* constant head tank, *6* thermometer, *7* regulation valve, *8* distributor, *9* plane packing, *10* spacer, *11* scale, *12* collecting tank, *13* stopcock.

Experimental. The amount of liquid passing through the slot was measured as follows: The pump 3 was turned on and the regulation valve 7 was set so as to achieve a predetermined height of liquid in the distributor. Having reached the steady state the weight of liquid in the tank *1* was read on the balance 2 and the cock *13* was shut off. From this instant the time necessary for draining a certain amount of liquid was measured. The experiments were carried out at different heights of liquid in the distributor and with liquids of different physical properties given in Table I for each width of the slot. The pressure drop was measured at a steady flow rate of gas and liquid by means of a U-manometer connected to the pressure probes at both ends of the plane packing. The U-manometer was filled with water and the accuracy of measurement was $\pm 0{\cdot}5$ mm of water head. The liquid holdup was measured by the well-know method consisting in mounting two solenoid valves controlled by one switch and measuring the amount of liquid collected in excess over the steady state liquid level 5 minutes after shutting the valves.

Experimental data processing. All experimental data obtained at measurement of the flow through the slot were processed by means of the relation

$$Q = \alpha ls(2gh)^{1/2} . \qquad (1)$$

This relation served to calculate α which in turn was correlated. Following relation is known for the laminar flow through a slot

$$Q = \frac{1}{12} \frac{hg}{h_s \nu} s^3 l . \qquad (2)$$

For α in the laminar region it follows from Eq. (*1*) and (*2*)

$$\alpha = \frac{1}{12(2)^{1/2}} \frac{s^2(gh)^{1/2}}{\nu h_s} . \qquad (3)$$

In order that the limits of validity of the relation (*3*) can be set, the values of α calculated from Eq. (*1*) were plotted *versus* $(s^2(gh)^{1/2}/\nu h_s)$ parameter on a log–log scale. It turned out that the relation (*3*) holds in the region where

$$s^2(gh)^{1/2}/\nu h_s \leqq 2{\cdot}5 .$$

TABLE I

Physical Properties of Liquids Used

Liquid	ϱ kg/m^3	$\nu \, . \, 10^6$ m^2/s	t_{min} mm
Water	1 000	0·8925	0·34
Ethanol	903·1 (950·3)	2·836 (2·671)	0·34
Glycerol	1 126·0	3·922	0·53
Glycerol	1 155·0	7·230	0·71
Glycerol	1 180·0	14·27 (12·46)	0·80

By statistical processing of the data from this region following relation was obtained

$$\alpha = 0.057 \left(\frac{s^2 (gh)^{1/2}}{\nu h_s} \right)^{0.94}, \tag{4}$$

with the correlation coefficient equal 0·97 for 204 data. In the region $(s^2(gh)^{1/2}/\nu h_s) > 2.5$ the data were correlated by the relation

$$\alpha = 0.4 \log (s^2(gh)^{1/2}/\nu h_s) - 0.032 \tag{5}$$

with the correlation coefficient 0·98 for 328 data. Both relations hold with the accuracy of $\pm 10\%$. The experimental values of the pressure drop and the liquid holdup are plotted in Figs 3–6. Another important problem worth inspecting is the question of minimum rate of wetting sufficient to form a uniform film on the sheet of packing. Since this problem involves a broader study of the contact angle, we confined ourselves to assessing the minimum flow rate for liquids listed in Table I. The last column of this table gives the minimum thickness of the film calculated from Nusselt's[5] relation

$$(3\nu \Gamma_{\min}/g)^{1/3} = t_{\min} \,. \tag{6}$$

DISCUSSION

It has been established that in region $(s^2(gh)^{1/2}/\nu h_s) \leqq 2.5$ the coefficient α, defined by Eq. (*1*), satisfies well the relation (*3*) following from the equation for the laminar flow. The exponents

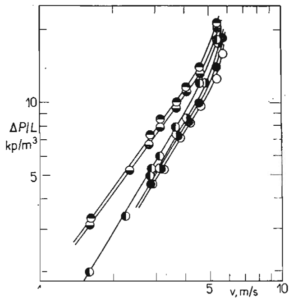

FIG. 3

Dependence of Pressure Drop on the Flow Rate of Gas and Liquid, Q (l min^{-1}), for a Smooth Sheet

○ 0·25, ● 0·50, ◐ 1·0, ◑ 2·0, ◒ 3·0, ◓ 4·0.

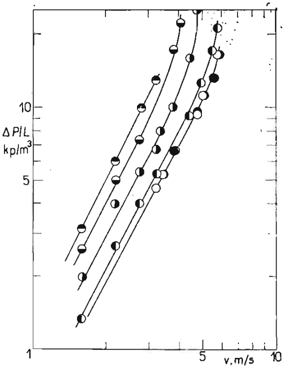

FIG. 4

Dependence of Pressure Drop on the Flow Rate of Gas and Liquid, Q (l min^{-1}), for 10 . 5 mm Expanded Metal

○ 0·15, ● 0·25, ◐ 0·5, ◑ 1·0, ◓ 2·0, ◒ 3·0.

and the constant are somewhat lower, which is due to the effects at the inlet and the outlet of the slot. The Reynolds number corresponding to the upper limit of this region is determined as follows: The linear dimension characterizing the slot is defined as usual

$$d_e = 4F/O\,. \tag{7a}$$

Neglecting the width of the slot in comparison to its length we get

$$d_e = 2s\,. \tag{7b}$$

For the Reynolds group we thus get

$$\mathrm{Re} = \frac{vd_e}{\nu} = \frac{Q}{ls}\frac{2s}{\nu} = 2\frac{Q}{\nu l}\,. \tag{8a}$$

On substituting for Q into Eq. (*8a*) from Eq. (*2*) and after some arrangements we get

$$\mathrm{Re}' = \frac{s}{h_s}\,\mathrm{Re} = \frac{1}{6}\left(\frac{s^2(gh)^{1/2}}{h_s\nu}\right)^2. \tag{8b}$$

Substituting 2·5 found experimentally for the value of the parameter on the right hand side of Eq.

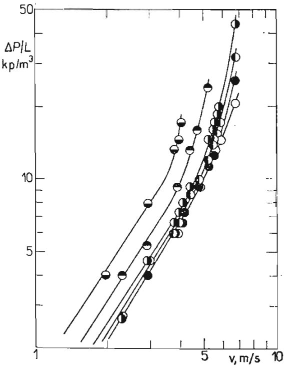

FIG. 5

Dependence of Pressure Drop on the Flow Rate of Gas and Liquid, Q ($\mathrm{l\,min^{-1}}$), for 16 . 5·5 mm Expanded Metal

○ 0·25, ● 0·50, ◐ 1·0, ◑ 2·0, ⊖ 3·0, ⊖ 4·0.

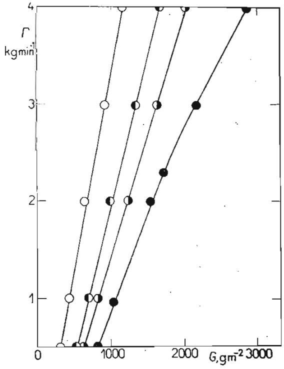

FIG. 6

Dependence of Liquid Holdup on Liquid Flow Rate

○ Smooth sheet, ⊖ 28 . 8 mm expanded metal, ⊖ 16 . 5·5 mm expanded metal, ● 10 . 5 mm expanded metal.

(*8b*) as the upper limit of validity of the relation (*4*) we get $\text{Re}' \approx 1$. The form of the dependence (*5*) found for $\text{Re} > 1$ corresponds to the form of the dependence between the dimensionless velocity and the Reynolds group defined by means of the friction velocity at the turbulent flow. It can be easily verified that the parameter on the right hand side can be expressed as

$$\frac{s^2 \sqrt{gh}}{h_s \nu} = 2\sqrt{2}\left(\frac{s}{h_s}\right)^{1/2} \frac{u^* s/2}{\nu}\,, \tag{9}$$

where $u^* = (\tau_0/\varrho)^{1/2}$ is the friction velocity. The pressure losses, as it is seen from Figs 3–5, are at gas velocities encountered in commonly used separation columns very low. As to the holdup, it was found that in the range 0–4 m/s the effect of velocity had little importance and could not be evaluated owing to the errors of measurement. Accordingly, the values plotted in Fig. 6 are the average values obtained in the given range of gas velocities. With increasing flow rate of liquid the holdup grows practically linearly in all cases except for the expanded metal with the smallest mesh.

LIST OF SYMBOLS

- d_e equivalent diameter
- F cross section of column
- g acceleration due to gravity
- G liquid holdup on the packing
- h height of liquid in distributor (measured from lower edge of spacer)
- h_s height of spacer (slot)
- l length of slot
- L length of packing
- O wetted periphery
- ΔP pressure drop
- Q volume flow rate
- Re Reynolds number
- s width of slot
- t thickness of film
- u^* friction velocity
- v velocity
- α coefficient defined by Eq. (*1*)
- Γ volume flow rate of liquid per unit width of wetted sheet of packing
- ν kinematic viscosity
- ϱ density of liquid
- τ_0 shear stress at the wall of slot

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