THE STUDY OF PRESSURE VARIATIONS AT THE BOTTOM OF A VIBRATING PLATE EXTRACTION COLUMN*

Radomir STEVANOVIĆ[a], Vladeta PAVASOVIĆ[a],
Dušan SIMONOVIĆ[b] and Stevan NEMODA[a]

[a] *The Boris Kidrič Institute of Nuclear Sciences-Vinča, 11001 Beograd, P.O.B. 522, Yugoslavia and*
[b] *Faculty of Technology, University of Beograd, 11000 Beograd, Yugoslavia*

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Pressure changes at the bottom of a vibrating plate extraction column, when single and two liquid phases are flowing through, were analysed. The model, which describes the action of the forces in the studied system, represents the solution of the macroscopic momentum balance. An experimental procedure for verification of the theoretical considerations consists of the following steps: *a*) measurement of the pressure drop at the bottom of the extractor, continuous determination of the dispersed phase hold-up, control of the flow rates of liquid phases and characterisation of the perforated plates vibrating motion; *b*) transfer of the measured data from a tape recorder to the computer system PDP-11, T-34 DIGITAL; and *c*) development of computer programs for data processing.

The hydrodynamics of vibrating plate extractors in the range of low and medium levels of agitation is strongly influenced by the interactions of the dispersed liquid phase with moving parts of the extraction equipment. The interactions of drops with perforated plates were also noticed in the pulsed extraction column[1,2]. This phenomenon, observed in both varieties of liquid–liquid contactors, was explained only qualitatively.

During the development of the method for continuous determination of the dispersed phase hold-up[3,4], in the Karr vibrating extraction column, it was found that the errors of the hold-up values were systematic and relatively high at low levels of agitation. The hold-up determinations were based on the measurements of pressure changes at the bottom of the extractor, which occured when the dispersed phase was introduced in the single-phase flow. Differences between the determined and the actual hold-up values were caused by interactions of perforated plates with droplets of the dispersed phase. This brought us an idea to study these interactions by comparative measurements of the instantaneous pressures at the bottom of the extractor, when successively single and two phases are flowing through it.

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In this paper, the model, which describes the interactions between the plates of vibrating plate extractor and the dispersed system, is given in a short form. The more detailed description of the model is given in[5,6,7].

In this article an experimental procedure for the verification of the model is presented. This procedure is the improvement of the earlier measuring method given by Pavasović and Kažić[6]. The experimental data of the pressure drops in segments of the extractor, and signals from photodiode, which give characteristics of vibrating motion of the perforated plates, were continuously recorded on a multichannel tape recorder. The data from the tape recorder were transferred to the computer system PDP-11, T-34 DIGITAL and computer programs were developed for data processing.

THEORETICAL

The theoretical consideration are based on the concept given by Procházka and Hafez[8,9]. The macroscopic momentum balance is applied to a control volume – a segment of the vibrating plate extraction column. Through the control volume two immiscible and incompressible liquid phases are flowing (Fig. 1*a*). All forces, which act at the surfaces of the control volume, are presented in Fig. 1*a*. More detailed explanations on development of the model are given in[5,6,7]. Application of the equation of momentum conservation to the flow through the control volume,

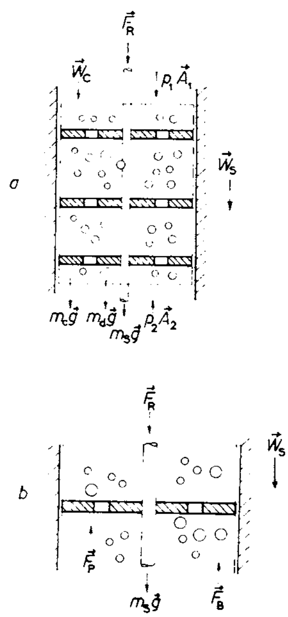

FIG. 1

Forces acting at: *a* surfaces of control volume, *b* vibrating plate; w_c = const., w_d = const.

knowing that all vectors corresponding to forces, velocities, and accelerations are parallel to the control volume axis, leads to the following scalar equation:

$$m_s \frac{\mathrm{d}w_s}{\mathrm{d}t} + m_c \frac{\mathrm{d}w_c}{\mathrm{d}t} + m_d \frac{\mathrm{d}w_d}{\mathrm{d}t} = (p_1 - p_2)\, A + F_R + (m_s + m_c + m_d)\, \boldsymbol{g}\,, \quad (1)$$

F_R is the fraction of the force, exerted by the vibrator on the rod and perforated plates, which is transferred to the liquid–liquid system. This force can be obtained from the momentum balance equation made for moving solid parts of the extractor (Fig. 1*b*):

$$m_s \frac{\mathrm{d}w_s}{\mathrm{d}t} = F_R - F_p + m_s \boldsymbol{g} - F_B\,. \quad (2)$$

F_p is the force exerted by the dispersed liquid system on the plates and F_B is the buoyancy force defined as:

$$F_B = \frac{m_s}{\varrho_s} \cdot \varrho_{mix} \cdot \boldsymbol{g} = \frac{m_s}{\varrho_s} (1 - x)\, \varrho_c + x \varrho_d\, \boldsymbol{g}\,. \quad (3)$$

For the particular case of the steady state flow of both liquid phases through a vibrating plate extractor Eq. (*1*) can be simplified. Combining Eqs. (*1–3*) and expressing the total mass of liquids as a product of volumes and corresponding densities, the following equation is obtained:

$$F_{pv} = \Delta P\,.\, A + AH(\varrho_c - \varrho_d)\, x \boldsymbol{g}\,, \quad (4)$$

where the pressure term ΔP is given by:

$$\Delta P = (p_2 - p_1) - \varrho_c \boldsymbol{g} H\,. \quad (5)$$

For a single phase flow, $x = 0$, Eq. (*4*) becomes:

$$F_{pv,o} = \Delta P_o\,.\, A\,. \quad (6)$$

The instantaneous power input, supplied to the liquid system by the motion of the plates, is a product of the instantaneous velocity of the plates, w_s, and the force exerted on the liquid by the plates:

$$N_v = w_s F_{pv} = w_s A[\Delta P + (\varrho_c - \varrho_d)\, \boldsymbol{g} x H] \quad (7)$$

$$N_{v,o} = w_s F_{pv,o} = w_s A\,.\, \Delta P_o\,. \quad (8)$$

Corresponding average values of the power input over the period T are:

$$\bar{N}_v = \frac{A}{T} \int_0^T w_s[\Delta P + \Delta \varrho g H] \, dt \tag{9}$$

$$\bar{N}_{v,o} = \frac{A}{T} \int_0^T w_s \, \Delta P_o \, dt \,. \tag{10}$$

EXPERIMENTAL

The measurements were performed on a Karr vibrating plate extraction column. A sketch of the column and electronic equipment is shown in Fig. 2. The column was 0·0254 m ID with a total height of 2·71 m. The perforated plates were mounted on a common rod and spaced at equal distances of 0·0254 m. The free area of the plates was 51%. By use of an eccentric mechanism, connected to a variable speed motor, the reciprocating motion of the plates of a simple harmonic

TABLE I

Physical properties of water–toluene system at 20°C

Phase	Density kg/m^3	Viscosity Ns/m^2	Interfacial tension N/m
Aqueous	997	$1{\cdot}021 \,.\, 10^{-3}$	$3{\cdot}60 \,.\, 10^{-2}$
Organic	864	$6{\cdot}15 \,.\, 10^{-4}$	

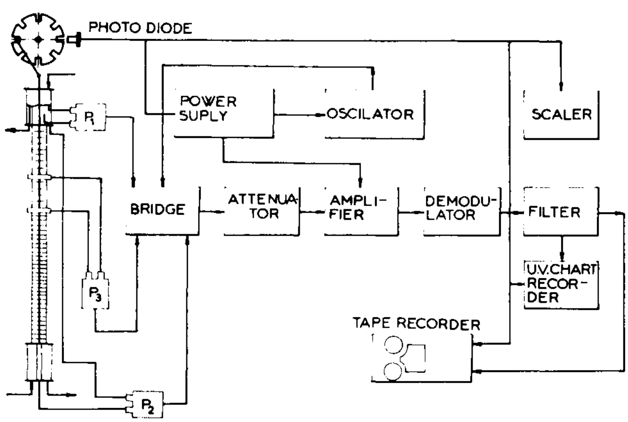

FIG. 2

Sketch of the vibrating column and electronic equipment; P_1, P_2, P_3 are pressure transducers character was obtained. In all experimental runs an aqueous phase was continuous and toluene was dispersed. Experiments were performed in the absence of mass transfer and at constant temperature of $20 \pm 0.5°C$. The physical properties of mutually saturated water–toluene phases are given in Table I.

Measuring Method and Instrumentation

For the measurements of the instantaneous pressure at the bottom of the extraction column, as well as for the continuous determinations of the dispersed phase hold-up, inductive pressure transducers were used (Types SE 180 and SE 1150, SE Laboratories, Feltham, England). Processing of the signals from the inductive transducers was performed by use of an electronic equipment which block diagram is shown in Fig. 2. The signals were further continuously recorded on a multichannel tape recorder. The character of the reciprocating motion of the perforated plates was controlled by a simple device consisting of: peripherally perforated metallic wheel mounted on the axis of the motor, light source, photo-diode and nonius was used for amplitude adjustment. The electronic impulses from the photo-diode were counted by a scaler and recorded paralelly with pressure signals on one channel of the tape recorder. In that way the time base was defined.

All experiments were performed without any net flow of continuous phase. The extraction column had been filled with a known volume of the aqueous phase, before the vibration and dispersing of the organic phase started. By doing so, experimental conditions were simplified and difficulties in continuous determination of the dispersed phase hold-up were avoided. Hold-up determination was based on the measurement of the hydrostatic head in the expanded top section of the vibrating extraction column. Since in such experiments only the dispersed phase was flowing, the change of the interface level in the expanding section is proportional to the dispersed phase hold-up in the column proper. The hydrostatic head was measured with an accuracy of ± 0.40 mm WG and the corresponding calculated values of dispersed phase hold-up were accurate in the range $\pm 2.0\%$. The range of independent variables (frequency and hold-up) covered by experimental investigation is as follows: amplitude 0·0205 m, frequency 0·275; 0·5; 0·75; 1·0; 1·5; 2; hold-up 0–20%.

Preliminary esperimental runs showed that random phenomena, as well as electrical noise, had significant influence on the precision of measured data. Therefore, for a quantitative evaluation, 30 consecutive signals which correspond to a single vibrating cycle were used.

Transfer of Experimental Data from the Tape Recorder to the Computer System PDP-11, T-34 DIGITAL

From the analogue voltage signal (recorded on the tape recorder) which is proportional to the pressure change, the limited number of discrete values taken at equal time intervals have to be sampled and the pressure drop function has to be presented with satisfactory accuracy with a series of discrete values. The frequency of sampling was chosen to be 100 times higher than the plate oscillation frequency. It turned out that this sampling frequency was much higher than necessary.

The electronic block diagram of equipment used for transfer and processing of analogue signals from the tape recorder is presented in Fig. 3. The frequency generator was used for setting the sampling frequency and for every experimental run it was adjusted at a frequency 100 times higher than the frequency of the plate oscillation.

The sampling was started by the impulse from the photodiode (recorded on the channel for time base) according to the computer program. In that way, one period of pressure drop (ΔP) was presented with hundred discrete values (with $T/100$ time interval between two successive values). For each experimental run 30 periods of pressure signals were sampled (3 000 discrete values). These 30 periods of one experimental run were averaged in one period and stored into an auxiliary computer memory.

During the averaging of signals, due to the variation of plate vibration frequency for one experimental run, the shifting of signals in the base appeared. The computer program was developed for correction of signals shifted in time.

Data Processing

The data, stored in the auxiliary computer memory were proccesed further. First, the data, corresponding to pressure drops, were transformed by multiplying with calibration constants to true values of pressure drops.

Each experimental run of pressure drop was represented by a table of 100 discrete values. These tables, which represent one period of pressure oscillation, were approximated by the Fourier series of 5 terms. The coefficients in the Fourier series have been determined by the least squares method. The computer program for determination of the coefficients in Fourier series was taken from the PDP 11 computer program library. The Fourier series of only 5 terms were taken for fitting the pressure drops experimental data. In that way, the harmonics of higher orders which were caused by friction of plates with the wall of the column and as such unimportant for our analysis were omitted.

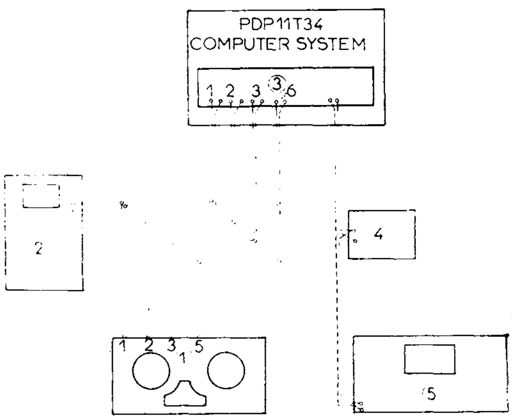

FIG. 3

Schematic diagram of electronic equipment for transfer and processing of pressure data; 1 Multichannel tape recorder, 2 Oscilloscope for viewing of recorded signals, 3 Analogue to digital (A/D) convertor 4 Signal generator, 5 Digital oscilloscope

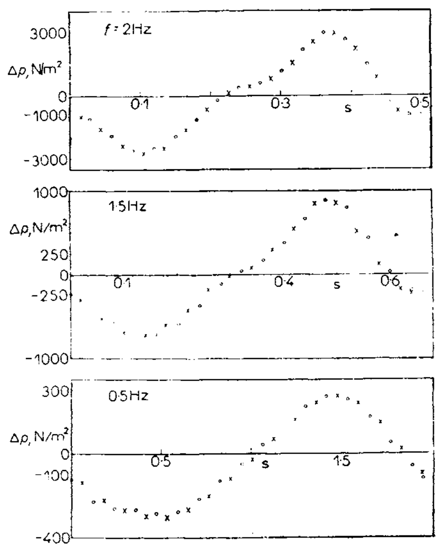

FIG. 4

Typical pressure drop signals; experimental ×, approximation ○

DISCUSSION

In Fig. 4 some of the typical experimental curves of pressure drops and their approximations with the Fourier series, are presented. As can be seen from Fig. 4 the approximation was quite satisfactory. For all further calculations the Fourier series approximations of pressure drops were used. From the time-averaged pressure drops in the expanding top section of the column for the single and two phase flows, the hold-up of the dispersed phase was calculated.

$$x = \frac{D^2(\Delta\bar{P}_{o,p} - \Delta\bar{P}_p)}{d^2(\varrho_c - \varrho_d)\,H} \qquad (11)$$

All pressure signals were corrected by the use of subprogram (SUBROUTINE KRP) for signals time shifting. The signals were corrected by shifting in time in such a way that their maxima occur at the same time when the plate velocity is maximum. The maxima of pressure drops and velocities should not occur at the same time but could differ (although very little) due to the inertia of the liquid mass which follows the plates.

The velocity of plates, w_s, is defined as a negative sine function:

$$w_s(i) = -2\pi f\,.\,a\,.\,\sin\left(\frac{2\pi i}{100}\right) \quad i = 1, 2, 3, \ldots, 100\,. \qquad (12)$$

The instantaneous power inputs for single and two phase flows were calculated according to Eqs (7) and (8). The averaged power inputs can be obtained by integrating the instantaneous power over the period T according to Eqs (9) and (10).

In Fig. 5 some typical curves of pressure drops for one vibrating circle at low vibration frequencies ($f = 0{\cdot}275$), for different hold-up values, are presented. The full line presents the pressure drop for single phase flow ($x = 0$). In order to compare the forces exerted by the plates to the single and two phase liquid systems, the term which corresponds to the hold-up, was added to pressure drop for two phase flow according to Eq. (4).

It is evident from Fig. 5 that there are differences between the pressure drops in single and two phase flows. These differences are very small when the plates are moving upwards and large when the plates are moving downwards. The differences are the largest when the plates are moving downwards with the maximum velocity.

Jiřičný and Procházka[12] also used the pressure drop method for measuring the hold-up profiles in a vibrating plate column. However, they did not notice the difference between the measured and the actual values. The hold-up measurement method is based on the following assumptions[7,12]:

1) There is no direct support of a part of the dispersed phase by the walls;

2) There is zero net flux of momentum of the phases through the upper and lower boundaries;

3) The densities of the phases are constant;

4) The drops are homogeneously distributed in the control volume, so that x is neither a function of coordinates nor of time;

5) There is no direct support of a part of the dispersed phase by the plates and the rod;

6) The friction force due to an increase in relative velocity between the plates and the continuous phase (brought about by introducing the dispersed phase into the system) should be negligible. For higher hold-ups, the above assumption may cause an appreciable error. Higher precision can be achieved repeating the one-phase measurement at flow rate corrected by means of the first approximation of the hold--up x.

In the paper by Jiřičný and Procházka[12] the perforated plates, provided with holes 0·02 m in diameter (free area 38%), were placed 0·075 m apart. Under the experimental conditions they performed, the conditions *1*–*6* were fulfilled, therefore there was no error in their hold-up measurements. In our experiments, the perforated

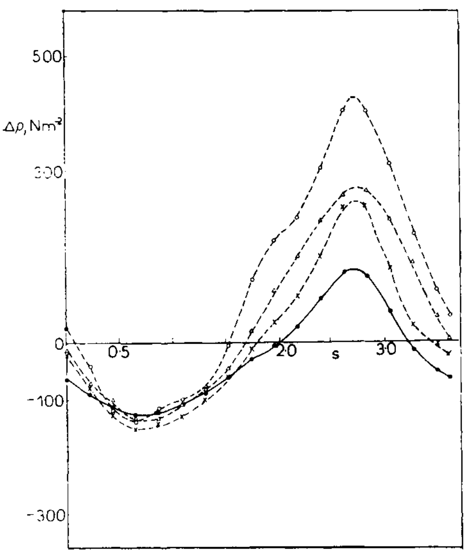

FIG. 5

Typical pressure drop signals at lower vibration frequency for different hold-up values; $a = 0{\cdot}0205$ m, $f = 0{\cdot}275$ Hz, single phase (●), $x(\%) = 5$ (×), 10 (△), 18 (○)

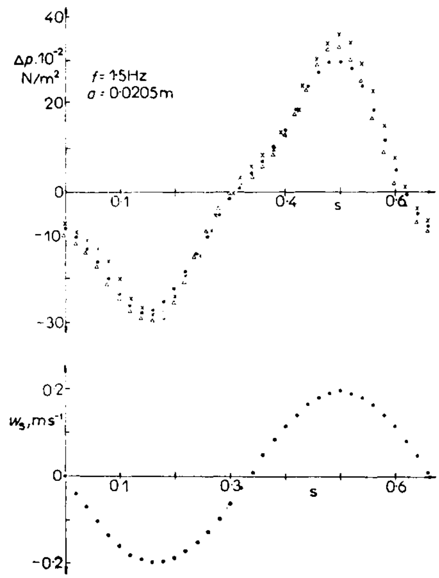

FIG. 6

Typical pressure drop signals at higher vibration frequency for different hold-up values; $x(\%) = 0$ (○), 2·5 (△), 12 (×)

plates provided with holes (0·008 m in diameter, free area 51%) were placed 0·0254 m apart. So, there were more plates per unity of length then in[12]. It was observed and photographed by a moving camera, that at lower frequences of vibration the drops were not homogeneously distributed. At these frequences the vibrating extractor works in the mixer-settler regime of operation. At the maximum downward plate velocity a large portion of drops was supported by the plates blocking the plate holes.

The increase in friction force over one cycle of oscillation will not be the same for homogeneously and nonhomogeneously distributed dispersions due to a nonlinear (square) relation between the friction force and the velocity. The friction force between freely moving drops and continuous phase is equal to buoyancy force which acts on drops. This friction force is detected by the pressure drop which is proportional to the dispersed phase hold-up. The decrease in velocities of drops due to collision with plates and suporting by the plates will result in lower hold-up detection. Collision and supporting of drops by the plates are higher for nonhomogeneously distributed dispersion than for the homogeneously distributed one. All of these have as a result a hold-up measurement error.

At higher oscillation frequencies, the extractor works in the emulsion regime of operation. The dimensions of drops in the emulsion regime are determined by the dimensions of eddies in the continuous phase[3,10,11] and, therefore, rather small. Due to small drops and the violent turbulence, the stages between the neighbouring plates are nearly perfectly mixed. Only a small portion of drops can be hit by the plates in a moment. The ratio between the drop and the plate opening diameter is much smaller than in the mixer-settler regime. Therefore, the previously mentioned conditions (*1*–*6*) are fulfilled and the hold-up can be measured by the pressure drop method. The typical results for pressure drops for single and two phase flows (term which corresponds to the hold-up value is added to pressure drop of the two phase flow according to Eq. (*4*) for different hold-up values) are presented in Fig. 6. There are no differences between the single and two phase pressure drops if they are presented in this way.

The instantaneous, as well as time-averaged power consumption, increases with an increase of the dispersed phase hold-up for lower oscillation frequences. At higher oscillation frequences (emulsion regime) there is no differences in power consumption between single and two phase flows.

CONCLUSION

The concept given by Procházka and Hafez[8,9] was applied to two phase flow in a vibrating plate extraction column. The expressions for the force exerted by the dispersed liquid system to the plates and for instantaneous power input were obtained. To verify these theoretical considerations, the experimental procedure was developed. The computer programs for experimental data processing were also developed. The pressure drops at the bottom of the extractor for different hold-up values and plate vibration frequences were compared. At lower vibration frequencies (mixer-settler regime) the differences between pressure drops in single and two phase flows were the largest at maximum downward plate velocities. At higher frequencies there were no differences between single and two phase flows.

At lower frequencies the power consumption was larger for two phase flow and increased with an increase in hold-up.

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LIST OF SYMBOLS

a	— amplitude of plates oscillation, m
A	— area of column cross section, m^2
A_0, A_j, B_j	— coefficients in Fourier series — diameter of column top — expansion section, m
d	— column diameter, m
f	— plate oscillation frequency, Hz
F	— force, N
g	— acceleration gravity constant, ms^{-2}
H	— height of the column, m
m	— mass, kg
p	— pressure, Nm^{-2}
$p_{1,2}$	— pressure acting on column cross sections, Nm^{-2}
N, N	— instantaneous and average power input, W
Δp	— pressure drop, Nm^{-2}
ΔP	— pressure term, Nm^{-2}
t	— time, s
T	— period of oscillation, s
x	— dispersed phase hold-up
w	— instantaneous velocity, ms^{-1}

Greek letters

ϱ	— density, kg m^{-3}
τ	— time interval, s

Subscripts

c	— continuous liquid phase
d	— dispersed liquid phase
o	— single phase
p	— plate
t	— two phase flow
v	— vibrating plate
mix	— mixture

A — surface
B — buoyancy
R — rod

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