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# Pressure drop in pulsed extraction columns with internals of discs and doughnuts

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## A B S T R A C T

A study on the pressure drop in pulsed extraction columns with internals of immobile discs and rings, usually called Discs and Doughnuts Columns (DDC) is carried out. The local pressure at a desired level of the column is obtained by resolving of turbulent flow model based on Reynolds equations coupled with  $k-\epsilon$  model of turbulence. Consequently, the pressure drop for a column stage or for a unit of column length is determined. The results are used for development of correlations for determination of pressure drop as a function of plate free area, interplate distance and pulsation parameters – amplitude and frequency. Good correspondence to experimental data is observed. The developed quantitative relations are useful for non-experimental numerical optimization of stage geometry in view of lesser energy consumption.

**Keywords:** Pressure drop; Pulsed flow; Discs and doughnuts column

## 1. Introduction

Pulsed extraction columns with internals of discs and rings (usually called Discs and Doughnuts Columns – DDC) have revealed themselves as promising devices for extraction processes in liquid–liquid media. They are used in different area, mainly spent nuclear fuel recycling (Movsowitz et al., 2001; Cocaud et al., 2004), hydrometallurgy (Buchalter et al., 2002; Kleinberger, 2001; Mason et al., 2003), non-metal extraction (Martin, 1987; Prat et al., 2006; Van Delden et al., 2006). They have demonstrated good overall performance characteristics and recently are subject of intensive research (Bi et al., 2007; Bujalski et al., 2005; Jahya et al., 2005, 2009; Torab-Mostaedi et al., 2011; Wang et al., 2005, 2006; Wu et al., 2006).

### 1.1. Apparatus description

A principal scheme of a DDC apparatus is shown in Fig. 1.

Alternated internals of immobile discs and rings (doughnuts) are mounted in a vertical cylindrical apparatus body. They are placed horizontally and centered with respect to the column axis. A stage is formed by two rings and a disc between

them. The outer edge of the rings is extended to the column wall. Two passages for the flow are formed – a central passage through the ring aperture and a peripheral passage through the annular aperture between the disc edge and column wall. A pulsing device is coupled to the column body, which induces reciprocal up and down movement of the fluids. The pulsation is characterized by its amplitude  $A$  and frequency  $f$ .

The column contains a number of equivalent stages. The geometry parameters of a stage are shown in Fig. 2.

$D_c$  is the column diameter and the outer diameter of the ring;  $D_a$  is the inner diameter of the ring aperture;  $D_d$  is the disc diameter;  $H$  is the distance between two consecutive plates. The disc diameter is larger than the ring aperture in order to hamper a direct flow in axial direction.

Pressure drop is a basic parameter, which supplies information about the energy consumption associated to apparatus type and operational conditions, and is an important design parameter. Usually it is obtained experimentally by tests on pilot columns. The purpose of this study is to derive a correlation for numerical determination of pressure drop as a function of stage geometry and pulsation intensity, based on hydrodynamic description of a pulsed flow in DDC.

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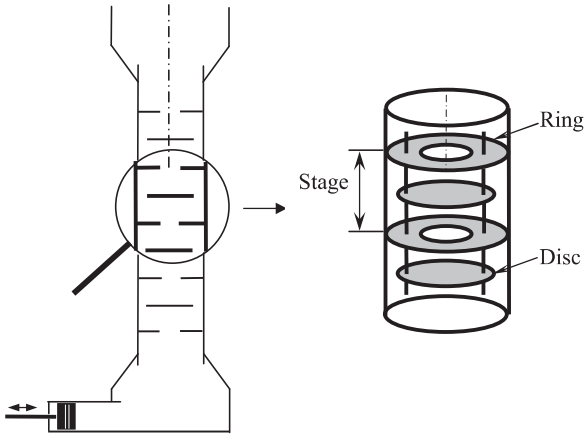


Fig. 1 - Scheme of a discs and doughnuts column.

## 1.2. Previous studies

There are some previous studies on pressure drop in this type of columns. They concern one-phase flow.

Laulan (1980) has determined the pressure drop regarding the pulsed flow as a permanent flow with velocity equal to the maximal velocity during the pulsation cycle. However, in reality the pulsed velocity changes with the time and attains its maximal value only in two peak moments of the pulsation period, otherwise being lesser and correspondingly, the real pressure drop being lesser.

Leroy (1991) has developed an experimental expression for pressure drop in DDC as a function of permanent flow velocity. It is an empirical correlation for a particular column, which does not account for the influence of stage geometry parameters.

In order to obtain the pressure drop in a pulsed column based on measurements in non-pulsed regimes, Milot et al. (1990) have supposed that if both flows have the same mean velocity, the pressure drop also will be the same.

It is seen that the attempts to measure or describe quantitatively the pressure drop in a single-phase pulsed DDC assume equality of permanent and pulsed flows.

All previous experimental studies on DDC with permanent flow have shown that for this type of equipment is valid the fundamental equation

$$\Delta p \frac{D_c}{Z_p} = kU^2 \quad (1)$$

which means that the pressure drop  $\Delta p$  for a unit mass and unit height in a DDC with given diameter  $D_c$  is proportional ( $k$ )

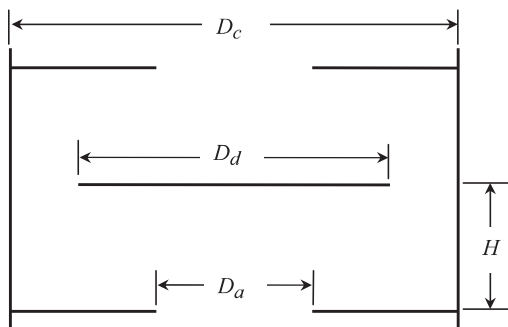


Fig. 2 - Scheme of a stage.

to square of velocity  $U$ .  $Z$  denotes distance between the levels of pressure measurement,  $\rho$  is density of the liquid flow.

## 2. Theory

In our opinion, when consider pulsed one-phase flow, instead of regarding it as a permanent flow with velocity equal to the mean velocity of the pulsed flow, it is more realistic to account for the periodical velocity changes due to imposed pulsation.

The instantaneous pulsation velocity created by a piston mechanical device is:

$$U_p(t) = \pi Af \cdot \cos(2\pi ft) \quad (2)$$

where  $A$  and  $f$  are pulsation amplitude and frequency.

The instantaneous velocity of the liquid in the column  $U(t)$  has two components: a permanent part due to the flowrate  $U_0$  and a pulsed part due to pulsation  $U_p(t)$

$$U(t) = U_0 + U_p(t) \quad (3)$$

The mean flow velocity  $U_m$  is a sum of permanent flow velocity  $U_0$  and mean pulsation velocity  $U_{pm}$ . The last term can be obtained by integrating Eq. (1) over a period of pulsation  $T$

$$U_m = \frac{1}{T} \int_0^T U(t) dt = 2Af \quad (4)$$

In practical situations the periodical component dominates over the permanent one. For DDC their ratio  $U_{pm}/U_0$  takes values from 50 to 90 (Buratti, 1988). Consequently, the permanent velocity component  $U_0$  represents 1–2% of the total flow velocity. For this reason the mean flow velocity can be considered equal to the mean pulsed velocity.

Re number for a pulsed flow is defined here with respect to its mean velocity

$$Re = \frac{2AfD_c}{\nu} \quad (5)$$

Introducing pulsed velocity expression (2) in (1) and taking an average value over the pulsation period, it is obtained

$$\frac{\Delta p D_c}{Z_p} = \frac{1}{T} \int_0^T k(\pi Af)^2 \cos^2(2\pi ft) dt = \frac{\pi^2}{8} k(2Af)^2 = k_p(2Af)^2 \quad (6)$$

$$k_p = \frac{\pi^2}{8} k = 1.234k \quad (7)$$

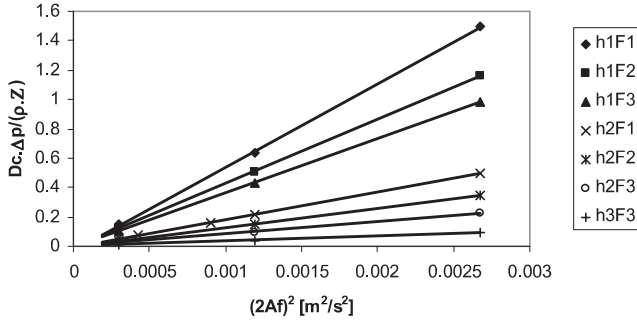
where  $k$  is a proportionality coefficient in case of permanent flow,  $k_p$  is for the case of a pulsed flow ( $2Af$ ) is mean velocity of the pulsed flow (Eq. (4)). We shall call  $k$  and  $k_p$  pressure drop coefficients.

It is seen that the pressure drop of a permanent flow (Eq. (1)) is not equal to that of a pulsed flow with same mean velocity (Eq. (6)), the last one being about 25% greater (Eq. (7)). So, it is not to recommend the use of equations for permanent flow in DDC for determination of pressure drop in pulsed regimes.

Now our task is to find how the pressure drop will change when vary the geometry parameters of the stage and pulsation parameters.

Two dimensionless parameters characterize the stage geometry:

- (a) Plate free section  $F$ . For the rings it is defined as ratio of the surface of ring aperture and column cross section. For the



**Fig. 3 – Pressure drop as depending on pulsation velocity:**  $h1 = 0.086$ ,  $h2 = 0.155$ ,  $h3 = 0.50$ ;  $F1 = 0.23$ ,  $F2 = 0.30$ ,  $F3 = 0.43$ .

discs it is the ratio of the surface of the annular aperture between the disc edge and column wall and column cross section. The dimensions of two types of plates are chosen to offer the same free area to the flow:

$$F = \frac{D_a^2}{D_c^2} = \frac{D_c^2 - D_d^2}{D_c^2} \quad (8)$$

(b) The ratio of distance between two adjacent plates  $H$  and column diameter  $D_c$  characterizes the interplate distance as a part of column diameter.

$$h = \frac{H}{D_c} \quad (9)$$

In order to obtain results for pressure drop at different stage configurations of DDC in pulsed turbulent single-phase flow, we have used turbulent flow model based on averaged equations of Navier–Stokes (Reynolds equations) coupled with the classical  $k-\varepsilon$  model of turbulence. The model equations, the method of their solution, and the boundary conditions are given in details in (Angelov et al., 1990, 1998; Angelov and Gourdon, 1997) along with evidence for good correspondence of simulations and experimental results.

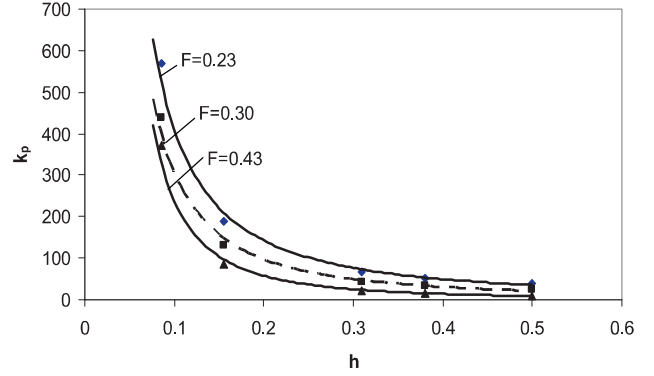
In the model equations, besides the terms characterizing the state of turbulence (turbulent kinetic energy and its dissipation rate), there is a term accounting for the pressure. The simulation solutions supply results for its local values, which have been used to calculate the corresponding mean values. The pressure drop has been determined as a difference between the mean pressure values at two different levels in the column, placed at the stage entry and exit.

### 3. Results and discussion

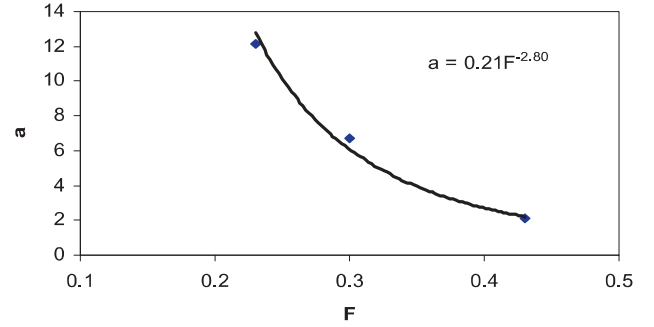
Fig. 3 illustrates some calculation results for the pressure drop in columns with different stage geometry as a function of mean pulsation velocity. The interval of variation of  $h$  is 0.08–0.5, for  $F$  it is 0.23–0.43.

For all stage configurations, the pressure drop in a pulsed DDC is a linear function of the square of mean pulsation velocity, which is in agreement with the general equations ((1) and (7)). The slope of the lines corresponds to the pulsed flow pressure drop coefficient  $k_p$ . As seen, it does not depend on flow velocity and takes specific values for each particular stage configuration. So,  $k_p$  characterizes the influence of stage geometry.

The attempt to correlate directly  $k_p$  to stage geometry by means of dimensional analysis has lead to an expression, giving results with about 20% deviation. Such a precision has been considered insufficient, and additional study has been carried



**Fig. 4 – Influence of interplate distance on pressure drop coefficient.**



**Fig. 5 – Coefficient  $a$  as depending on plate free area  $F$ .**

out in order to elucidate the influence of each of geometry parameters  $h$  and  $F$ .

Fig. 4 shows the influence of plate distance  $h$  on the coefficient  $k_p$  at several constant values of free cross-section  $F$ . The curves interpolate the points by a power law of the form

$$k_p = a(F)h^{\alpha(F)} \quad (10)$$

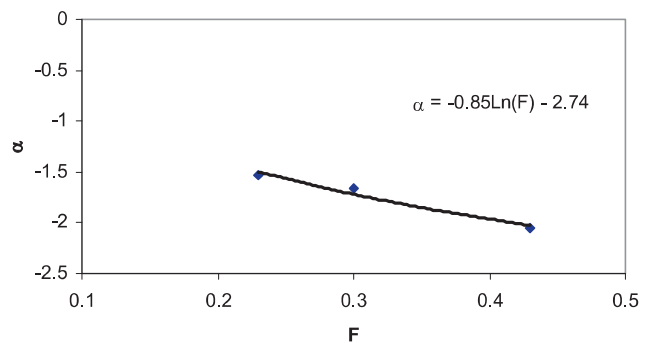
where coefficients  $a$  and  $\alpha$  depend on  $F$  – Figs. 5 and 6.

Introducing in (10) the equations for  $a$  and  $\alpha$  from Figs. 5 and 6, it is obtained

$$k_p = 0.21F^{-2.80} h^{-0.85 \ln F - 2.74} \quad (11)$$

The above Eq. (11) determines the pulsed flow pressure drop coefficient  $k_p$  with a deviation less than 10%.

As it is seen, the pulsed flow pressure drop coefficient  $k_p$  defined by the above correlation, does not depend on  $Re$  number. At a first glance it might seem strange, because  $k_p$  should integrate the influence of two types of hydraulic losses:  $Re$  dependent friction losses (flow in pipe) and  $Re$  independent



**Fig. 6 – Coefficient  $\alpha$  as depending on plate free area  $F$ .**

local resistance losses (flow through orifices). Consequently,  $k_p$  should depend on  $Re$ . A possible explanation can be found when consider separately the impact of hydraulic losses. Calculations of friction and local resistance losses have shown that the pressure drop due to friction is below 2% of total pressure drop, i.e. the local resistance losses in the studied column strongly dominate. In such a case, in view of the correlation precision of about 10%, negligible impact of  $Re$  number on  $k_p$  might be expected. It is to mention, that correlations ((16)–(19)) given below, concerning one-phase flow in perforated plate columns with immobile or oscillating plates, except that of Hafez and Prochazka (1974) – (Eq. (18)), show no influence of  $Re$  on pressure drop, thus it might be considered as a common case.

#### 4. Comparison to experiments

The measurement of pressure drop operating with a permanent single phase flow is a standard task. Using a differential manometer, the level difference  $\Delta h$  is measured, which is related to  $\Delta p$  by:

$$\Delta p = \rho g \Delta h \quad (12)$$

By use of Eqs. (1) and (7) the expression (12) becomes

$$\Delta h = k \frac{Z}{D_{cg}} U^2 \quad (13)$$

Introducing the relation (7) between  $k$  and  $k_p$  it becomes

$$\Delta h = \frac{8}{\pi^2} k_p \frac{Z}{D_{cg}} U^2 \quad (14)$$

$\Delta h$  and  $\Delta p$  for a permanent flow can be calculated through Eqs. (14) and (12) using relation (11) to obtain the pressure drop coefficient  $k_p$  in a pulsed flow. These numerical results for permanent flow obtained by applying a correlation for pulsed flow can then be compared to experimental data for permanent flow, which are easy to obtain. The rate of coincidence might be used to estimate the accuracy of proposed pulsed flow correlations.

The experiments are carried out in a in a column of total height 3.50 m. Two settling zones of 0.45 m in diameter are placed at both ends. The main body filled with plates of thickness 3 mm is 0.29 m in diameter and 2.50 m in height. The number of doughnuts and discs is 26 and 25 correspondingly. They are placed at 0.045 m distance and form 25 constructive stages. The discs are of diameter 0.254 m, and the aperture diameter of doughnuts is 0.14 m. At these dimensions the dimensionless stage parameters (Eqs. (8) and (9)) are: free area  $F=0.23$  and interplate distance  $h=0.155$ . A differential manometer is connected to holes at column wall, placed at 0.56 m one from the other in the median space between a disc and a doughnut.

A single phase (water) has been fed at the top of the column, and measurements of height loss  $\Delta h$  have been taken varying the water flowrate from 0.014 to 0.021 m/s, which corresponds to  $Re$  numbers in the interval 4000–6000.

Fig. 7 shows pressure drop per unit column height at different  $Re$  numbers.

Calculations through Eq. (11) are presented along with our experimental measurements and also experimental results of other authors (Oh, 1983) for permanent single- phase water flow in a column with the same geometry and plate parameters.

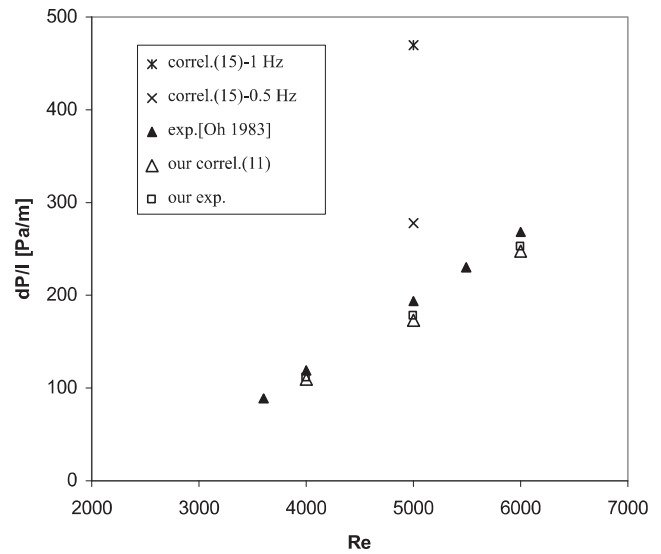


Fig. 7 – Comparison of experimental and calculated results.

The deviation of calculation from experiments is in the frames of 10% and could be considered as fairly good. It is also a positive test for the reliability of starting Eq. (11), on which the calculation is based.

A numerically obtained relation for determination of pressure drop in pulsed DDC is proposed in Aoun (1995), which shows an asymmetrical influence of  $A$  and  $f$ :

$$k_p = 0.033 \left(\frac{1}{h}\right)^{1.22} \left(\frac{1}{F}\right)^{1.30} \left(\frac{D_c}{A}\right)^{0.39} \left(\frac{\rho U_c^2}{\nu}\right)^{0.37} \quad (15)$$

Eq. (15) is applied here to the same experimental column, and the results are plotted also in Fig. 7. This relation produces different results for the same  $Re$  number and same mean pulsation velocity ( $=2Af$ ), obtained by different combinations of  $A$  and  $f$  (shown data for  $Re=5000$ ,  $2Af=0.0172$  m/s obtained by  $A=0.0172$  m,  $f=0.5$  Hz and  $A=0.0086$  m,  $f=1$  Hz). Significant deviation from the experiment is registered.

Regarding the results of Fig. 4, it is seen that for all tested values of free area  $F$ , the changes of pressure drop coefficient  $k_p$  are more significant at lower values of interplate distance  $h$  up to  $h=0.3$ . The conclusion is that further increase of  $h$  is useless, because no energy is saved, while the number of stages in a unit of height will be reduced, which will reduce the overall apparatus efficiency. A choice of free area  $F=0.2-0.3$  seems to be a reasonable compromise from energetic point of view. Further increase of  $F$  will not save much energy, but will create more favorable conditions for formation of axial flow that will reduce mass transfer efficiency due to promotion of undesired axial mixing effects (Godfrey and Slater, 1994). This choice is supported also by the empirical experience with other types of pulsed columns, recommending values of  $F$  in this interval.

#### 5. Comparison to correlations for perforated plate columns

Among the column extractors, the most similar to our case are these with perforated plates. They are of two types – with immobile plates and pulsed flow, and with reciprocating plates and permanent flow. The first type is hydrodynamically closer to our column, which also has immobile plates with pulsed flow. Similarity with the second type can also be

assumed because of the analogous process of movement of liquid through the plate, although the source of the movement is different – flow pulsation in the first case and plate movement in the second one. There are a number of correlations for determination of pressure drop or power dissipation in column extractors with perforated plates, and it might be useful to test their applicability to columns with internals of discs and doughnuts. Below are given the most important correlations.

Thornton (1957) has proposed an expression for pressure drop  $\Delta p$  in perforated plate columns for sinusoidal pulsation of a single phase and no flow through the column:

$$\Delta p = n \frac{\rho(1-F^2)}{2C_d^2 F^2} \left( \frac{dy}{dt} \right)^2 \quad (16)$$

where  $n$  is number of plates,  $\rho$  is flow density,  $F$  is plate free area,  $C_d=0.6$  is discharge coefficient,  $dy/dt$  is instantaneous flow velocity.

Eq. (16) can be deduced from a more general expression of Jealous and Johnson (1955), if taking into account only the frictional losses. This is not a shortcoming, because it is found that for the commonly used combinations of plate geometry and intensity of agitation, the frictional component of the pressure drop is at least 2 orders of magnitude higher than the inertial component (Noh and Baird, 1984; Harikrishnan and Varma, 1992).

Hafez and Baird (1978) have used a similar expression based again on the Jealous and Johnson (1955) development.

Harikrishnan and Varma (1992) have expressed the pressure drop as a function of the relative velocity between the plate and liquid. In case of no flow, the velocity equals the pulsed velocity and their relation becomes identical to that of Thornton (1957).

All authors above assume no pressure recovery downstream of the plate. Some modifications are made by Miyauchi and Oya (1965) by accounting for the pressure recovery in the space between the plates

$$\Delta p = n \frac{\rho(1-F)(1-F^2)}{2C_d^2} \left( \frac{dy}{dt} \right)^2 \quad (17)$$

Hafez and Prochazka (1974) have given an empirical correlation for the friction losses of reciprocating plates in turbulent regime:

$$\Delta p = \frac{n[1.5 - 2.5F + F^2 + (1 - \beta^2)/\beta^2 + 0.316s/(dRe_o^{0.25})]}{(2F^2)} \left( \frac{dy}{dt} \right)^2 \quad (18)$$

where  $\beta=0.65$  is coefficient of contraction,  $s$  is plate thickness,  $d$  is diameter of perforations,  $Re_o$  refers to the velocity in the open area.

Noh and Baird (1984) have considered co-current flow in reciprocating plate Karr column. Their aim is to exploit the possibility for higher capacity offered by the co-current flow pattern. In addition to plate velocity, this correlation includes as main variable the permanent flow velocity, which is not negligible. It cannot be applied to our case (flow velocity is neglected compared to pulsed velocity) as it produces a value zero for the pressure drop.

Din et al. (2010) have modeled perforated plates as a porous medium. Their expression for pressure drop is derived for a particular case of plates with 25% free area.

$$\Delta P = 10^7 \times U - 2190.5 \quad (19)$$

Surprisingly, the pressure drop is not quadratic but linear function of the velocity  $U$ . Because of its limited validity this expression will not be used for comparative calculations.

When apply Eq. (4) for mean pulsation velocity, the term  $(dy/dt)^2$  in Eqs. (16)–(18) takes the form  $(2Af)^2$  and relations (16)–(18) refer to the mean pressure drop.

The correlations (16)–(18) can be rearranged to fit the form of Eq. (6), and corresponding expressions for  $k_p$  can be obtained. The number of plates  $n$  multiplied by plate distance  $H$  gives the total height occupied by the plates  $L$ . Thus  $n$  can be replaced by  $L/H$ . Eqs. (16)–(18) become correspondingly

$$\frac{D_c \Delta p}{\rho L} = \frac{1-F^2}{2hC_d^2 F^2} (2Af)^2 \quad (20)$$

$$\frac{D_c \Delta p}{\rho L} = \frac{(1-F)(1-F^2)}{2hC_d^2 F^2} (2Af)^2 \quad (21)$$

$$\frac{D_{1c} \Delta p}{\rho L} = \frac{1.5 - 2.5F + F^2 + (1 - \beta^2)/\beta^2 + 0.316s/(dRe_o^{0.25})}{2hF^2} (2Af)^2 \quad (22)$$

They supply expressions for  $k_p$  (the term before  $(2Af)^2$ ), which can be compared to results of Eq. (11) that are validated for discs and doughnut columns.

Concerning the only relation that shows dependence of  $k_p$  on  $Re$  (Eq. (22)), the term containing  $Re$  has rather small contribution to the total value of  $k_p$ . For example, for  $F=0.23$  and  $h=0.086$  (first line of Table 1) for  $Re=4000$ , which corresponds to  $Re_o=17,400$  at  $F=0.23$ , the value of  $k_p$  without accounting for  $Re$  is 257.70 and 257.78 with  $Re$ . Thus the influence of  $Re$  could be neglected.

Table 1 summarizes the results for  $k_p$  obtained through different correlations ((11) and (20)–(22)).

The results obtained by the correlation of Thornton (20) differ from our results (Eq. (11)) from 0.76 to 77% with occasional better fits below 10% (0.76, 2, and 8.8%). The results calculated by Miyauchi and Oya relation (21) differ from ours from 2 to 87% (fits below 10% being 2.2, 5.9, 7.9%). The deviation of correlation of Hafez and Prochazka (1974) is from 0.25 to 80%, best fits being 0.25, 3 and 7%.

The configuration  $F=0.23$ ,  $h=0.155$  (second line of Table 1) corresponds to the real column at which experimental measurements of pressure drop have been taken. As it is seen, for this case although its 23% relative deviation, Thornton equation is closer to our results, followed by that of Hafez and Prochazka. The relation of Miyauchi and Oya gives worse results, and it might be attributed to the fact, that Miyauchi has considered pressure recovery downwards the plates that happens at distance 4–8 hole diameters after the flow contraction (Green and Perry, 2007). In case of perforated plates this assumption seems realistic, because 4–8 diameters of small perforations are lesser than the interplate distance. Unlikely, in our case (plate with a single orifice 0.145 m in diameter), the orifice diameter is much bigger, and the interplate distance (0.045 m) is not large enough to allow for pressure recovery.

**Table 1 – Values of pressure drop coefficient  $k_p$  obtained by different correlations.**

| F    | h     | $k_p$                 |                                |  |  |  |  |  |
|------|-------|-----------------------|--------------------------------|--|--|--|--|--|
|      |       | Eq. (11)<br>This work | Eq. (20)<br>Thornton<br>(1957) | Relative<br>deviation<br>(11)–(20) [%] | Eq. (21)<br>Miyachi<br>and Oya<br>(1965) | Relative<br>deviation<br>(11)–(21) [%] | Eq. (22)<br>Hafez and<br>Prochazka<br>(1974) | Relative<br>deviation<br>(11)–(22) [%] |
| 0.23 | 0.086 | 498.66                | 289.14                         | 42.02                                  | 222.64                                   | 55.35                                  | 257.70                                       | 48.32                                  |
| 0.23 | 0.155 | 207.21                | 160.43                         | 22.58                                  | 123.53                                   | 40.39                                  | 142.98                                       | 31.00                                  |
| 0.23 | 0.310 | 73.73                 | 80.21                          | 8.79                                   | 61.76                                    | 16.23                                  | 71.49  | 3.04                                   |
| 0.23 | 0.380 | 54.43                 | 65.44                          | 20.22                                  | 50.39                                    | 7.43                                   | 58.32  | 7.15                                   |
| 0.23 | 0.500 | 36.15                 | 49.73                          | 37.56                                  | 38.29                                    | 5.92                                   | 44.32  | 22.60                                  |
| 0.30 | 0.086 | 412.42                | 163.29                         | 60.41                                  | 114.31                                   | 72.28                                  | 142.56                                       | 65.43                                  |
| 0.30 | 0.155 | 150.03                | 90.60                          | 39.61                                  | 63.42                                    | 57.73                                  | 79.10  | 47.28                                  |
| 0.30 | 0.310 | 45.65                 | 45.30                          | 0.76                                   | 31.71                                    | 30.53                                  | 39.55  | 13.36                                  |
| 0.30 | 0.380 | 32.18                 | 36.96                          | 14.83                                  | 25.87                                    | 19.62                                  | 32.26  | 0.25                                   |
| 0.30 | 0.500 | 20.09                 | 28.09                          | 39.79                                  | 19.66                                    | 2.15                                   | 24.52  | 22.04                                  |
| 0.43 | 0.086 | 318.87                | 71.19                          | 77.67                                  | 40.58                                    | 87.27                                  | 62.16  | 80.51                                  |
| 0.43 | 0.155 | 96.86                 | 39.50                          | 59.22                                  | 22.53                                    | 76.74                                  | 34.49  | 64.40                                  |
| 0.43 | 0.310 | 23.84                 | 19.75                          | 17.15                                  | 11.27                                    | 52.74                                  | 17.24  | 27.67                                  |
| 0.43 | 0.380 | 15.79                 | 16.11                          | 2.03                                   | 9.19                                     | 41.80                                  | 14.07  | 10.92                                  |
| 0.43 | 0.500 | 9.07                  | 12.25                          | 35.08                                  | 6.99                                     | 22.94                                  | 10.69  | 17.93                                  |

Following this logic, the relation of Miyachi and Oya should give more imprecise results. Nevertheless, his expression (21) produces more consistent results with monotonous logical evolution as depending on F and h. From Table 1 it is seen that the relative deviation becomes lower at higher interplate distance h, which creates larger space for pressure recovery. Also, the deviation becomes higher at larger plate free area F, when the conditions for pressure recovery become worse, because larger F corresponds to bigger orifice diameter, and correspondingly bigger interplate distance is needed to allow for pressure recovery.

Generally, in most cases the predictions of correlations for perforated plates differ significantly from our correlation developed especially for discs-doughnuts plates. It is not very surprising and might be expected, because there are some important differences between these two types of plates. The doughnut plates offer not many small perforations but one single opening. Although most authors have based their developments for perforated plates on the assumption that their resistance is equal to the resistance of an orifice plate with the same open area, this is shown to be not very correct because of rather different hydrodynamics – single jet contracts suddenly in a single orifice and then suddenly leaves and enlarges as single jet, while in case of sieve plates a single jet is split in multiple separate jets, and it creates deviations from pressure drop predictions based on orifice equation (Gan and Riffat, 1997; Noh and Baird, 1984). Additionally, the plates considered here are not only of orifice type (doughnut), but also of disc type forming an annular aperture. Unlikely the perforated plates, a specific flow pattern is created in disc-doughnuts columns characterized by formation of two macro-structured vortices in each stage (Angelov et al., 1998; Bujalski et al., 2005). It seems that the different flow pattern produces pressure drop specific for this plate type.

## 6. Conclusion

It is shown that at the same velocity the mean pressure drop in case of a pulsed flow in DDC is not equal to that of a permanent flow. Based on simulations with turbulent flow model, a correlation for calculation of mean pressure drop in

a pulsed extraction column with internals of discs and rings is developed as a function of stage geometry parameters and pulsation regime. The results of this study of pressure drop as depending on plate free area and interplate distance are helpful for non-experimental optimization of stage configuration in view of lesser energy consumption.

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