https://doi.org/10.3311/PPch.21914

Periodica Polytechnica Chemical Engineering, 67(2), pp. 310–315, 2023

CFD Investigation of Dry Tray Pressure Drop of Perforated Trays without Downcomer

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Received: 23 January 2023, Accepted: 22 March 2023, Published online: 12 May 2023

Abstract

The dry tray pressure drop behaviors in trays without downcomer with different inclination of holes (standard, 75°, 60° and 45°) and tray thickness (2.5, 5, and 10 mm) are investigated. The trays are investigated using computational fluid dynamics (CFD) in Ansys Fluent® software. 20 °C air was used to represent the gas phase with 20–50 m^3/h flow rates. The column there are four trays with 7 mm of hole diameter.

The CFD results determined that the higher angle of the holes with respect to the tray causes smaller dry tray pressure drop and turbulence intensity in the gas flow. Furthermore, in 75° hole inclined perforated tray and the standard hole the dry tray pressure drop is similar. From the simulation results it is also determined that in case of higher tray thickness the dry tray pressure drop is lower.

On the basis of the CFD simulation results some correlations can be determined for the calculation of the dry tray pressure drop of the different trays.

Keywords

dry tray pressure drop, trays without downcomer, trays without downcomer with inclined holes, CFD simulation

1 Introduction

Sieve tray columns are frequently used in industrial practice because of the simple geometry and low manufacturing cost. Description of the hydrodynamics of sieve trays has an important role [1–3].

The flow conditions in a column depend on the structural design, sizing of the diameter and internal structure of the equipment is based on hydraulic calculations to determine the appropriate column dimensions [4].

During the investigation of a column, the pressure drop along the length of the tower plays an important role, as it affects the efficiency of the separation and the operation of the tray. The pressure drop must be determined for each tray and the results must be summarized [1].

Significant part of the pressure drop, which is formed along the height of the column is the dry tray pressure drop. This is the pressure drop that occurs when the vapor or gas phase passes through the perforations, in this case there is no liquid phase in the system [5]. The dry tray pressure drop affects the liquid weeping phenomenon [2, 6] and it is used for the hydraulic study of the tray. The higher gas velocity means higher dry tray pressure drop [7]. This parameter is influenced by gas velocity, free hole area and tray structure, for example the hole diameter, the direction of the perforations [8, 9].

In recent years, the use of CFD for the solution of hydraulic problems has become increasingly common [10]. CFD modelling has many advantages over experimental methods, as it is relatively low cost, fast, and can model both the ideal and the real case. CFD can also be used to model tray efficiency and hydrodynamics [11]. Usually the k-ε turbulence model is used for simulating turbulence and hydraulics of a column with CFD method [12–14]. It can be an accurate method of modelling industrial problems [15].

2D and 3D CFD simulation studies to investigate the operation of sieve trays is performed by Krishna and Van Baten [1]. They found that the use of CFD techniques is an effective tool for the investigation and design of trays. Their studies have demonstrated that CFD simulations can

Cite this article as: Kállai, V., Mizsey, P., Szepesi, G. L. "CFD Investigation of Dry Tray Pressure Drop of Perforated Trays without Downcomer", Periodica Polytechnica Chemical Engineering, 67(2), pp. 310–315, 2023. https://doi.org/10.3311/PPch.21914

describe hydrodynamic changes and have shown that large diameter trays have a plug-like flow of fluid. However, variations in the diameter of the column have little effect on the height of the clear liquid and the retention of the gas phase. The authors concluded that CFD can be an efficient tool for design and modelling sieve trays [16, 17].

Rahimi et al. have worked also on 3D, two-phase CFD modelling of sieve trays. Their study was aimed at estimating the efficiency, hydraulics, and mass transfer of sieve trays. To estimate the efficiency, two trays with similar geometries, but different perforations were investigated, while the effect of the diameters of the perforations was studied. The results were compared with experimental data from distillation of a mixture of methanol and n-propanol. It was found that the tray with the smaller diameter of perforations has a liquid flow pattern closer to plug flow and a higher mass transfer rate [18].

Gesit used CFD techniques to investigate the efficiency of sieve trays using steady-state simulations. The author has concluded from his research that CFD modelling is an effective tool for the study of mass transfer via sieve trays and can be used as a suitable tool for the analysis and design of a tray [19].

Brondani et al. have presented a relationship that determines the dry tray pressure drop of a dry tray without downcomer with 2.0 mm tray thickness [20].

Zhao et al. investigated the hydrodynamics of sieve-fixed valve tray with CFD simulation. They designed a sieve-fixed valve tray with flow-guiding and the added sieve holes on the valve caps of the original trapezoid valve. In their study the pressure drop, weeping, entertainment and clear liquid height were experimented and compared in case of the two investigated types of trays. With this study they proved that CFD method can test modification of equipment and give information which could not be gained in experimental way. The CFD simulation is necessary part of designing and altering the internals of columns [21].

The hydrodynamics of an industrial scale column with 14% valve trays and air-water operation is investigated by Zarei et al. They presented empirical correlations and compared the results of experiments and CFD simulations. At this industrial scale the simulation results correlated with the experimental results [22].

The effects of the free area ratio to the efficiency of commercial-scale sieve trays with CFD simulations are studied by Roshdi et al. The results of their investigation showed that it is possible to determine the geometrical modification effects on entrainment and efficiency [23].

In this study the dry tray pressure drop is investigated in case of trays without downcomer with straight and inclined (75°, 60° and 45°) holes, furthermore in case of different tray thickness (2.5, 5 and 10 mm). CFD simulations with k-ε turbulence model was used to determine the dry tray pressure and turbulence intensity in the investigated trays with air flow at 20 °C.

2 The investigated system

Fig. 1 shows the design of the investigated system. The inner diameter of the column is 96.3 mm and the height of it is 1.02 m. In the column there are four same sieve trays without downcomer. The trays have 7 mm hole diameter, approximately free area ratio of 15% and thickness of 5 mm. Fig. 2 shows the different types of the investigated trays, these are the follows:

- with straight perforations,
- with 75° angle of inclination oblique perforations,
- with 60° angle of inclination oblique perforations,
- with 45° angle of inclination oblique perforations.

Table 1 shows the number of perforations of the investigated trays. In Table 1 A_p is the perforations area, while A_t is the tray area.

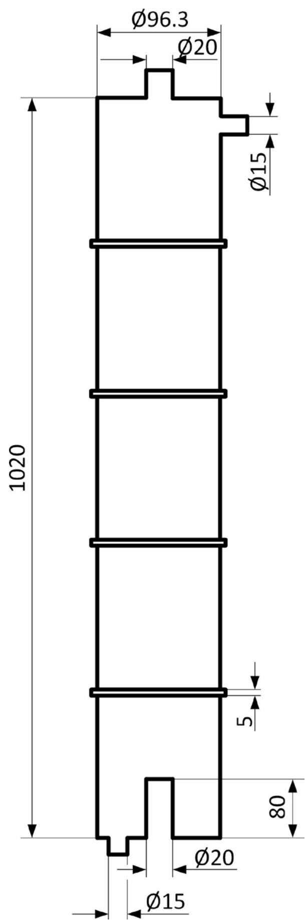

Fig. 1 Schematic figure of the investigated column

Fig. 2 Figures of the investigated trays in top and bottom view. The figures from up to down: straight perforated, 75° inclined perforated, 60° inclined perforated, 45° inclined perforated

Table 1 Parameters of the investigated trays

Type of tray	Number of perforations	A_p/A_t [%]
straight holes	28	15.7
75° inclined holes	27	15.6
60° inclined holes	24	15.5
45° inclined holes	20	15.8

The simulations were made with Ansys Fluent® software. The meshing was performed using Ansys Mesher® with a mesh size of 3×10^{-3} m containing triangular elements. A refinement of 10 layers was used along the wall at the entry and exit cross-sections and at the perforations of the trays. The flow analysis was carried out using k-ε turbulence model [24, 25].

During the mesh independence test in case of 50 m^3/h air flow, a coarser mesh has been used with approximately 3 million number of elements and a finer mesh has been used with approximately 7 million number of elements. There were no significant differences between the dry tray pressure drop values (around 0.7%), therefore in the further simulations the coarser mesh was used.

3 Results of the simulations

During the simulations in the column the flow rate of the air flow was 20, 30, 40 and 50 m^3/h. The dry tray pressure drop and the turbulence intensity of the different type of trays was investigated and the Fig. 3 is demonstrated the results of these studies.

From the results of the simulations (Fig. 3) it is determined that the tray with 45° inclined holes had the highest dry tray pressure drop, while the tray with straight holes had the smallest. From the viewpoint of the dry tray pressure drop the tray with straight holes and with 75° inclined holes are almost the same.

During operation, it is necessary to try to minimize pressure drops. However, it can be seen from the results that in case of higher pressure drops the turbulence intensities are also higher, which suggests that higher mass transfer constants may be obtained, which could mean higher efficiency of mass transfer.

Fig. 4 shows the representations of the turbulence intensity of the investigated trays in case of 50 m^3/h flow rate of air. It can be determined that in case of the trays with

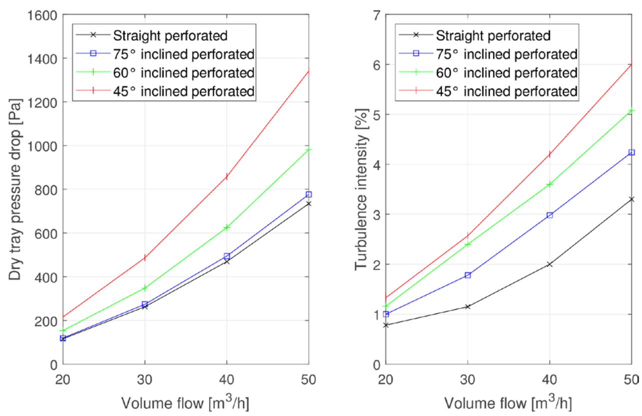

Fig. 3 Column dry tray pressure drop and turbulence intensity for different trays

60° and 45° inclined holes the resulting flow pattern is not appropriate. In these two cases, the maldistribution of the gas flow is experienced what can cause lower efficiency of the separation due to inadequate phase contact.

3.1 Correlations of dry tray pressure drop

Based on the literature [13, 20] a correlation for each type of investigated trays was determined, which can be used to determine the dry tray pressure drop of a tray at air flow rate of 20–50 m^3/h, a tray thickness of 5 mm and a ratio of the perforations and tray area of 15%.

In the correlations to determine the dry tray pressure drop (ΔP_d) [Pa] the density of the gas flow (ρ_g) [kg/m^3] and the velocity of the gas flow in the perforations of the tray (u_{tray}) [m/s] were taken into consideration.

The correlation of trays with straight holes:

$$\Delta P_d = 0.890 \rho_g u_{tray}^{2.005}. \quad (1)$$

The correlation of trays with 75° inclined holes:

$$\Delta P_d = 0.902 \rho_g u_{tray}^{2.020}. \quad (2)$$

The correlation of trays with 60° inclined holes:

$$\Delta P_d = 1.120 \rho_g u_{tray}^{2.021}. \quad (3)$$

The correlation of trays with 45° inclined holes:

$$\Delta P_d = 1.749 \rho_g u_{tray}^{1.985}. \quad (4)$$

3.2 Dry tray pressure drop in case of different tray thickness

In case of the trays with straight and with 75° inclined holes the influence of the tray thickness was investigated too. The setting of the simulations was the same as in the previous cases, the flow rate of air was modified between 20 and 50 m^3/h. The dry tray pressure drop was investigated for the 2.5-, 5- and 10 mm tray thickness. The results shows (Table 2) that the thinner the tray, the greater the dry tray pressure drop in the column. This is in contradiction with the Fanning-equation [26], but the dry tray pressure drop of the tray is determined by the sudden decrease or increase in cross-section during the inlet and outlet of the tray.

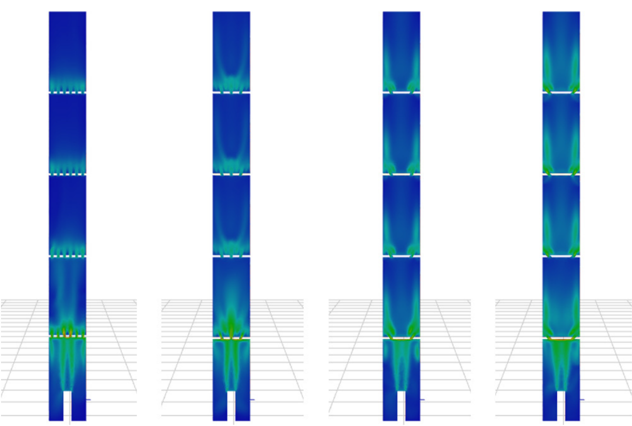

Fig. 4 Representation of turbulence intensity for different trays in case of 50 m^3/h flow rate of air. The sectional figures from left to right: trays with straight holes, 75° inclined holes, 60° inclined holes, 45° inclined holes

Based on the literature [27, 28] and considering both the thickness of the trays and the diameter of the perforations, the correlations of the dry tray pressure drop of the tray could be written for the investigated types of trays.

Thorat et al. [29] studied that the ratio of the tray thickness and the diameter of the hole has a large effect on the resistance coefficient. In case of thin trays ($t_t/d_h \leq 1$) the vena contracta of the gas jet arises above the tray and consequently there is a pressure recovery. Furthermore, in case of thick trays ($t_t/d_h > 1$) the vena contracta is in the hole. Therefore, for thin trays have a higher pressure drop than for thick trays [29].

Taking into consideration the tray thickness the following correlations could be used to predict the dry tray pressure drop in the case of tray with straight holes:

$$\Delta P_d = 0.531 \rho_g \frac{u_{tray}^{2.005}}{C}. \quad (5)$$

In case of tray with 75° inclined holes:

$$\Delta P_d = 0.504 \rho_g \frac{u_{tray}^{2.022}}{C}. \quad (6)$$

The C constant parameter is calculated with the following correlation (Eq. (7)):

$$C = a \left(\frac{d_h}{t_t} \right)^b. \quad (7)$$

In different cases the a, b and C constants have the values, which are summarized in the Table 3, d_h is the hole diameter and t_t is the tray thickness.

Equations (1)–(4) and (5)–(7) were determined with regression calculations and fitting exercise with least square method to predict the relationships from the CFD simulation results.

4 Conclusions

In this study perforated trays without downcomer with straight and inclined holes were investigated with CFD simulation from the viewpoints of the dry tray pressure drop and turbulence intensity. From simulation results a correlation is determined for each type of trays, which were investigated to predict the dry tray pressure drop of them.

Table 2 Dry tray pressure drop in case of different tray thickness

Flow rate [m^3/h]	Dry tray pressure drop [Pa]					
	Tray with straight holes			Tray with 75° inclined holes		
	t_t = 2.5 mm	t_t = 5 mm	t_t = 10 mm	t_t = 2.5 mm	t_t = 5 mm	t_t = 10 mm
20	125.59	115.99	109.92	128.22	119.47	108.28
30	280.99	262.40	245.60	294.09	274.09	247.66
40	496.43	469.41	439.15	516.93	494.64	441.41
50	787.24	734.31	692.31	819.66	776.40	690.34

Table 3 Values of constants for the dry tray pressure drop correlations considering the tray thickness

Type of tray	Tray thickness [mm]	*a*	*b*	*C*
	2.5			0.5765
Straight holes	5	0.6284	−0.08372	0.6110
	10			0.6475
	2.5			0.5337
75° inclined holes	5	0.6031	−0.11680	0.5787
	10			0.6275

From the results it is determined that the trays with 45° and 60° inclined holes have an inappropriate flow pattern which could mean a lower efficiency of separation. However, higher dry tray pressure drop values and higher turbulence intensity also occur in the case of these two types of trays, which could mean higher mass transfer rates.

From the results it is also determined that the dry tray pressure drop is almost the same in the cases of the trays with straight and with 75° inclined holes. For these trays, the dry tray pressure drop is also investigated in the case of different tray thickness. From these investigations it is concluded that the smaller tray thickness results in higher dry tray pressure drop. The new suggested calculation of the dry tray pressure drop equation consider the tray thickness too.

Acknowledgement
This research was supported by the European Union and the Hungarian State, co-financed by the European Regional Development Fund in the framework of the GINOP-2.3.4-15-2016-00004 project, aimed to promote the cooperation between the higher education and the industry.

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