Experimental Studies on the Conical Cap tray Performance

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Abstract

In the present study, experimental investigations about the hydrodynamics of the conical cap tray (ConCap tray) have been carried out. The ConCap tray is an innovative and novel type of cap trays. The effect of the different weir height (2.5, 5 and 7 cm) on the weeping, entrainment and the total pressure drop for the ConCap tray was measured, compared and correlated. The hydraulic experiments were carried out in an industrial scale simulator rig with an inner diameter of 1.2 m which has two test trays (ConCap tray) and two chimney trays. It was found that the weir height affects only on the pressure drop. The recommended weir height for the ConCap tray must be 2.5 cm because of observed spray flow regime on the tray and experimental results in different weir height which shows no effect on the weeping and entrainment rates. Moreover, the hydraulic behavior of the tray in the lower operating limits was also investigated.

Keywords

Conical gap tray;
Hydrodynamic;
Weeping;
Entrainment;
Weir height.

1. Introduction

Commercial and technical maturities make tray towers as widely used fractionating devices in separation technologies. To increase their capacity and efficiency, it is needed to improve their design. Nye trays [1], MD trays [2], Swirltube, ConSep [3-5], Ultra-Frac [6, 7], CoFlo [8, 9], UOP SimulFlow [10, 11], JCTP-Coflow [12] and Chimney type centrifugal trays [13] are among the novel design that have been developed and installed in distillation towers. In the same manner, a significant research task is developing new column equipment to improve unit capacity and economic benefits [14, 15].

Lately, a novel cap tray which is a novel case of cap trays called conical cap tray (ConCap tray) was presented in our previous works [16, 17]. The image of the Conical Cap is given in Fig. 1. Tray details have been described in our previous article. That article indicated that the new tray has some advantages of the bubble cap tray such as well turn down ratio, while the pressure drop of the tray is acceptable and is not high like the bubble cap tray. The pressure drop of the ConCap tray is in the scope of the conventional trays such, as valve tray [16]. The weeping and entrainment rates of the tray are acceptable in comparison with bubble cap and valve trays [16]. In the our previous articles, the hydro-

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Figure 1. The picture of the ConCap tray.

dynamic behavior of a tray carried out without any optimization on the tray geometry specification such as weir and riser height, hole area percentage and etc. The ConCap tray design was based on the conventional tray design procedure (such as a bubble cap tray). But, in the following, it is important to investigate the effect of geometry parameter to find the best tray design.

The present work is about an investigation of the ConCap tray hydraulic behavior in the different operating conditions. The experiments have been performed at an industrial sclale simulator rig with 1.2 m diameter for hydraulic measurements [16]. This simulator rig has two test trays (ConCap tray) and two chimney trays above and under the test trays and capable to measure the pressure drop, weeping and entrainment of the ConCap tray at different gas (air) and liquid (water) rates. Table 1 shows characteristics of the ConCap tray. Hydraulic change of the ConCap tray in the lower operating limits was investigated. One of the most important variables to design and operation of distillation and absorption columns is the amount of liquid height on trays. It influences tray efficiency, the pressure drop, operating window and flow regime on a tray [18]. So, in this paper three weirs height, 2.5, 5 and 7 cm were investigated through experiments on the tray hydrodynamics. The pressure drop, weeping and entrainment for the ConCap tray were measured and compared with each other. The consequences for the ConCap tray were correlated by a regression analysis method for the pressure drop and weeping in different weir heights.

2. Hydraulic Change of the ConCap Tray in the Lower Operating Limits

The pressure drop is the main hydrodynamic variable to show the tray behavior inside the column. Fig. 2 shows the tray pressure drop versus weep percent for various gas velocities at liquid flow rate of 74.4 (m^3/h)/m for the ConCap tray. It is obvious that as gas flow rate was reduced, the tray pressure drop was also reduced and finally weeping is started due to small pressure drop. Consequently the clear liquid height was also decreased by weeping and this again makes a more pressure drop. As shown in the Fig. 2, at constant liquid flow rates, the slope variation of the pressure drop curve can be specified as a graphical weep point (GWP). As seen in the Fig. 2, GWP was ocuured at the F_S=1.1m/s(kg/m^3)$^{0.5}$. From this point until

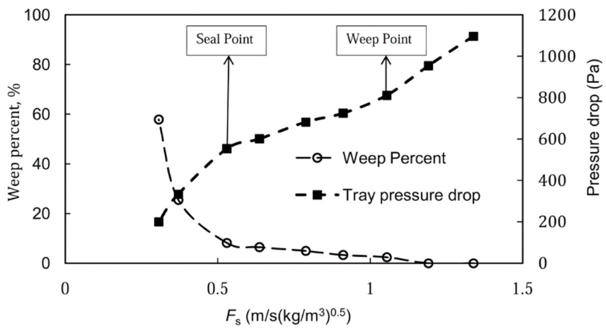

Figure 2. The tray pressure drop and weeping rate versus F-factor at liquid flow rate of 74.4 m^3/m · h.

Table 1. ConCap tray specification.

Tray diameter, mm	1200	Riser height, mm	55
Tray spacing, mm	610	Percentage of hole area	14%
Weir length, mm	730	Active area, mm^2	1007760
Downcomer clearance, mm	40	Top radius of the cones, mm	20
Riser diameter, mm	90	Bottom radius of the cones, mm	63
No. of caps	21	Vertical distance between the cones, mm	50
Tray thickness, mm	2	Weir height (adjustable), mm	50

seal point (F_S=0.54m/s(kg/m^3)$^{0.5}$), the slope of the pressure drop is near constant. This region, called weeping range. The weeping rate in the weeping range is acceptable and has not trouble problem in performance. In the lower gas flow rate, the slope of pressure and weep percent changed again. This point is called the seal point. At the seal point, weeping condition changes to rain. Gas flow rates lower than seal point are called raining region. Mechanism of weeping is changed from drop weeping to continuous weeping and in worse condition convert to dumping. The seal point of the ConCap tray is accrued in the lower gas flow rates than conventional trays [19]. Therefore, the pressure drop curve and weeping behavior have a closed relation together. The slop variation is the same for the tow parameters. Consequently, the weeping behavior can be supervised with the pressure drop measuring without any weeping calculation.

Fig. 3 shows the variation of liquid level in the downcomer of the ConCap tray versus weeping rate for various gas flow rates and Q_L=74.4(m^3/h)/m. As expected, Figs. 2 and 3 show weeping rate was increased when the gas flow rate (F_s) was decreased. As it is seen, when the gas flow rate was increased, the liquid level in the downcomer was also increased.

The higher gas flow rate causes the higher pressure drop and then, the clear liquid height and weir liquid loads was also increasing. Therefore, the backup level in the downcomer is essentially independent of the tray spacing. The back up level in the downcomer is important for the gas and liquid residence time required. This higher liquid level leads to a good gas and liquid contact time and bubbling formation. On other hand, the liquid head on the tray decreases with reducing pressure drop by the wept liquid through the tray holes. As a consequence, the tray pressure drop is an important parameter in the liquid level in the downcomer and hydraulics.

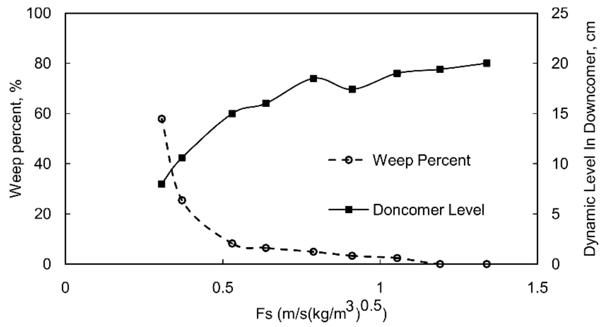

Figure 3. The liquid level in the downcomer and weeping rate versus F-factor at liquid flow rate of 74.4 m^3/m · h.

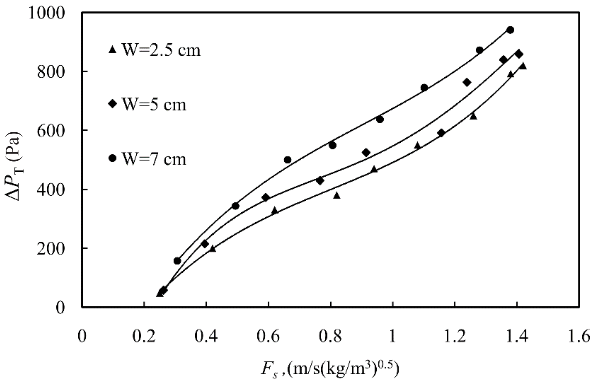

Figure 4. Total pressure drop of the ConCap tray versus F-factor at liquid flow rate of 29.9 m^3/m · h.

3. Effect of the Weir Height on the ConCap Tray Performance

The outlet weir provides a desired liquid level and subsequent proper gas-liquid contact and bubble formation on a conventional tray. It affects the efficiency and pressure drop through this way. The effects of weir height on the pressure drop, weeping and entrainment for the ConCap tray will be discussed. The experiments carried out in different liquid rates, 29.9, 44.4, 60 and 74.4 (m^3/h)/m of weir length and gas flow rate in terms of F-factor between 0.2 to 1.5 m/s(kg/m^3)$^{0.5}$. The experimental liquid loads were 29.9, 44.4, 60 and 74.4 (m^3/h)/m of weir length and gas flow rate in terms of F_s in the range of 0.2 to 1.5 m/s(kg/m^3)$^{0.5}$.

3.1. Effect of the weir height on the pressure drop

The ConCap tray pressure drop was studied at weir heights of 2.5, 5 and 7 cm. Fig. 4 illustrates the result of the weir height on the total pressure drop at low (29.9 (m^3/h)/m) and high liquid flow rates (74.4 (m^3/h)/m), respectively. It can be seen that the total pressure drop increases when the weir height is increased. These behaviors are similar with other conventional trays. When the weir height was increased, the clear liquid height of the tray was also increased which leads to increased the pressure drop. In other hand, despite the conventional trays, this higher pressure drop does not caused by the better contact between the gas and liquid on the tray, because of the different gas and liquid pathway on the Cone of the tray. Therefore, higher weir height has a negative effect on the tray performance.

The following correlations were obtained by regression analysis. Fitting the data gave Equation 1 for the pressure drop, ΔP_T, which is depends on the weir height and flow rates.

$$\Delta P_T=394F_S^{\,2}+2.1275Q_L+22.3W \qquad R^2=0.91 \qquad (1)$$

3.2. Effect of the weir height on the weeping

Liquid weeping through the holes reduces the tray efficiency since it reduces contacting time between gas and liquid on the tray.

Fig. 5 demonstrates the effect of the weir height on the weeping rate at low and high liquid rates. It can be understood that the variation in the weir height has no significant effect on the weeping rate. In general, in conventional trays, when the weir height was increased, the clear liquid height and weeping rate were also increased, but in the ConCap tray the riser height limits effect on the weir height. The height of the riser is 5.5 cm and it prevents from the weeping of the liquid.

The weeping data have been correlated by plotting the weep flux versus Fr^1 for conventional trays [20]. The same procedure was employed for the ConCap tray. The Froude number, Fr, based along the hole gas velocity is:

$$Fr = U_h\left(\frac{\rho_G}{g h_{cl}\rho_L}\right)^{0.5} \qquad (2)$$

h_{cl} is the clear liquid height, which was approximated from the total and dry pressure drop difference. The weep flux ,WF, is defined as:

$$WF = \frac{weep\ rate\ (m^3s^{-1})}{A_T} \qquad (3)$$

From a linear regression, the best correlation for the weep flux was achieved:

$$WF=0.0044Fr^{-1}-0.0004W-0.0006 \qquad R^2=0.92 \quad (4)$$

3.3. Effect of the weir height on the entrainment

Fig. 6 illustrates the effect of the weir height on the entrainment at 74.4 m3/m · h liquid flow rate. 2.5, 5 and 7-cm weir height were investigated. Results show that the weir height has negligible effects on the entrainment rates. The spray regime was observed in the entrainment conditions. Under the spray regime conditions, liquid hold up is independent of weir height [21]. Therefore, the weir height has a small effect on the entrainment.

In conventional trays which operate in the spray regime (for example, in vacuum towers), low weir heights (2.5 to 5 cm) are suitable. Thus, the height of 2.5 cm for the weir is recommended for the ConCap tray in these operating conditions. Higher weir height has more pressure drop and its consequence on the liquid hold up is not considerable and also has not any influence on the weeping rate.

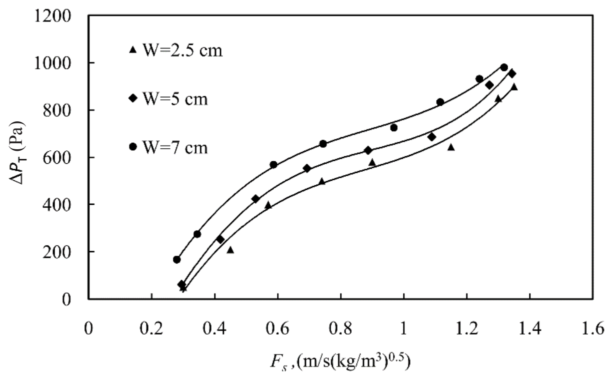

Figure 5. Total pressure drop of the ConCap tray versus F-factor at liquid flow rate of 74.4 m^3/m · h.

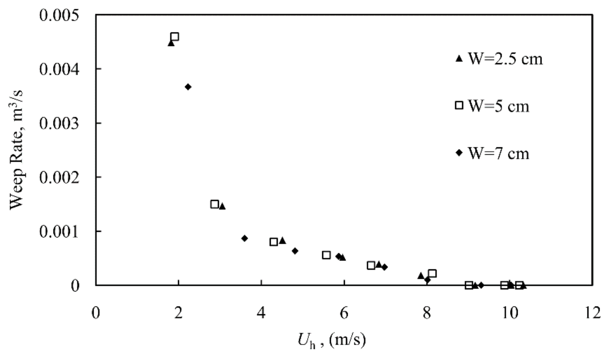

Figure 6. Weeping rates of the ConCap tray versus hole gas velocity at liquid rate of 29.9 m^3/m · h.

4. Conclusion

The ConCap tray is a new cap tray and good knowledge about this novel type of tray is necessary. The influence of weir height and various operating conditions on the ConCap tray were investigated. The experiments were carried out in a simulator rig with a diameter 1.22 m. Results show the weir height on the ConCap tray affects the pressure drop of the ConCap tray, but its effects on the weeping and entrainment is negligible. The recommended weir height for the ConCap tray can be 2.5 cm because of observed spray flow regime on the tray and experimental results in different weir height which shows no effect on the weeping and entrainment rates. Experimental results confirm that the pressure drop on the tray has a significant influence on the tray's hydraulics such as weeping, clear liquid height and downcomer back up. Further studies in the various geometries of the ConCap tray, for example, combine it with centrifugal structure, are essential and it's remained for future works.

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Nomenclature

A	Cross section of the cone, m^2
A_T	Total hole area, m^2
a	Speed of sound
e	Entrainment rate, kg of liquid entrainment rate per kg of total gas flow rate
Fr	Froude number
F_s	F-factor = $V_S\sqrt{\rho_G}$, (m/s(kg/m^3)$^{0.5}$)
g	Acceleration due to gravity, m/s^2
h_{cl}	Clear liquid height, m
M	Mach number, ratio of speed of gas in the cone and the speed of sound
$\dot{m}$	Mass flow rate, kg/s
Q_L	Liquid flow rate across tray, liquid flow rate per weir length, (m3/h)/m
R	Gas constant, 8.31 J/(mol K)
R^2	Coefficient of determination
r	Volume fraction
T	Temperature, K
t	Time, sec
V_S	Superficial gas velocity, m/s
U_h	Hole gas velocity, total gas flow rate per total riser hole area, m/s
WF	Weep flux, (m^3/s)/m^2
W	Weir height, cm
ΔP_T	Tray pressure drop, Pa
ρ_G	Gas density, kg/m^3
ρ_L	Liquid density, kg/m^3
γ	Specific heat ratio, the ratio of the heat capacity at constant pressure to heat capacity at constant volume
μ	Viscosity, Pa.s

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