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Experimental Study of Hydrodynamic Characteristics of Improved Sieve Tray with Push Valves

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ABSTRACT

This paper addresses an experimental investigation in the hydrodynamic behavior of a modified slotted sieve tray. Slotted sieve tray (Push valve sieve tray) is a sieve tray in which the push valves have been utilized on the tray deck to eliminate liquid gradients and non-uniformity of liquid distribution on the tray. The air-water system was used in an industrial scale experimental rig with an internal diameter of 1.2 m. The dry pressure drop, total pressure drop, weeping and entrainment of the modified slotted sieve tray were measured and compared with the conventional sieve tray. Weeping and pressure drop data for the tray were correlated. Results show better hydrodynamic behavior of the modified push valve sieve tray than a conventional sieve tray. This modification can be an effective and inexpensive way to debottleneck sieve tray columns, because it has good characteristics of sieve tray and eliminates the disadvantage of sieve tray by increasing the operating window of it.

1. Introduction

Distillation is a separation process of major importance in the chemical industries and is known as the energy-intensive process. In order to minimize the investment costs, more accurate design is required for trays of gas-liquid contactor devices [1]. So, it is necessary to improve or enhance performance characteristics of distillation and absorption trays. It is important to consider the loss in the tray efficiency as the size of the tray is increased to accommodate larger liquid and vapor loads.

Over the past few years, many designs of new trays have been developed. Nye trays [2], MD trays [3], Swirltube, ConSep [4-6], Ultra-Frac[7, 8], CoFlo [9, 10], UOP SimulFlow [11, 12], JCTP-Coflow [13], ConCap tray [14] and Chimney type centrifugal trays [15] are among the new designs that have been developed and used successfully in industrial processes. However, most of the high capacity trays cannot deliver the same efficiency as well-design conventional trays such as sieve

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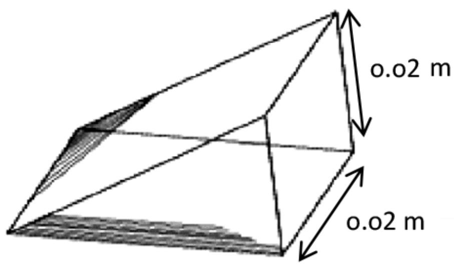
and valve trays [16], hence improving existing sieve or valve trays is more desirable [17-20]. Valve trays are widely used in distillation column, especially in the cases with high gas flow rates. Several studies have been done in developing a different valve tray design. Valve trays can be divided into two main categories, namely fixed-valve trays and floating-valve trays. The new fixed-valve trays such as MVG trays [21-24] have several unique advantages such as the horizontal dispersion of the vapor into liquid on the tray, thereby less entrainment and increased capacity of the tray. The MVG tray can be used for debottlenecking capacity-limited column, and for debottlenecking those towers that may be only efficiency limited, especially at low pressures. In fact, this tray is particularly cost efficient for those debottlenecking jobs where only tray deck replacement is needed [23].

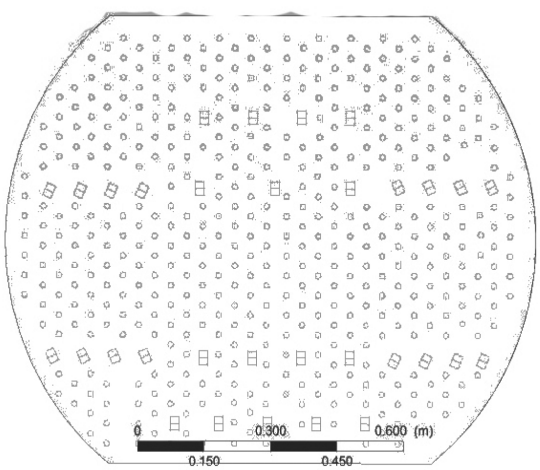
Qian et al. [25] innovated a new high-powered adaptive valve tray (HAVTH) which integrates the high performance of fixed-valve tray and float-valve tray. The capacity of the high-powered adaptive valve trays in comparison with Glitsch V1 float-valve trays, can be increased by 20-30 %. The tray efficiency is also increased by about 10 %, and the pressure drop is decreased by about 20 %. Li et al. introduced the novel FGS-VT, a tray with combination of sieve and valve tray, with high efficiency and operation flexibility, large capacity, low pressure and manufacturing cost [26]. Recently, Brahem et al. investigated the hydrodynamic of valve tray and proposed some correlations [27, 28].

On the other hand, sieve trays have remained as common mass transfer devices in oil and gas industries and they have kept their own good characteristics. The simple geometry of the sieve tray causes liquid leakage through the deck holes at low vapor rates [29]. Sieve trays have very good efficiency, but the operating window of this type of tray is small. The operating window or performance diagram of the tray can be defined by the vapor and liquid rates. At low values of vapor rate, the liquid weeped, while at a high vapor rate, the entrainment phenomenon occurred. Moreover, the existence of a considerable difference in liquid depth between inlet and outlet weir as well as the existence of liquid stagnation and back mixing are a cause of reduction in the tray efficiency and subsequently its poor operation.

One method to eliminate liquid gradients and non-uniformity of liquid distribution in the sieve tray is by means of a directional valve or push valve which has been suggested in some patents and papers [30-34]. A push valve or vapor directional valve, Fig. 1(a), is an opening through a tray deck that preferentially directs vapor in a concentrated direction in an effort to influence the liquid flow on the tray deck (like stationary valve on the jet tray). Figure 1(b) shows the push valves layout on the sieve tray. The liquid may be boosted across the tray without relying upon the hydrostatic gradient by orienting the apertures in the desired direction of the liquid flow. The push valves transmit momentum of vapor flow to the liquid flow. This causes movement of liquid, thus the stagnation points and back mixing can be eliminated in the proper arrangement of the push valves on the tray [35]. However, less attention has been paid to the hydraulics of this type of tray. Hu et al. [36] experimentally determined the hydraulic gradients of the small-hole sieve trays with and without slots. A two-layer model was suggested to describe the gradient of clear liquid height on these trays. This model can help to manipulate the hydraulic gradient by changing the slot open area ratio. The proposed model has significant limitations because of a rectangular tray and constant physical property was used.



(a)



(b)

Figure 1. (a) Schematic of a push valve (b) Tray deck configuration of the push valve sieve tray.

In the present study, we have used the computational fluid dynamics results of our previous work [35] in order to design push valves on the sieve tray. The design of push valves on the sieve tray including parameters such as number of push valves, their location and arrangement and their total hole area is inflexible and depends on the operating condition. The ratio of the push valves' open area to the total hole area has been considered an important parameter in push valve designs. A satisfying balance between factors such as pressure drop, bubble formation and hydrostatic gradient is very important to achieve the best design. In that CFD model it was found that the ratio of the push valves' open area to the total hole area is approximately 14.31 % which is considered as a design parameter [35]. In this article, experimental studies on the pilot plant were used to better understand the effects of the push valve on the sieve tray. At the beginning, a sieve tray was tested and then push valves were installed in it. Hydrodynamic behaviors of the trays are also investigated. Dry and total pressure drop, weeping and entrainment of the sieve tray were measured and compared with the sieve tray with 32 push valves by 14.59 % push valves' open area to the total hole area.

2. Experimental setup

The 1.2 m diameter column simulator rig is shown in Fig. 2. The test column was constructed from four 1.2 m diameter trays of stainless steel 410 including weeping chimney tray (2), weeping test tray (1), entrainment test tray (1) and entrainment chimney tray (2) from the bottom to top of the column, respectively. The liquid entering the tower was provided from a liquid storage tank (4) using a centrifugal pump (5), via a distributor in the inlet downcomer (7) to the entrainment test tray (1). Liquid from the weeping test tray (1) returned to the feed tank (4). The air flow from the blower (3) was measured by using a calibrated pitute tube. Dry tray pressure drop was measured by blocking off the clearance under the downcomers. The pressure drop of each tray was measured by the manometers connected to the pressure connections. The first and the second pressure connection taps were at 10 cm below and 40 cm above the test tray, respectively. The pressure drop and the weeping rate of the weeping test tray and the entrainment rate of the entrainment test tray were reported in this article. The liquid weeping from the weeping test tray was collected in the weeping chimney tray (2). The entrained liquid from the air out of the entrainment tray was trapped in a 125 mm thick demister pad (12) after passing through the entrainment chimney tray. The entrained liquids that were dropped down on a demister pad were collected in the entrainment chimney tray and were drawn by a pipe for measurement. Experiments were carried out at atmospheric pressure and 25 °C temperature. Characteristics of the sieve and push valve sieve tray (slotted sieve tray) are shown in Table 1.

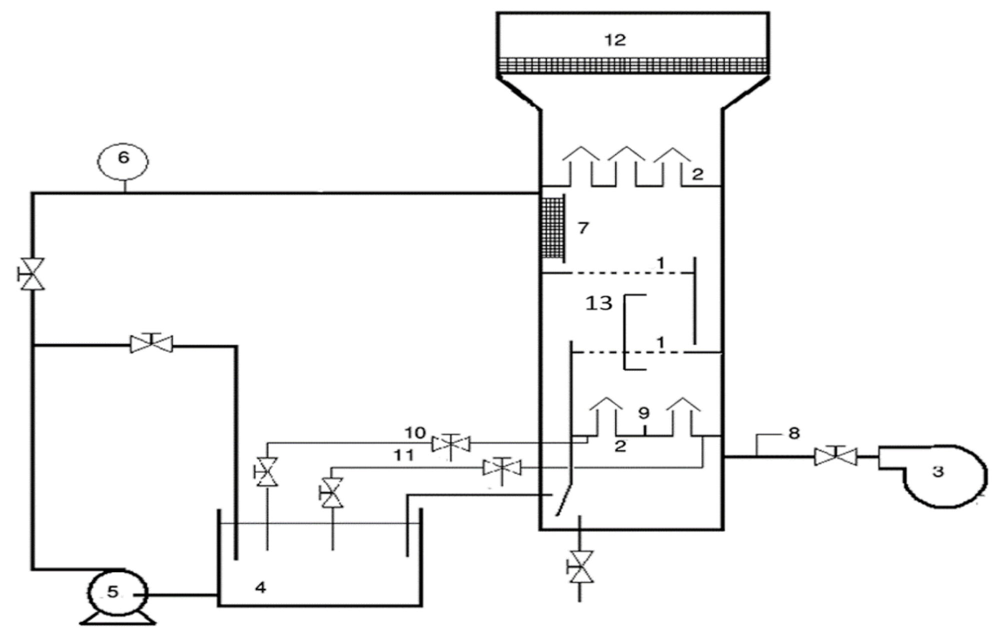


Figure 2. Schematic diagram of the experimental setup.

Table 1
Trays specifications of experimental set up.

	Tray diameter (m)	Hole diameter (mm)	Plate active area (m^2)	Hole area (%)	Number of holes	Number of push valve	Weir height (mm)	Push valve area (m^2)	Ratio of the push valves' open area to the total holes area
Sieve tray	1.2	12.7	0.9156	7.039	560	0	50	0	-
Push valve sieve tray	1.2	12.7	0.9156	7.039	480	32	50	0.003255	14.59 %

3. Results and discussion

3.1. Dry pressure drop

The dry tray pressure drop as a function of the F-factor for sieve tray and push valve sieve tray is shown in Fig. 3. It is obvious that dry pressure drop of push valve sieve tray is more than sieve tray. Dry pressure drop directly depends on the geometry of the tray. Push valves on the tray cause a change in the direction of the air and consequently increase the dry pressure drop.

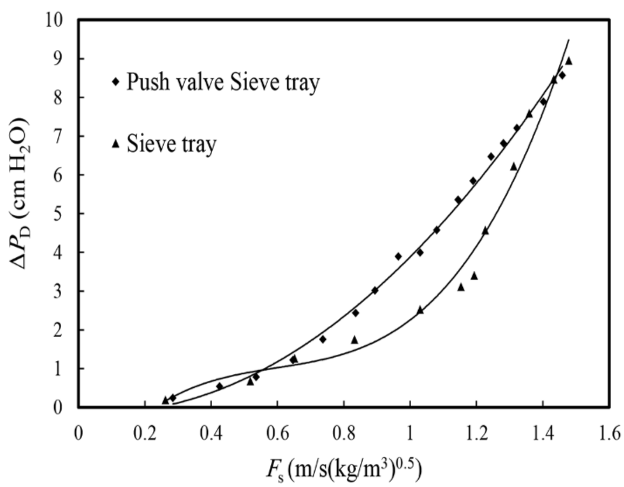


Figure 3. The dry pressure drop of sieve and push valve sieve tray.

3.2. Total pressure drop

Total pressure drop for both of the trays versus increasing gas velocity for liquid loading, 29.9, 45 and 60 m^3/m.h are depicted in Figs. 4, 5 and 6 respectively. The trend of the total pressure drop of push valve sieve tray is the same as sieve tray; however, the dry pressure drop is more than sieve tray.

The total pressure drop across a tray is the sum of the pressure drop across the disperse unit (dry tray pressure), and the pressure drop through the aerated mass. The presence of liquid may affect the way the vapor flows into the holes, so altering the discharge coefficient; some of the holes may be partially blocked by liquid, and variations in the local liquid head may cause local fluctuations in the vapor flow, and a fluctuating vapor flow has a larger pressure drop than an equal steady flow [29].

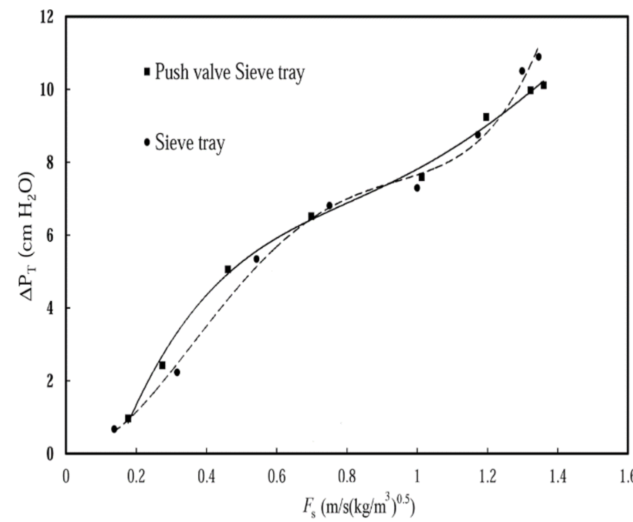


Figure 4. The total pressure drop of sieve and push valve sieve tray at Q_L=29.9 m^3/m.h.

The push valves can affect the liquid distribution on the tray and eliminate back mixing and stagnant point. Back mixing and stagnant liquid on the tray cause a larger pressure drop than uniform liquid distribution. So the uniform liquid distribution on the tray can compensate the larger dry pressure drop of push valve sieve tray and total pressure drop of push valve sieve tray is obtained the same as sieve tray.

The fit of the data gave Eq. (1) for variation of pressure drop, ΔP_T, with gas and liquid flow rates.

$$\Delta P_T = 3.8422\ F_S^2 + 0.021\ Q_L + 3.262$$
$$R^2 = 0.92 \quad (1)$$

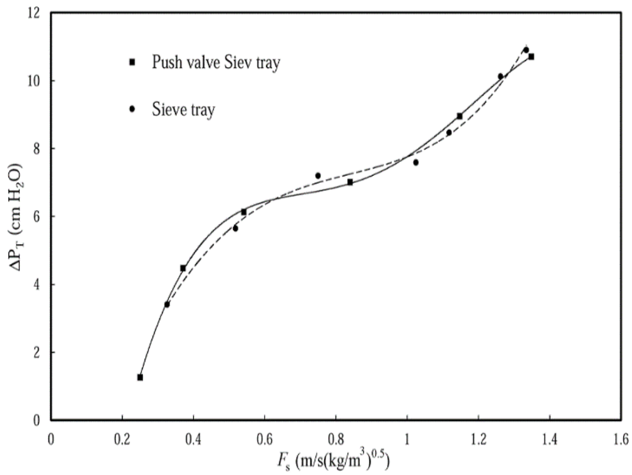


Figure 5. The total pressure drop of sieve and push valve sieve tray at Q_L=45 m^3/m.h.

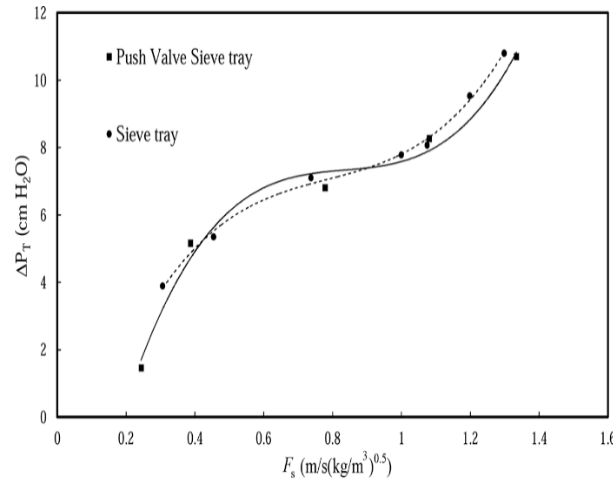


Figure 6. The total pressure drop of sieve and push valve sieve tray at Q_L=60 m^3/m.h.

3.3. Weeping

Through the experiments, the different values of hole gas velocity in the range of 5-19 m/s and different liquid rates were used. Figures 7, 8 and 9 show weeping rate as a function of hole gas velocity at liquid rates of 29.9, 45 and 60 m^3/m.h, respectively. It is obvious that the weeping rate of push valve sieve tray is less than sieve tray in each operating condition. One of the advantages of using the vapor to influence liquid flow on the tray is that trays need to take some amount of vapor side pressure drop to maintain enough resistance to prevent weeping of liquid through the tray orifices.

Weeping occurs when the pressure drop of the vapor passing through the tray deck is insufficient to support the liquid. Then, the turn-down ratio is increased when the dry tray pressure drop is increased. In sieve tray, by using a small fractional hole area, the weeping rate is decreased. The difficulty is that an excessively high pressure drop is obtained at design conditions. The possibility of spray regime operation and excessive entrainment at design conditions are other points to consider. Push valve sieve tray with the same fractional hole area produces more dry pressure drop than sieve tray though it does not have the mentioned problems.

It can also be observed that the effect of gas flow rate of the liquid weeping is more than the liquid flow rate. Moreover, by decreasing the gas velocity, the weep point is achieved. As it is seen, the weep point of push valve sieve tray is less than sieve tray. The weep point is obtained where the weeping phenomenon starts for a specific hole's gas velocity.

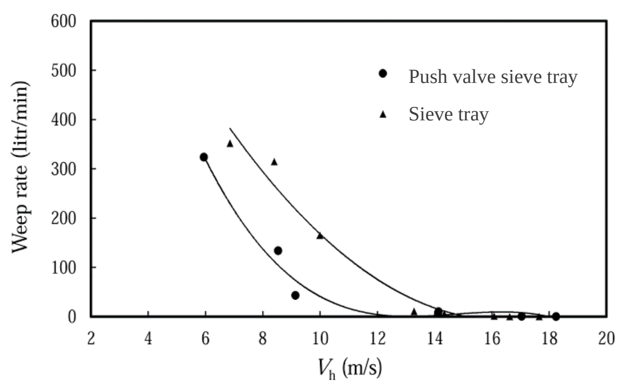


Figure 7. Weep rate vs. hole gas velocity at liquid flow rates of 29.9 m^3/m.h for sieve and push valve sieve tray.

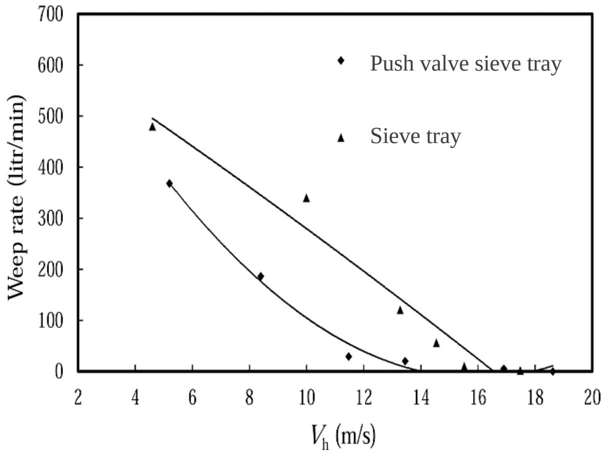


Figure 8. Weep rate vs. hole gas velocity at liquid flow rates of 45 m^3/m.h for sieve and push valve sieve tray.

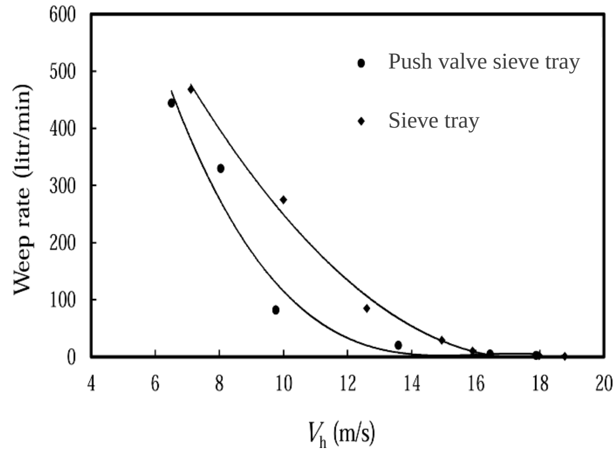


Figure 9. Weep rate vs. hole gas velocity at liquid flow rates of 60 m^3/m.h for sieve and push valve sieve tray.

3.3.1. Weeping correlations

Locket and Banik [16] correlated weeping data by plotting the weep flux versus Fr^{-1} for the sieve tray. For the Push valve sieve tray, the same process was used. The Froude number, Fr, based along the hole gas velocity is [16]:

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

The weep flux, *WF*, is defined as [16]:

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

The clear liquid height, h_{cl}, was calculated from the difference between the total and dry pressure drops. The best correlation for the weep flux which was obtained from linear regression is:

$$WF = 0.0047Fr^{-1} - 0.0029$$
$$R^2 = 0.92 \quad (4)$$

3.4. Uniformity of weeping

The differences between the inlet and outlet weeping show the vapor maldistribution. Weeping from the inlet half has a more serious effect on tray efficiency than weeping from the exit half [37]. Measurements of weeping from the half closer to liquid inlet and the half close to the outlet weir were made. It was found that weeping was not uniformly distributed over the tray and excess of weeping could occur over the inlet half or over the exit half depending on the prevailing conditions. Figures 10 and 11 show the weep rate from the inlet, the exit halves and total weep rate of the push valve sieve tray at liquid loads of 45 and 60 (m^3/m.h). The figures show relatively uniform weeping in each liquid flow rate, although the inlet half weep rate is slightly more than the exit half. As the liquid load was increased, the inlet and exit half weep rates become closer to each other.

Relatively uniform weeping in the push valve sieve tray prevents vapor maldistribution and excessive liquid gradient on a tray. Vapor maldistribution and excessive liquid gradient have a detrimental effect on tray efficiency and in severe cases can lead to premature entrainment flood by a self-acceleration mechanism [38, 39].

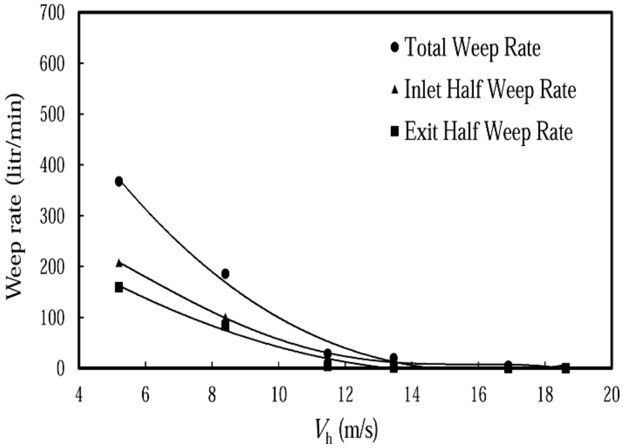


Figure 10. Inlet half, exit half and total weep rate of the push valve sieve tray at liquid flow rate of 45 m^3/m.h.

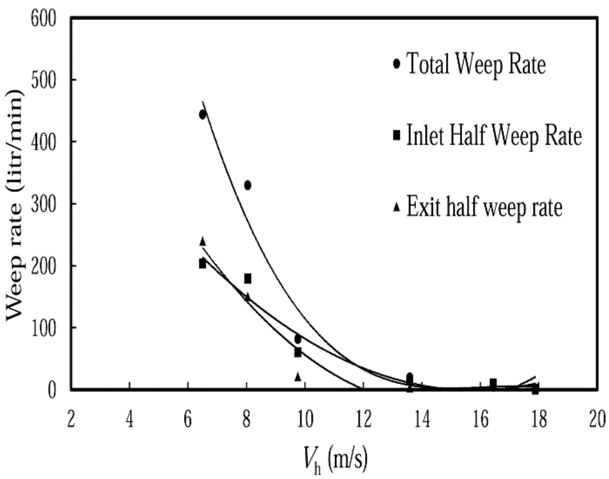


Figure 11. Inlet half, exit half and total weep rate of the push valve sieve tray at liquid flow rate of 60 m^3/m.h.

3.5. Hydraulic change of trays in weeping

The pressure drop is a main hydraulic parameter to identify the two phase behavior inside the tower. Figures 12 and 13 show the variation of tray pressure drop and weep percentage for different gas flow rates at a constant liquid flow rate of 60 m^3/m.h for both the sieve and the push valve sieve tray respectively. It is revealed that by decreasing gas flow rate, the tray pressure drop becomes smaller and finally weeping is triggered due to small pressure drop. Therefore, the clear liquid height of the tray decreases by weeping and once more causes the pressure drop to reduce.

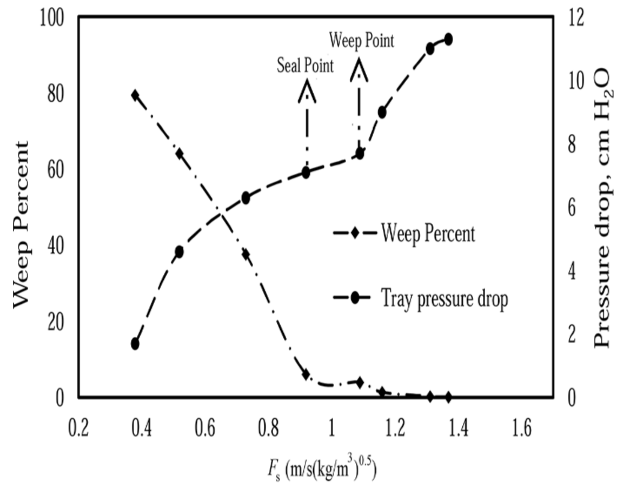


Figure 12. Behavior of the pressure drop and weeping rate at different Fs and Q_L= 60 m^3/m.h for the sieve tray.

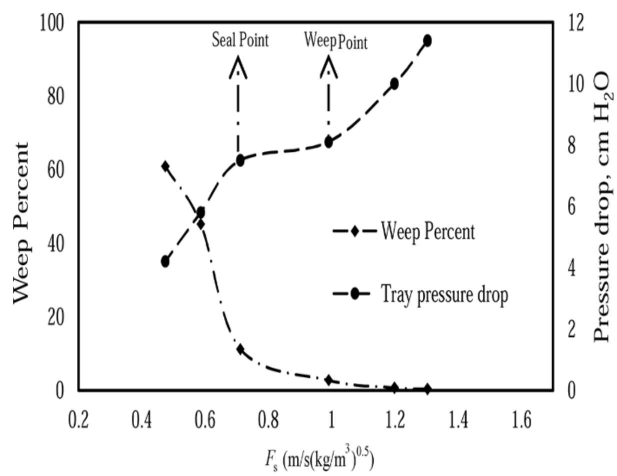


Figure 13. Behavior of the pressure drop and weeping rate at different F_S and Q_L= 60 m^3/m.h for the push valve sieve tray.

As shown in Figs. 12 and 13, a graphical weep point (GWP) can be defined from the change in slope of the pressure drop curve at constant liquid rates [37]. From this point until seal point, the slope of pressure drop is almost constant. This region is called weeping range. The weeping rate in the weeping range is acceptable and has no trouble in operation. In lower gas flow rate, the slope of pressure and weep percentage 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 caused dumping. As it is seen in Figs. 12 and 13 seal point of push valve sieve tray is accrued in lower gas flow rate than sieve tray. For sieve trays the weeping rate increases rapidly at low gas flow. For similar operating conditions, the weeping rate for a push valve sieve tray can be an order of magnitude lower than the corresponding weeping rate for a sieve tray with the same open area.

3.6. Entrainment of the sieve and the push valve sieve tray

Figure 14 compares sieve and push valve sieve trays entrainment at liquid loads of 44.4 m^3/m.h. The figure showed that the entrainment of the sieve tray was more than that of the push valve sieve tray at various gas flow rates. The push valves transmit momentum of vapor flow to the liquid flow on the tray. This causes movement of liquid, thus the stagnation points and back mixing can be eliminated in the proper arrangement of the push valves on the tray. But the excess momentum of gas in the sieve tray caused entrainment. Therefore, push valve sieve tray solves the lower operating window of sieve tray in addition to uniform liquid distribution on the tray.

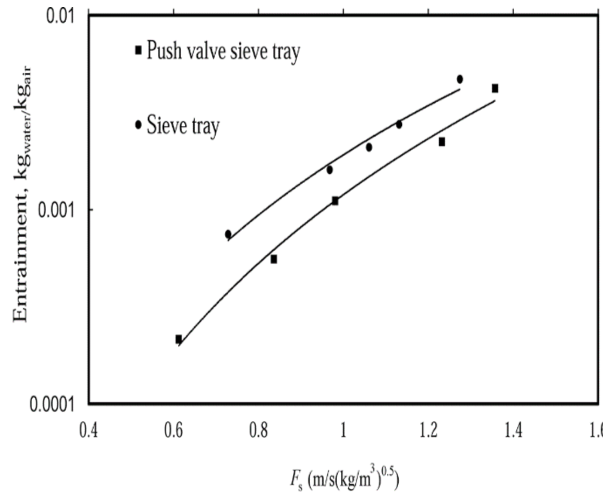


Figure 14. Entrainment vs. F_S at liquid flow rates of 44.4 m^3/m.h for sieve and push valve sieve tray.

4. Conclusions

Experimental results of the optimum push valve sieve tray show some advantages of push valve sieve tray than sieve tray: lower weeping and entrainment and same pressure drop, uniform liquid distribution, uniform weeping, uniform gas distribution. Uniform liquid distribution and eliminating stagnant zone may also cause the fouling problem in the push valve sieve tray to be reduced. Turn-down ratio of the push valve sieve tray is more than sieve tray because of lower weeping. Uniform liquid distribution causes uniform weeping, uniform bubbling activity and eliminate vapor cross flow. Although the dry pressure drop of push valve sieve tray is more than sieve tray, the total pressure drop of both of them is the same. Another important result is that excessive momentums of gas in this optimum push valve sieve tray improve liquid distribution on the tray. In the sieve tray, the excessive momentum causes entrainment and reduces efficiency of the tray.Moreover, push valves have such simple structures which are mechanically strong and inexpensive. It is a good choice to revamp the existing tray column because it has good characteristics of the sieve tray and eliminates the disadvantage of sieve tray by increasing the operating window of the tray.

Acknowledgment

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Nomenclature

A_T	total hole area [m^2].
F_S	F factor $=V_S\sqrt{\rho_G}$ [m/s(kg/m^3)$^{0.5}$].
Fr	Froude number.
h_{cl}	clear liquid height [m].
Q_L	liquid flow rate across tray, liquid flow rate per weir length [m^3/m.h].
V_S	gas phase superficial velocity based on the bubbling area [m/s].
WF	weep flux [(m^3/s)/m^2].
ρ_G	gas density [kg/m^3].
ρ_L	liquid density [kg/m^3].
V_h	hole gas velocity [m/s].
ΔP_D	dry tray pressure drop [cm H_2O].
ΔP_T	total pressure drop [cm H_2O].

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