A COMPUTATIONAL FLUID DYNAMICS AND AN EXPERIMENTAL APPROACH TO THE EFFECTS OF PUSH VALVES ON SIEVE TRAYS

Rahbar Rahimi[1], Ali Zarei[1], Taleb Zarei[1], Hamed Naziri Firoozsalari[2], Mortaza Zivdar[1]

[1]Chemical Engineering Department, University of Sistan and Baluchestan, Zahedan, P.OBox.98164-161, Iran, Rahimi@hamoon.usb.ac.ir

[2]Research and Development center, Azar Energy Co., Tabriz, Iran, info@azarenergy.com

Abstract

In this study to improve hydraulic performance of sieve tray, push valves have been utilized on the sieve tray deck. The hydraulic effects have been investigated using computational fluid dynamics simulation and experimentation. The computational fluid dynamics (CFD) model used 1.213 m diameter Solari and Bell [1] sieve tray. In the CFD model it is 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. The experimentally investigated sieve tray had 7.039 % hole area and 32 push valves. The ratio of push valves' open area to the total hole area was 14.59%. The dry pressure drop, total pressure drop and weeping were measured. The experimental results of this modified sieve tray and the sieve tray without push valves were compared with each other. Results show that better hydrodynamic behavior of the modified push valve sieve tray than conventional sieve tray.

Key words: sieve tray, push valves, pressure drop, weeping, CFD

1. Introduction

Distillation is a separation process of major importance in the chemical industries, and known as the energy- intensive process. In order to minimize the investment costs, more accurate designs for trays of gas-liquid contactor devices are required [2]. That is to improve or enhance performance characteristics of trays of distillation and absorption columns. It is important to consider the decrease in the tray efficiency as the size of the tray is increased to accommodate larger liquid and vapor loads [3]. Over the past years, many different designs of new trays have been developed. However, most of these high capacity trays cannot deliver the same efficiency as well-designed conventional trays such as sieve and valve trays [4], hence improving existing sieve or valve tray is more desirable. 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 cause of reduction in the tray efficiency and its poor operation.

One method of eliminating liquid gradients and non uniformity of liquid distribution in the large diameter column is by means of a directional valve or push valve which has been suggested in some patents and papers [3, 4, 5, 6], But design parameters for push valve on the tray deck are not reported. A push valve or a vapor directional valve, Figure 1, 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. By orienting the apertures in the desired direction of the liquid flow, the liquid may be boosted across the tray without relying upon hydrostatic gradient. The push valves transmit momentum of vapor flow to the liquid flow. This causes movement of liquid, thus elimination of the stagnation points and by proper arrangements elimination of back mixing. In this study push valves are used on sieve trays to improve their hydraulic behavior, and attempts were made to obtain optimum opening area of push valves on sieve trays using 3-dimensional geometry for computational fluid dynamics (CFD) simulation. A sieve tray and a sieve with the push valves having optimum openings were compared experimentally for their performances.

2. CFD Approach

The dispersed gas and the continuous liquid phases at steady state condition are modeled in the Eulerian frame work as two interpenetrating phases, having separate transport equations. The details of equations of CFD model illustrated in our previous work [7]. The standard k-ε turbulence model with

the default model coefficients are used for simulating turbulence behavior of the liquid phase. turbulence models have not been used for the gas phase.

The key to proper CFD model is the estimation of the momentum exchange, or drag coefficient between the gas and liquid phases [8]. The drag coefficient has been estimated using the drag correlation of Krishna et al. [9] for both of the sieve and push valve sieve tray as because the same flow regime was observed at experimentally. A CFX 10.0 software package was used to solve the equations for the two fluid mixtures.

2.1 Tray Geometry and mesh generation

Due to the existence of symmetry plane for the purpose of reduction of computational effort only half of the tray with exit downcomer was simulated. Sieve tray geometry is based on the 1.213 m tray diameter of Solari and Bell [1] sieve tray. Different arrangement of push valves on the sieve tray was simulated. One of the simulated push valves was shown in figure 1. The specification of the different arrangements of push valves on the sieve tray was depicted on the table 1.
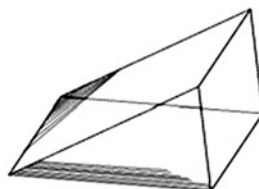

Figure 1. Simulated Push valve on the sieve tray

Unstructured meshes have been used in these simulations because of the complexity of the push valve and a large number of holes on the tray. The number of nodes on a tray is about 80000.

Table 1. Specification of each arrangement of push valve sieve tray which was simulated

Tray No.	1	2	3	4	5	6	7	8	9
Number of push valves on the half of sieve tray	42	36	28	24	18	14	12	8	4
ratio of the push valves' open area to the total holes area	52%	47.36%	40.2%	35.66%	28.94%	23.8%	19.3%	14.31%	8%

2.3 Wall and Boundary Conditions

A parabolic profile is assumed for the liquid inlet velocity. The outlet specification will be in agreement with the specification of inlet where only one fluid was assumed to enter. A no-slip wall boundary condition was specified for the liquid phase and a free slip wall boundary condition was used for the gas phase. At the plane of symmetry, the normal component of velocity is zero and the gradient of the other variable in the transverse direction are taken to be zero.

2.3 Velocity Distribution

The simulations were performed at liquid flow rates of 0.0178 and 0.00694 m3/s and gas flow rates with Fs factors equal to 0.462, 0.801, 1.015 and 1.464 m/s(kg/m^3)$^{0.5}$,but only liquid velocity of one of operating condition was shown in this article (Figure 2). The sieve tray model validated with the experimental data of Solari and Bell [1] in our previous work [7]. It was found that the agreement between the CFD model results and experimental data were satisfactory.

Having established the applicability of CFD sieve models [9], it is employed for sieve trays that have push valves since the push valves do not change the flow regime considerably. The best configuration of push valve sieve tray is tray No.8 as seen at Figures. Simulation shows at F_s=0.462 and Q_L=0.0178 the effect of push valves are not significant and various arrangements have almost little effect on the liquid velocity on the tray because of the momentum which was transferred from gas to liquid stream is insufficient. As the vapor velocity was increased, push valves have been shown more effect on the liquid velocity. The stagnant zone was eliminated at corner of the tray. (Figure 2)
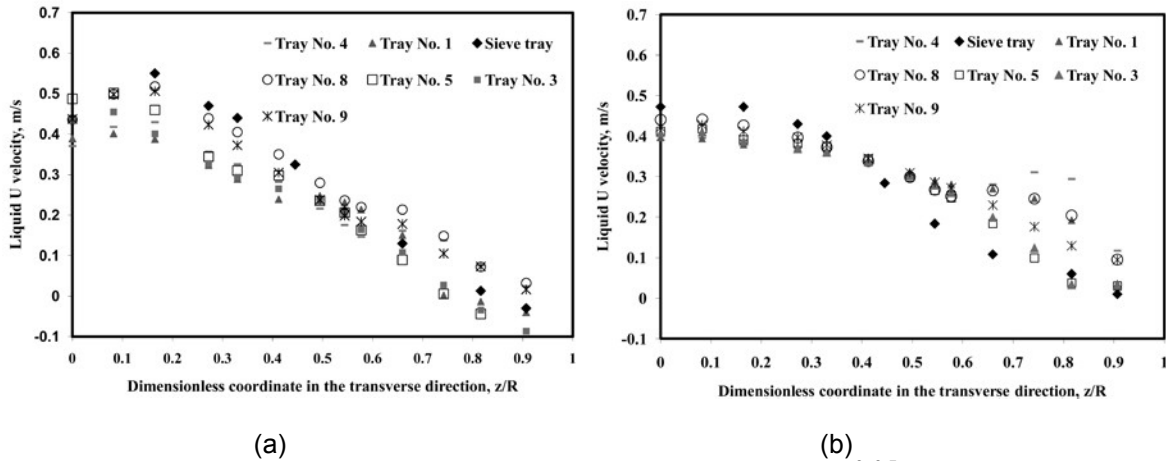

(a)   (b)

Figure 2. Liquid velocity profile, $Q_L = 17.8 \times 10^{-3} m^3 / s$, $F_S = 0.801$ m/s(kg/m³)$^{0.5}$: (a) upstream profile; (b) downstream profile

At very high gas rate, the momentum transfer to liquid stream is high and at Push valve zones on the tray a shock on the liquid velocity was observed and liquid velocity increase significantly. The mechanical structure and function of the push valve cause to pressure drop in the gas stream more than conventional orifice. As the number of push valves on the tray was increased, the pressure drop also increased. This CFD model could not predict the total pressure drop because of the thickness of tray was not simulated. Additional insight into liquid flow pattern behavior predicted by the CFD model can be gained with the aid of velocity vectors. Vectors on the sieve tray and tray No. 8 were compared with each other (Figure 3). The liquid vectors on the tray No. 8 are more uniform than liquid flow on the sieve tray.
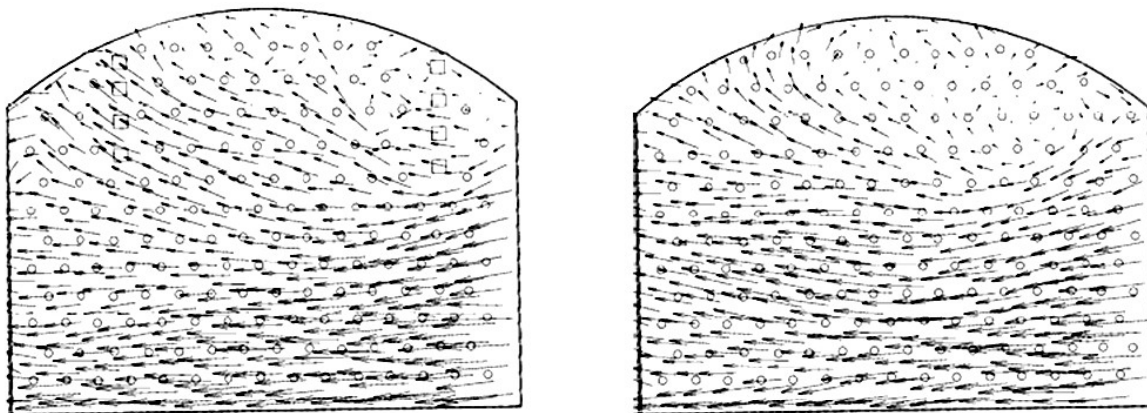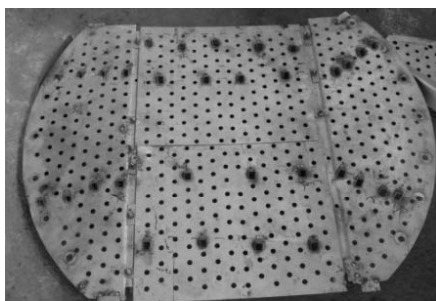

Figure 3. : Liquid velocity vectors at 38 mm above the tray deck, $Q_L = 17.8 \times 10^{-3} m^3 / s$, $F_S = 0.801$ m/s(kg/m³)$^{0.5}$

3. Experimental Approach

In an experimental approach, the hydrodynamic behavior of a sieve tray and a push valve sieve tray, which has 14.59% ratio of the push valves' open area to the total holes area, were compared with each other. The specifications of those trays are given in table 2. The photograph of the push valve sieve tray is shown in Figure 4a.

3.1 Experimental Setup

The 1.2-m diameter column simulator rig is shown in Figure 4b. The air flow was measured by using a calibrated pitot tube. The test column itself was constructed from four 1.2 m diameter sections of stainless steel 410, and it has 3 trays. The bottom tray, tray 1, was a chimney tray which collected the weeping liquid from a test tray, tray 2. Tray 2 and tray 3 were the push valve sieve tray and the simple sieve tray, respectively.

(a)

(b)

Figure 4. Photograph of a) Push valve sieve tray, b) column simulator rig

The liquid to the trays was supplied from a liquid storage tank, via a distributor in the inlet down- comer of the top sieve tray, tray 3, using a centrifugal pump. Liquid from the bottom tray returned to the feed tank. The data of the test trays, tray 2 and 3 were reported in this article.

Table2. Specifications of test trays

	Tray diameter	Hole diameter	Plate active area	hole area%	Number of holes	Number of push valve	Weir height	Push valve area	ratio of the push valves' open area to the total holes area
Sieve tray	1.2m	12.7mm	1.0078 m^2	7.039	560	0	50mm	0	-
Push valve sieve tray	1.2m	12.7mm	1.0078 m^2	7.039	480	32	50mm	0.003255 m^2	14.59%

3.2 Dry Pressure Drop

The dry pressure drop as a function of the F- factor for sieve tray and Push valve sieve tray are shown in Figure 5a. It is obvious that dry pressure drop of push valve sieve tray is more than sieve tray.

3.3 Total Pressure Drop

The data of the total pressure drop for both of the trays, with respect to increasing gas velocity at liquid loading, 45 m^3/mh are depicted in Figure 5b. The trend of the total pressure drop of push valve sieve

tray is the same as the sieve tray; however the dry pressure drop for the push valve tray is more than that for the simple sieve tray.

The total pressure drop across a tray is sum of the pressure drop across the disperser unit, (dry tray pressure), and the pressure drop through the aerated mass [10]. 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 [11].

As mentioned in CFD simulation, the push valves can affect the liquid distribution on the tray and eliminate back mixing and stagnant point. Back mixing and stagnation of liquid on the tray are among the causes of pressure drop of liquid flow on the tray. So the uniform liquid distribution on the tray can compensated for the higher dry pressure drop of push valve sieve tray. Therefore the total pressure drop of push valve sieve tray nearly equals to the simple sieve tray.
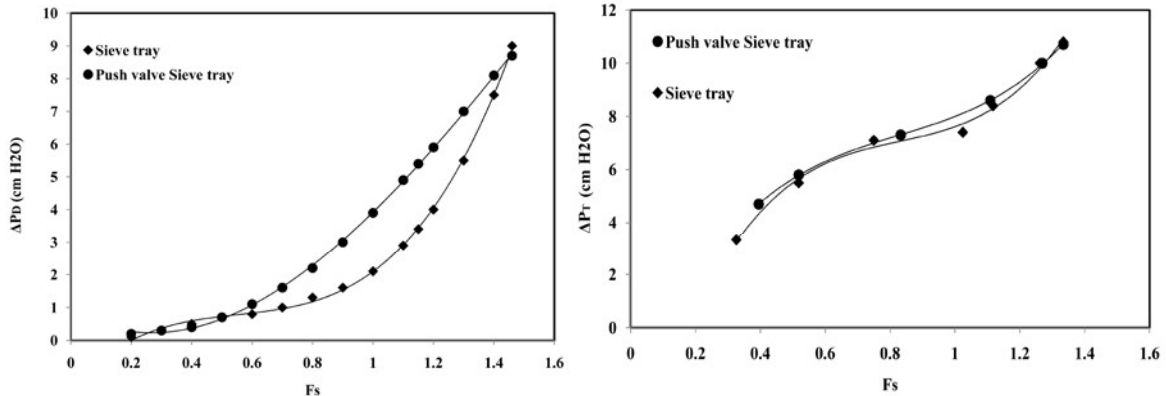

Figure 5. a) Dry pressure drop, b) Total pressure drop

3.4 Weeping

Figure 6 shows weeping rate as a function of hole gas velocity at liquid rates of 45 m^3/mh. It showed that the weeping rate of push valve sieve tray is less than sieve tray. One of the advantages of using vapor to influence liquid flow 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.
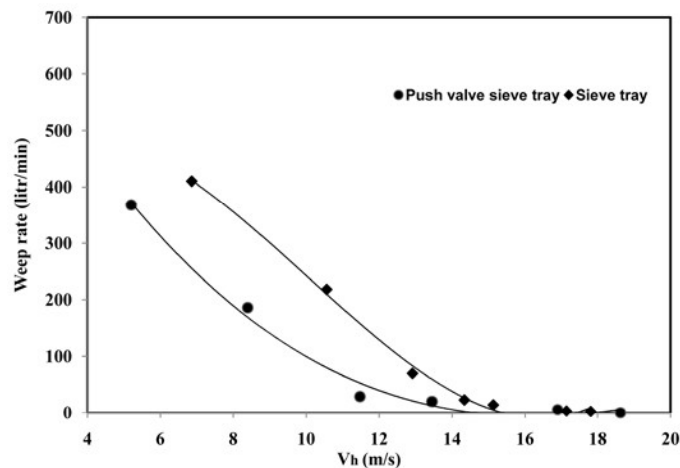

Figure 6. Weeping rate of sieve and push valve sieve tray at liquid rate of 45 m^3/mh

Weeping occurs when the pressure drop of the vapor passing through the tray deck is insufficient to support the liquid. Therefore, by increase of pressure drop the liquid turndown ratio increases. At design stage reducing the hole diameter of sieve tray reduces the weeping rate but increases the pressure drop. The possibility of spray regime operation as well as excessive entrainment is a point to consider at design stage. Though, push valve sieve tray with the same fractional hole area as the simple sieve tray produced more dry pressure drop than the sieve tray but did not show increase of weeping rate, entrainment and possibility of change of the flow regime to spray regime.

4. Conclusion

In this article, to achieve the design of push valve on the sieve tray, CFD and an experimental approach were employed. The design of push valves on the sieve tray is inflexible and depends on the operating condition. The ratio of the push valves' open area to the total holes area has been considered as important parameters in push valves designs. A satisfactory balance between factors such as pressure drop, bubble formation and hydrostatic gradient is very important to achieve the best tray designed.

Push valves have simple structures and are mechanically strong and inexpensive to construct. It is a good choice in revamping of existing tray column. Turndown ratio of the push valve sieve tray is more than sieve tray because of lower weeping. Uniform liquid distribution causing uniform weeping, uniform bubbling activity and eliminate vapor cross flow. However, the dry pressure drop of push valve sieve tray is more than sieve trays, but the total pressure drop of both trays are the same.

Nomenclature

F_S [m/s(kg/m^3)$^{0.5}$]   F factor=$V_S \sqrt{\rho_G}$

Q_L [m^3/s]   Liquid volumetric flow rate

z   [m]   Coordinate position in the transverse direction to liquid flow across tray

R   [m]   Radius of the tray

V_S [m/s]   Gas phase superficial velocity based on the bubbling area,

ρ_G [kg/m^3]   Gas density

V_h [m/s]   Hole gas velocity

ΔP_D [cm H$_2$O]   Dry tray pressure drop

ΔP_T [cm H$_2$O]   Total pressure drop

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