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CFD and experimental studies on the effect of valve weight on performance of a valve tray column

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ABSTRACT

In the present study, the volume of fluid (VOF) method implemented in the commercial CFD package, FLUENT6.2 has been used to model the gas–liquid flow in a valve tray column. The effect of valve weight has been investigated using three valves having different weights. An experimental Perspex column equipped with a single valve tray, a weir and two downcomers has been used. A fluctuating plate has been utilized for measuring the quality of gas distribution inside the liquid phase. In order to prove the repeatability and consistency of the measurements, the results were analyzed using two-stage nested designs. Bubble size distributions obtained from photographs confirm that more bubble dispersions can be obtained using heavier valves with cost of higher pressure drops, which is quantified by interface–pressure drop performance. The CFD predictions, using upward momentum integral (UMI) parameter, also show that the produced gas–liquid interface increases by employing heavier valves.

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1. Introduction

Mass transfer tray columns are gas–liquid contact devices that are widely used in the oil refining and chemical industries (Branan, 1976). Their design, performance and optimization are therefore thoroughly studied topics. In a trayed column, liquid flows down the column through downcomers and then across the tray deck, while vapor flows upward through the liquid inventory on the tray.

Several well known trays have been proposed for use in these columns. Sieve trays were in widespread use since 1950 (Wijn, 1996). Distillation columns provided with sieve trays were shown to enable much higher column throughputs than columns with bubble-cap trays, which had been in use before. The leakage of liquid through the holes upon lowering the vapor flow rate is one of the operating limits in sieve trays. As sieve tray was introduced commercially in the chemical industries, some research was devoted to this topic and the valve tray was proposed. A valve tray is a sieve tray with large holes, having a disc mounted over each hole, which can move. At a sufficiently high vapor flow rate, the valve is lifted by the vapor flow and the holes will be opened. In contrast, as the vapor flow decreases, the disc return back and closes off the hole and stops the liquid leakage.

Gas and liquid interaction on the tray may generate certain regimes, depending on loads and physiochemical properties of both and these regimes, in turns, determine how the fluids will behave. Hence, the gas–liquid interface and the efficiency of trays are strongly affected by fluid hydrodynamics upon them. Numerous studies were carried out to understand the gas–liquid hydrodynamics on the trays and the effect of various parameters on the efficiency of these devices. Wijn (1996) investigated the role of downcomer layout on the large-diameter trays. He developed a model based on the multi-branch/multi-cell approach to predict the effect of downcomer positioning patterns on the tray efficiency. He reported that various downcomer layout patterns had significant effect on the efficiency. In continuing his study (Wijn, 1998), he described the lower operating flow rate limits in the sieve and valve tray columns. The author presented a model for predicting the weeping range and their effects on the column efficiency. His model included the simultaneous solution of two equations describing the liquid flow across the tray and over the outlet weir, as well as countercurrent liquid flow through the free hole area of the tray. He claimed that the model could be used for calculating the gas flow rate of the weep and seal point. He also reviewed the two-phase flow regimes on the trays describing the mechanisms of liquid flow over outlet weirs of distillation and absorption trays (Wijn, 1999). Rao, Goutami, and Jain (2001) presented a method that used the tray efficiency matrix directly in simulations. The tray efficiency matrix used in the simulation was obtained from point efficiency matrix. They used the direct incorporation of efficiency matrix in the Naphtali Sandholm method (1971)

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and reported that their modified method had better convergence characteristics than the original Naphtali Sandholm method for distillation, absorption and extraction columns. Wang, Li, Wozny, and Wang (2003) proposed a model to express the startup behaviors of batch columns starting from an empty cold state. They verified their model through experiments on a pilot batch plant with a bubble-cap tray column to separate a methanol/water mixture.

Due to progresses in computer hardware and software and consequent increase of the calculation speed, the Computational Fluid Dynamics (CFD) modeling technique would be a powerful and effective tool for understanding the complex hydrodynamics in many industrial processes. Mehta, Chuang, and Nandakumar (1998) analyzed the liquid phase flow patterns on a sieve tray by solving the time-averaged governing equations of mass and momentum for the liquid phase. In their study, interactions with the vapor phase were taken into account using the interphase momentum transfer coefficients determined from empirical correlations. The two-phase flow behavior on a sieve tray column was studied by Yu, Yan, You, and Liu (1999) using a two-dimensional model. They focused on the description of the hydrodynamics along the liquid flow path while variations in the direction of gas flow along the height of the dispersion were ignored. van Baten and Krishna (2000) developed a CFD model for describing the hydrodynamics of sieve trays. They modeled the gas and liquid phases in the Eulerian framework as two interpenetrating phases. The interphase momentum exchange coefficient was estimated based on the Bennett, Agrawal, and Cook (1983) correlation. In their study, several three-dimensional transient modelings were carried out for a 0.3 m diameter sieve tray by varying the gas superficial velocity, the column weir height and liquid loads. Their CFD model reflected chaotic tray hydrodynamics and revealed several liquid circulation patterns, which had true three-dimensional characteristics. They reported that the predicted clear liquid height obtained from their models was in good agreement with the Bennett correlation.

Gesit, Nandakumar, and Chuang (2003) employed the commercial CFX package to predict the flow patterns and hydraulics of a commercial scale 1.22 m diameter air–water sieve tray. In their investigation, the velocity distributions, clear liquid height, froth height, and liquid holdup fraction in froth were predicted for various combinations of gas and liquid flow rates. In their model, each phase was treated as an interpenetrating continuum having separate transport equations and interaction between the two phases was considered via an interphase momentum transfer. They claimed that CFD could be used as a valuable tool in tray design and analysis. A CFD model using the commercial CFX code was introduced by Hoffmann, Ausner, Repke, and Wozny (2005) in order to model two and three-phase transient film flow in packed towers. An Euler–Euler algorithm for multiphase calculations with free surfaces was used. Similar to the VOF method, averaged phase fractions inside the finite volume cells and the surface tension was implemented in the model. The turbulence modeling was not taken into account due to the relatively low range of the Reynolds number in the simulation, which was less than 350. Farmer, Pike, and Cheng (2005) outlined the numerical models available for analyzing complex processes having flow instabilities and complicated geometries such as spray combustion, acoustic waves and transient start-up. Breach and Ansari (2007) derived a numerical method to model dynamically varying vapor–liquid phase equilibrium for non-ideal binary systems by augmenting the existing constitutive equations of the CFD. Mass transfer during condensation and vaporization was modeled via equivalently varying source and sink terms. The mass transfer was governed by chemical potential at the liquid–vapor interface. Equilibrium was assumed at the phase boundary during transient mass transfer prior to steady state conditions.

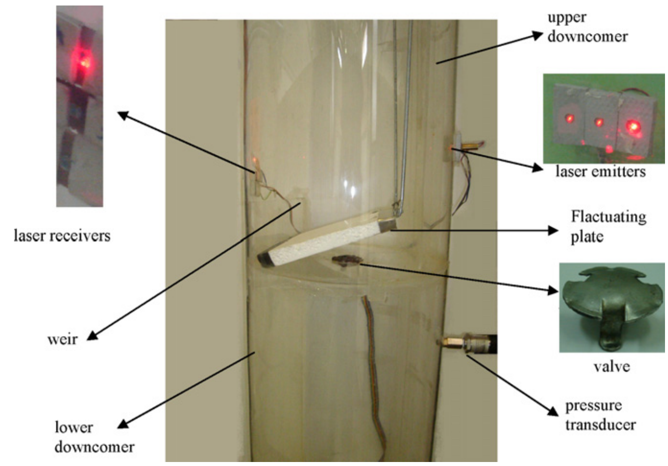

Fig. 1. The rig and its components.

Based on this survey, a reasonable number of CFD modeling studies have been undertaken to model the hydrodynamics and flow pattern in packed and sieve tray columns. However, a limited CFD modeling was done to model fluid hydrodynamics over valve trays. This is probably due to the complex gas–liquid contact upon the tray caused by this type of valve.

2. Experimental aspects

The experimental rig comprised a 30 cm diameter, 120 cm height transparent column equipped with a single valve tray, an 8 cm height weir and two downcomers as shown in Fig. 1. A novel method was employed to investigate the quality of gas–liquid contact. A very light fluctuating plate which was able to move in upward/downward directions, was installed at a height of 8 cm from the tray. This plate was fabricated from polystyrene foam with a density of 10 kg/m^3 with a total weight of 6.5 g. The air bubbles trapped by the liquid caused the fluid to hit the fluctuating plate and move it upward. The fluctuation frequency of this plate was used as a criterion for identifying the gas–liquid contact performance on the tray. Three pairs of laser emitter/receivers were placed at heights of 8.5, 9.5 and 10.5 cm from the tray. The fluctuating plate as well as the laser emitter/receivers are also shown in Fig. 1. The red laser intercepted by the receiver is sent to a digital counter that records the number of disconnections between emitter and receivers caused by the fluctuating plate. Three valves all of the same shape but different weights of 10, 13.5 and 20 g were examined.

In order to provide more quantitative results, a set of photographs using a digital camera were taken from gas bubble distribution inside the liquid phase. Experimental photographs have been analyzed using "Olysia M3" computer software (available with "Olympus GX71" microscope and "Olympus DP12" camera) to measure the bubble size distribution in the liquid for the three examined valves.

2.1. Experimental design method

Analysis of variance (ANOVA) is a reliable tool to analyze and determine the degree of certainty of experimental data. Nested or hierarchical design which is an arrangement of ANOVA method, is applied when the levels of one factor (e.g., factor B) are similar but not identical for different levels of another factor (e.g., A). In this design, the levels of factor B nested under the levels of factor A (Montgomery, 2001). In the present study, the repeatability of the measured values and the effect of valve weight on its performance were investigated using two-stage nested designs.

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