CHEMICAL ENGINEERING RESEARCH AND DESIGN 91 (2013) 2333–2345

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

CFD and experimental studies of liquid weeping in the circular sieve tray columns

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ABSTRACT

Sieve trays are widely used in fractionating devices like tray distillation towers existing in separation and purification industries. The weeping phenomenon that has a critical effect on the efficiency of tray towers was studied by a numerical model and some experiments. The experiments were carried out in a pilot scale column with the diameter of 1.22 m that includes two test trays and two chimney trays. Weeping rates and some hydraulic parameters were measured in sieve trays with the hole area of 7.04%. Furthermore, the total weeping rate and weeping rate in inlet and outlet halves of the test tray were determined. It was also used an Eulerian–Eulerian computational fluid dynamics (CFD) method for the present study. The model was able to predict the dry tray pressure drop, total pressure drop, clear liquid height, froth height, and weeping rate simultaneously. Furthermore, the obtained CFD results were in a good agreement with the experimental data in terms of pressure drop and the model properly predicted several hydraulic parameters like the liquid weeping behavior along the tray.

Keywords: CFD; Hydraulic; Circular sieve tray; Weeping

1. Introduction

In order to design a distillation tray, it is needed to combine theoretical and empirical findings obtained in this field. An appropriate tray design leads to a proper phase contact and an enhancement in the efficiency of a tray. It is well known that the trays have a good flexibility to operate in a satisfactory region of operating conditions; such a region is called the operating window or performance diagram of the tray that can be defined by the vapor and liquid rates. At a low value of vapor rate, the liquid weeping leads to the decrease of tray efficiency, while at a high vapor rate, the froth reaches the above tray and the entrainment phenomenon occurs. There are many distillation columns that operate at a capacity lower than their design capacity, thus, determination of the liquid weeping and entrainment limits of the trays can give proper information in order to improve the efficiency of these systems. The dry tray pressure drop and the weep fraction are two vital hydraulic parameters that determine the lower operating limit for a tray (Biddulph, 1975; Summers, 2004; Kister, 1992).

The sieve trays have been 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 the leakage of liquid through the deck holes at low vapor rates and reduces its normal operating window. Moreover, the weeping phenomenon is considered as one of the common reasons of mal-functions of trays in refineries, chemicals, olefins and gas plants (Kister, 2003).

Several studies have been done for developing relations to predict the liquid weeping in a tray with a single hole or a perforated plate containing many holes (Lockett, 1986; Lockett and Banik, 1986). Most of these works led to many useful correlations for hydraulic parameters, the accuracy of which was not always sufficiently high depending on the details of geometry, chemical components, and their properties, etc.

Lockett et al. (1984) calculated reduction of the distillation tray efficiency, which was occurred due to the uniform liquid weeping. They tried to extend the applicability of the previous analyses (Kageyama, 1966; O'Brien, 1966; Kageyama, 1969) for

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Received 6 July 2012; Received in revised form 2 March 2013; Accepted 18 March 2013
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http://dx.doi.org/10.1016/j.cherd.2013.03.006

Nomenclature

A_b	tray bubbling area (m^2)
A_h	tray perforated area (m^2)
C_D	drag coefficient (–)
d_G	mean bubble diameter (m)
F_s	F-factor = $V_S\sqrt{\rho_G}$ ($m/s(kg/m^3)^{0.5}$)
g	gravity acceleration (m/s^2)
k	turbulent kinetic energy ($J\,kg^{-1}$)
L	liquid flow path on tray or tray length (m)
M_{GL}	interphase momentum transfer ($kg\,m^{-2}\,S^{-2}$)
p_G	gas phase pressure ($N\,m^{-2}$)
p_L	liquid phase pressure ($N\,m^{-2}$)
Q_L	liquid volumetric flow rate ($m^3\,s^{-1}$)
R	radius of the tray (m)
S_{GL}	rate of mass transfer from gas phase to liquid phase ($kg/m^3\,s$)
S_{LG}	rate of mass transfer from liquid phase to gas phase ($kg/m^3\,s$)
u_G	velocity vector of gas phase (m/s)
u_L	velocity vector of liquid phases (m/s)
U_h	hole gas velocity (m/s)
U_S	gas superficial velocity (m/s)
U_T	droplet terminal velocity (m/s)
V_S	gas velocity through column cross sectional area (m/s)
V_{slip}	slip velocity (m/s)
x	coordinate position in the direction of liquid flow along tray (m)
x/L	dimensionless coordinate position along tray (–)
y	coordinate position in the direction of vapor flow across tray (m)
z	coordinate position in the transverse direction of liquid flow across tray (m)
z/R	dimensionless coordinate position across tray (–)

Greek letters

α_G	volume fractions of the gas phase (–)
α_L	volume fractions of the Liquid phase (–)
$\alpha_L^{average}$	average liquid holdup fraction (–)
$\alpha_G^{average}$	average gas holdup fraction (–)
ε	dissipation rate of k ($w\,kg^{-1}$)
ρ_G	gas density (kg/m^3)
ρ_L	liquid density (kg/m^3)
$\mu_{eff,G}$	effective viscosity of gas ($kg\,m^{-1}\,s^{-1}$)
$\mu_{eff,L}$	effective viscosity of liquid ($kg\,m^{-1}\,s^{-1}$)

Subscript and superscript

G	gas
L	liquid phase

industrial columns by considering the point that the vapor is not mixed among the trays.

Moreover, Lockett and Banik (1986) obtained some valuable experimental data for the liquid weeping on the sieve tray; it was shown an exponential increasing trend for the liquid weeping with decrease of the hole gas velocity. They also investigated the effects of some hydraulic parameters, weir height, and hole diameter on the rate of weeping and proposed a correlation for weeping rate in sieve trays and finally illustrated the physical analysis of this phenomenon. Fasesan (1985) measured the rate of liquid weeping from distillation/absorption trays in two identical trays for an absorption column with a diameter of 24 in. for air–water system. The data were obtained by two independent methods of weepage catch tray and dye trace technique. Furthermore, Fasesan (1985) used a chimney tray to measure the weeping rate for sieve and valve trays by a direct volumetric method. He found that the liquid weeping rate varies from tray to tray. The obtained results indicated that the weeping rate for a sieve tray operating in the weeping regime increases linearly with increase of liquid load.

In order to make more effective use of sieve tray towers for industrial applications an improved theoretical understanding of the sieve tray hydraulics is essential. The knowledge of some important and measurable parameters such as pressure drop is necessary but not sufficient. Therefore, it is needed to understand the detailed behaviors of instantaneous vapor and liquid flows in the column. The mathematical models for predicting the liquid weeping and its rate have been previously developed (Wijin, 1998; Zhang and Tan, 2000, 2003a,b) as alternative ways to get better understanding of a tray behavior during weeping conditions. Wijin (1998) developed a model for lower operating limits of distillation and absorption trays. His work represented a new method for calculating the minimum gas flow rates of sieve and valve trays operating in the bubble, churn and turbulent flow regimes. He also checked the connection between weeping and tray efficiency.

While the new approach in experimental investigation of sieve tray columns has provided much necessary information, the computer simulation techniques are utilized as useful tools for obtaining detailed information about the flow behavior in such systems. Computational fluid dynamics (CFD) has recently emerged as an effective tool for investigation of the hydraulic parameters of tray towers and prediction of the tray efficiency (Mehta et al., 1998; Fischer and Quarini, 1998; Yu et al., 1999; Krishna et al., 1999; Van Baten and Krishna, 2000; Liu et al., 2000; Gesit et al., 2003; Wang et al., 2004; Hirschberg et al., 2005; Rahimi et al., 2006; Noriler et al., 2009; Teleken et al., 2009, 2010a,b; Li et al., 2009; Zarei et al., 2009; Alizadehdakhel et al., 2010; Rahimi et al., 2010; Jiang et al., 2012). In the recent years, CFD has been used for modeling multiphase flows to reduce the design time and cost (Hosseini et al., 2010; Razavi and Hosseini, 2012; Zhong et al., 2009; Wang et al., 2009).

Mehta et al. (1998) utilized the CFD for investigating the hydraulics of sieve trays and gave a deep insight to the researchers in this field. In addition, Yu et al. (1999) and Liu et al. (2000) investigated the tray hydraulics in two-dimensional (2D) frameworks by CFD. Their models focused on the liquid phase hydraulics and the variations in the direction of gas flow along the height of the dispersion neglected in the models. Fischer and Quarini (1998) developed a transient 3D CFD model for investigation of the gas–liquid hydrodynamics of a sieve tray by considering a constant drag coefficient of 0.44 in the model. Furthermore, Krishna et al. (1999) and Van Baten and Krishna (2000) improved the hydraulics of a sieve tray by estimating a new drag coefficient for a swarm of large bubbles based on the correlation of Bennett et al. (1983). Gesit et al. (2003) developed a 3D model to predict the flow patterns and hydraulics of the sieve tray by CFD tool using Colwell (1981) correlation for the liquid holdup, which worked well in the froth regime. Hirschberg et al. (2005) obtained a novel simulation model for the two-phase flow in column trays. They