

MODELING FRACTION JETTING ON DISTILLATION TRAYS

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Introduction

The bi-phases on distillation trays can function in several different regimes depending on the physical properties of the system and the liquid-to-vapor ratio. Predicting the fraction of the vapor transported as jets, or fraction jetting, on a tray operating in the mixed-froth regime can bridge froth and spray regime models, explain the gradual changes in tray efficiency during the froth-spray transition, and eliminate the need to predict the froth-spray transition point when separate froth and spray regime models are used. Fraction jetting models will also facilitate multi-regime models, such as the Syeda, Afacan, and Chuang (2007) sieve tray efficiency model, that are valid for both froth and spray regimes. Current fraction jetting models are empirical and developed from limited data. In this paper, the concept of fraction jetting on a tray is discussed and a new semi-empirical model to predict fraction jetting as an alternative to existing models is presented. The applicability of the new fraction jetting model in the Syeda et al. sieve tray efficiency model is also illustrated.

The Concept of Fraction Jetting

Flow regimes have been used as a basis for fundamental modeling as they provide a generalization of the bi-phase behavior. On a distillation tray, the flow regime describes the two-phase mixture, which could be liquid-continuous-vapor-dispersed, vapor-continuous-liquid-dispersed, or both. The two-phase dispersions on a tray are classified into five flow regimes (Lockett, 1986): emulsion, foam, bubble, spray, and froth. This paper is focused on the bi-phase mechanisms and modeling in the froth and spray regimes.

In the spray regime, the vapor is the continuous phase and the liquid is the dispersed phase. Jets of vapor rise through the tray openings and atomize the liquid on the tray projecting liquid droplets into the intertray spacing. The liquid droplets are simultaneously subject to drag, gravity, and buoyancy forces and, as a result, fall back on to the tray to repeat the projection process or get entrained to the tray above.

In the froth regime, liquid and vapor continuous dispersions could coexist. The vapor transport in the froth regime, bounded by the bubble and spray regimes on a regime diagram, gradually changes from bubble dominated to jet dominated with increasing F-factor. However, jetting begins well before the transition to the spray regime. For this reason, the froth regime was also referred to as being made up of two subregimes — the bubbling froth where the vapor transport is only by bubbles and the mixed-froth — where the vapor transport is by both bubbles and jets (Hofhuis & Zuiderweg, 1979). In the froth regime at lower rates, the vapor transport is primarily in the form of bubbles. As the vapor rates are increased, intermittent vapor jets begin to form, and eventually, the jets break through the liquid layer on the tray (Figure 1). At much higher rates, the vapor jets dominate the bi-phase on the tray and the bi-phase resembles a spray .

The mixed froth regime can therefore be envisioned in terms of a fraction jetting, which is zero at the bubble-mixed boundary and one at the mixed-spray boundary, and is defined as

$$f_j = \frac{V_j}{V_b + V_j} = \frac{\text{Volume of the vapor transported as jets}}{\text{Volume of the vapor transported as bubbles and jets}} \quad (1)$$

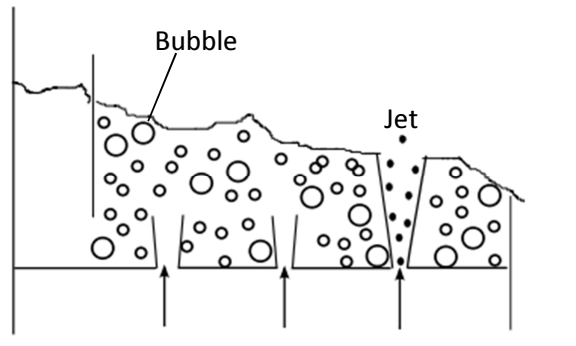


Figure 1: Vapor in the mixed-froth regime is transported as bubbles and jets simultaneously.

Implications of the flow regime on modeling

The flow regime, which characterizes the dispersion, is central to fundamental hydraulic and mass transfer models on trays. To address the flow regimes in modeling, researchers chose one of the following options: (a) a semi-empirical model that extrapolates into adjoining regimes (Chen & Chuang, 1993) taking advantage of the gradual change in properties or (b) a separate model for each regime (Bekassyolnar and Mustafa, 1991; Zuiderweg, 1982) coupled with correlations to detect the regime boundaries.

The extrapolation approach is inherently flawed because a model developed on the assumption of liquid continuous phase, for instance, is unreliable when the liquid becomes a dispersed phase. The two model approach, on the other hand, assumes that a flow regime transition point exists and occurs suddenly. The uncertainty in the predicted transition point, in addition to the likely presence of a transition zone instead of a transition point, invariably introduces model uncertainties. In either approach, the simultaneous bubble and jet transport is unaccounted.

An alternate approach, the fraction jetting approach, is that the change in flow regime is not sudden, but gradually changes with the change in operating conditions as the dominant modes of vapor transport change. By accounting for all transport mechanisms, the regimes are naturally bridged.

The fraction jetting approach has been successfully incorporated into the mass transfer efficiency models on sieve trays in the research led by Prof. Fair (Prado & Fair, 1990; Garcia & Fair, 2000) and later by Prof. Chuang (Syeda, Afacan, & Chuang, 2007) .

A fraction jetting model is used to combine the relative contributions of the efficiencies of the bubbling and the jetting zones to the observed efficiencies using an equation such as

$$E_{OG} = f_j E_j + (1 - f_j) E_b \quad (2)$$

Where, E_{OG} is the point efficiency, E_b and E_j are the bubbling and jetting efficiencies.

Evidently, the fraction jetting model becomes an important piece or sub model in the efficiency prediction. The use of f_j in efficiency modeling is not only closer to reality, but can also explain the drop in

efficiency at higher rates as a result of increased jetting (which has a lower efficiency than bubbling) in addition to entrainment. Incorporating jetting in efficiency models can explain crowned efficiency-rate patterns, provide better predictions at higher rates, and allow a single model to be used in the froth and spray regimes.

Fraction Jetting and efficiency prediction

In this section, the measurement and modeling of fraction jetting in the literature are presented.

The measurement of fraction jetting is often indirect. The conductivity probe, also called the bubble probe, is used to account for all vapor transported as bubbles. The unaccounted vapor is the vapor that bypasses the probe in the form of jets. The construction and working of the conductivity probe is described in detail elsewhere (Burgess & Calderbank, 1975; Raper, Hai, Pinczewski, & Fell, 1979; Raper, Kearney, Burgess, & Fell, 1982).

Only two sources of fraction jetting data are available in the literature – Prado and Fair (1990) and Raper et al. (1982). Both use the conductivity probe technique and the air-water system. However, the Prado et al. data are collected with the probe located at the orifice whereas the Raper et al. data are collected with the probe located in the dispersion.

Not surprisingly, there are only two models for fraction jetting in the literature. The Prado et al. model based on the Prado et al. data and Syeda et al. model based on Raper's data. The model equations for the two models are listed below.

The Prado and Fair model is

$$f_j = \frac{u_b - u_{b,0}}{u_{b,100} - u_{b,0}} \quad (3)$$

$$u_{b,0} = 0.1\rho_G^{0.5}\rho_L^{0.692}h_w^{0.132}d_h^{-0.26}\phi^{0.992}L^{0.27}$$

$$u_{b,100} = 1.1\rho_G^{0.5}\rho_L^{0.692}h_w^{0.132}d_h^{-0.26}\phi^{0.992}L^{0.27}$$

Where $u_{b,0}$ and $u_{b,100}$ are the vapor velocities based on the bubbling area at 0% and 100% jetting, ρ_G and ρ_L are the vapor and liquid densities, h_w is the weir height, d_h is the hole diameter, ϕ is the fractional open area, and L is the liquid rate.

The Prado et al. model has eight estimated parameters. The variables included in Prado's fraction jetting model are the most common variables used in several froth-spray transition studies. However, the Prado data used for the Prado model were based on the orifice phenomenon and included a fraction of liquid cover in addition to bubbling and jetting. The fraction liquid cover indicated the amount of inactive holes or insufficient information whether a particular hole is jetting or bubbling.

The Syeda et al. model equation is

$$f_j = -0.1786 + 0.9857 (1 - e^{-1.43F_b}) \quad (4)$$

The Syeda model was developed from Raper et al.'s data and has three fitted parameters. The Syeda model only considers the F-factor as a variable in the fraction jetting model. However, the Syeda model captures the nonlinear rate of fraction jetting dependence on the F-factor by using an exponential relationship. The Syeda model is artificially limited to a value of 0.8071 for high F-factors due to its empirical model structure.

In summary, both fraction jetting models are empirical, based on air-water data, and only the Syeda et al. model is developed from fraction jetting data in the dispersion.

The fraction jetting model is a critical component used in the recent sieve tray efficiency models to relate the contributions of the jetting zone and the bubbling zone to the observed overall effect. However, not much modeling effort was expended on the fraction jetting model. In addition, the fraction jetting models have to be extrapolated to other systems than air-water to be useful for efficiency modeling. Therefore, there is clearly a need for a new fraction jetting model that has a phenomenological basis.

New model structure and regression

The premise of the fraction jetting concept is that the formation of vapor jets with an increase in vapor rate during the normal operation of a tray in the mixed-froth regime is responsible for the changes in the hydraulic and mass transfer properties in the two-phase mixture. Moreover, a key feature of the fraction jetting model is that the transition point is not a specific operating point, but is an operating range over which fraction jetting increases from zero to one.

The jet penetration theory, proposed by Lockett, provides the theoretical basis for describing the phenomenon of jetting. According to the jet penetration model, the force of the weight of the liquid above a jet tends to form a liquid bridge across the jet and acts to collapse it. The force of the gas momentum acts to resist the liquid bridge formation. A stable jet is formed when the gas momentum exceeds the liquid weight force.

The forces favoring and resisting jet formation are well represented by the modified Froude number. The modified Froude number is the ratio of the inertia of the vapor (square root of the kinetic energy of the vapor) to the resistance to the vapor traveling through the dispersion on the tray due to the presence of the liquid (square root of the potential energy of the liquid on the tray). The modified Froude number, defined in terms of the vapor velocity based on the bubbling area, u_b , and the clear liquid height, h_{cl} is

$$Fr' = \frac{u_b \rho_G^{0.5}}{(\rho_L g h_{cl})^{0.5}} \quad (5)$$

Therefore, it follows that the modified Froude number is the dimensionless number appropriate for correlating fraction jetting. The modified Froude number was previously used by Hofhuis and Zuiderweg (1979) and Colwell (1981) as an independent variable in their mixed-froth regime hydraulic correlations.

The modified Froude number represents the propensity of the vapor to be transported in the form of jets rather than bubbles. In other words, the ratio of the volume of the vapor transported as jets to the ratio of the volume of the vapor transported as bubbles is proportional to the modified Froude number. The phenomenological relation can be represented in equation form as

$$\frac{V_j}{V_b} \propto Fr' \quad (6)$$

Where V_j is the vapor flow as jets (m^3/s) and V_b is the vapor flow as bubbles (m^3/s). From Equations (1) and (6),

$$\begin{aligned} \frac{1}{f_j} - 1 &= \frac{V_b}{V_j} \propto \frac{1}{Fr'} \\ \frac{1}{f_j} - 1 &= \frac{\beta}{Fr'} \end{aligned} \quad (7)$$

where f_j is the fraction jetting, and β is the proportionality constant. The proportionality constant β is the value of the modified Froude number where $V_b = V_j$. If $Fr' > \beta$, the volume of the vapor transported as jets is greater than that transported as bubbles and vice versa. Re-arranging Equation (7), the new model structure for the fraction jetting model may be obtained as

$$f_j = \frac{Fr'}{\beta + Fr'} \quad (8)$$

Results and discussion

For estimating β , the experimental fraction jetting data of Raper et al. (1982) on sieve trays are used. The fraction jetting data were plotted against the modified Froude number, which was calculated from Raper's data and a clear liquid height calculated from the Bennett et al. (1983) correlation. A least squares estimation of β results in

$$f_j = \frac{Fr'}{0.0449 + Fr'} \quad (9)$$

The goodness-of-fit of the new correlation is shown in Figure 2. The new model describes the Raper et al. data over the entire experimental range. Furthermore, the model allows all f_j values between 0 and 1 depending on the F-factor and h_{cl} . The physical significance of the parameter can be explained in terms of the change in dominant mode of vapor transport from bubbles to jets.

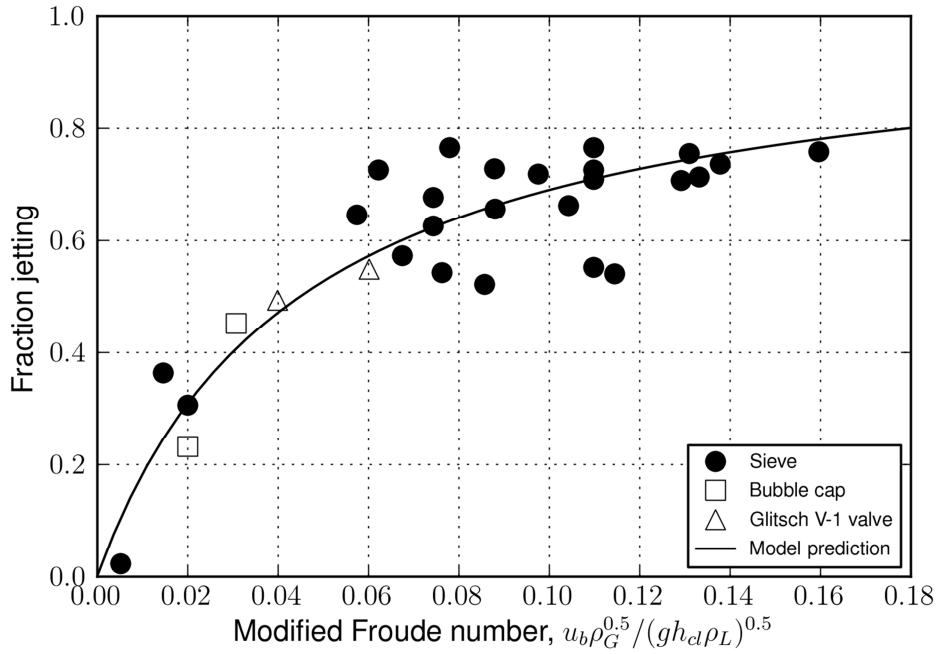


Figure 2: Fit of the new fraction jetting model using the sieve tray data of Raper et al. (1982).

Correlations based on the modified Froude number have been used to predict the gas hold up fraction or the liquid holdup fraction on trays (Colwell, 1981; Hofhuis and Zuiderweg, 1979). The correlation by Hofhuis and Zuiderweg is shown in Figure 3. If the β value of Equation (9) is plotted on the Hofhuis and Zuiderweg correlation plot, it coincides with an inflexion zone where a rate of change occurs. This provides further evidence that the modified Froude number at the numerical value of 0.0449 is indicative of a change in the dominant mode of vapor transport from bubbles to jets.

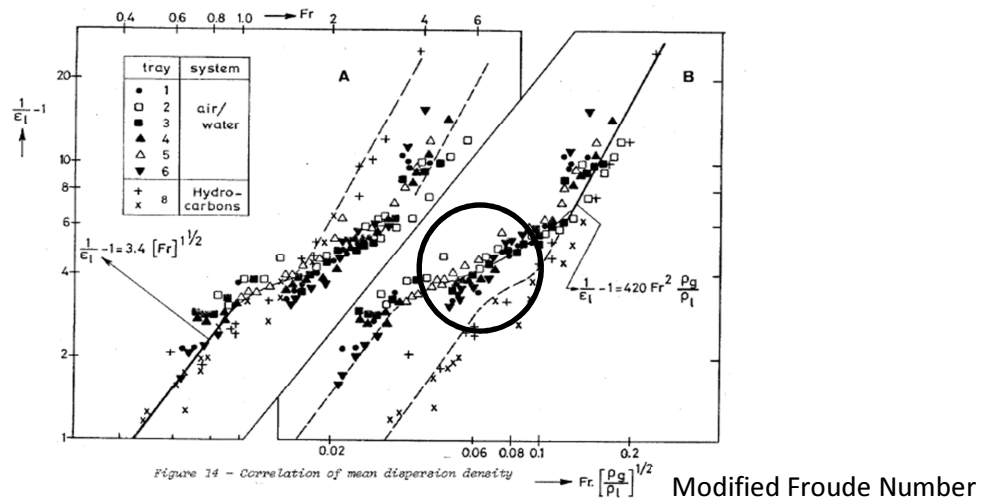


Figure 3: Correlation of hold-up fraction with the modified Froude number. Source: Hofhuis and Zuiderweg (1979)

Application to the existing sieve tray efficiency model

The new fraction jetting model is developed so that it can directly replace the existing fraction jetting models used in an efficiency model that incorporates jetting. The ability of the fraction jetting model to replace the existing Syeda et al. fraction jetting model in the Syeda et al. efficiency model is tested by using the data used by Syeda et al. for their efficiency model.

The data used for the efficiency predictions are the same as those used by Syeda et al. to develop their sieve tray efficiency model. The data were obtained on a 1.22 m diameter column (FRI data) on two binary hydrocarbon systems — cyclohexane/n-heptane (C6/C7) system and isobutane/n-butane (IC4/NC4) system. The data are categorized by system, pressure, and fractional hole area into seven sets: IC4/NC4 system at 1138 kPa, 8.3% hole area; IC4/NC4 system at 1138 kPa, 14% hole area; IC4/NC4 system at 2068 kPa, 8.3% hole area; IC4/NC4 system at 2758 kPa, 8.3% hole area; C6/C7 system at 34 kPa, 14% hole area; C6/C7 system at 165 kPa, 14% hole area; and C6/C7 system at 165 kPa, 8.3% hole area. The IC4/NC4 system data at 2068 kPa and 2758 kPa pressures was corrected by Syeda et al. using the Hoek and Zuiderweg (1982) method for vapor entrainment.

The Syeda et al. sieve tray efficiency predictions with the new fraction jetting model are compared to the Syeda et al. sieve tray efficiency predictions with the original fraction jetting model. For all of the data sets, the difference in predictions of the Syeda et al. efficiency model when the Syeda et al. fraction jetting model was replaced by the new fraction jetting model was less than 0.031. This provides evidence that the new fraction jetting model can effectively replace Syeda's fraction jetting model in Syeda's sieve tray efficiency model.

A key feature of the Syeda et al. sieve tray efficiency model is its ability to predict the crowned efficiency patterns observed in the experimental data. Using the new fraction jetting model in place of Syeda et al.'s fraction jetting model retains the crowned pattern prediction capability of the sieve tray efficiency model as seen in Figure 4. The result reconfirms that the new fraction jetting model can effectively replace Syeda's fraction jetting model in Syeda's sieve tray efficiency model.

The advantage of using the new model in place of the Syeda fraction jetting model is that it is semi-empirical, not artificially limited to the fraction jetting value of 0.8071, and the parameter value is consistent with a completely independent set of data in the literature.

Table 1: Comparison of the predictions of the Syeda et al. sieve tray efficiency model using (a) Syeda fraction jetting model and (b) new fraction jetting model. The maximum and average absolute deviations quantify how the model predictions differ from each other for the two cases.

System	Pressure kPa	Hole area %	Maximum abso- lute deviation	Average abso- lute deviation
IC4/NC4	1,138	14.0	0.046	0.014
IC4/NC4	2,068	8.3	0.032	0.013
IC4/NC4	1,138	8.3	0.055	0.014
IC4/NC4	2,758	8.3	0.038	0.014
C6/C7	165	8.3	0.034	0.018
C6/C7	165	14.0	0.070	0.020
C6/C7	34	14.0	0.040	0.031

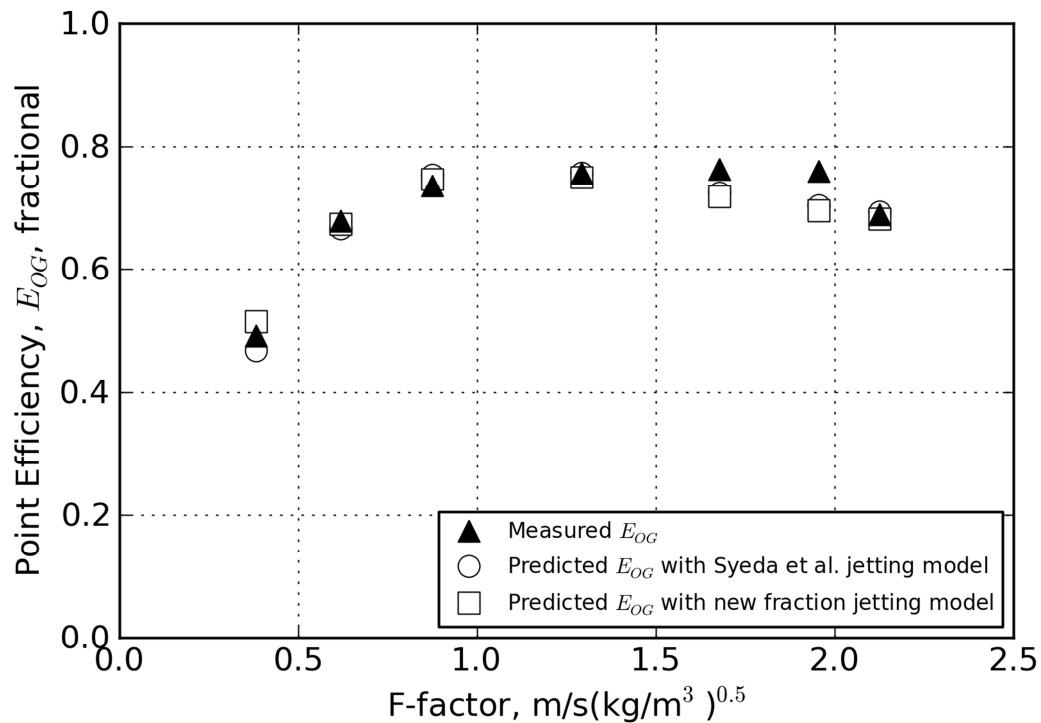


Figure 4: Comparison of efficiency predictions for the IC4/NC4 system, 1138 kPa, 14% hole area.

Conclusions and Future work

The modified Froude number based fraction jetting model has been developed and used to correlate Raper et al.'s fraction jetting data. The model describes Raper's data over the entire experimental range.

The proposed fraction jetting model has a phenomenological basis, agrees with the current models, and has the ability to replace the existing fraction jetting models used in multi-regime tray efficiency models.

The fraction jetting model is expected to lead to improved models for predicting multi-regime efficiency as it is based on a phenomenological understanding of the mechanisms that lead to jetting. The methodology and the model structure developed in this work provides a basis for further improvement of the model with the availability of additional data.

Fraction jetting data are needed on systems other than air-water to allow verification that the proposed new fraction jetting model has broad applicability. In addition, the data collected on commercial scale columns will be valuable to capture the vapor flow patterns on large trays. Another valued addition to this work would be the study of fraction jetting on different tray types.

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