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Predicting valve tray efficiency

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A B S T R A C T

Existing literature models for predicting the mass transfer efficiencies of binary hydrocarbon, distillation columns employing moving valve trays are evaluated. Only four models for predicting valve tray efficiencies exist in the open literature. All of these models use data from valve trays. The last theoretical model was published in 1972, 42 years ago. By comparison, sieve tray efficiency models are numerous and recent. Sieve tray models were developed from large databases. There are no valve tray equivalents to the fundamental mechanistic models available for sieve trays. Despite the differences between valve and sieve trays, many of the phenomena on sieve and valve trays are similar. Consequently, sieve tray models can be employed to provide estimates for valve trays. In this work, using public FRI data on round moving valves, the performance of the Chen and Chuang sieve tray mechanistic model is compared to the performance of four valve tray models. It appears that, in the absence of fundamental (and qualified) valve tray models, the sieve tray models present a potential alternative for valve tray efficiency predictions.

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1. Introduction

Valve trays are the most popular choice for trayed distillation column internals in the industry (Kister, 1992). Predicting the mass transfer efficiency or the tray efficiency of valve trays therefore has significant economic and process design implications.

Often, the best source of tray efficiency information is experience with a similar service. However, efficiency data for valve trays are limited. Vital et al. (1984a,b) compiled a list of laboratory and industrial tray efficiencies including valve tray efficiencies, but that list had not been updated in 30 years. When efficiency data are unavailable from an industrial application, efficiency is estimated using tray efficiency models. Even when efficiency data are available, tray efficiency models can provide valuable information on the effect of design changes.

Tray efficiency models can be broadly classified as empirical or theoretical. The empirical models are data-driven and developed to describe the experimental efficiency data in terms of the physical properties, tray geometry, and operating

conditions. The empirical models express efficiency either as a functional relationship or as relationships of dimensionless groups. The theoretical models are based on phenomenological relationships developed from the analysis of the phase characteristics, mass transfer resistances, and the cross-flow hydraulic effects on the tray.

The published literature has only four valve tray efficiency models – the theoretical Todd and Van Winkle (1972) model, and the empirical Tarat et al. (1974), Scheffe and Weiland (1987) and Peytavy et al. (1990) models. The only theoretical valve tray model was published more than 40 years ago.

Most of the tray efficiency modeling work was focused on sieve trays. The most recent sieve tray efficiency model was published by Syeda et al. (2007). Due to the similarities in the operating characteristics of sieve and valve trays, many of the hydraulic and mass transfer studies on sieve trays are potentially applicable to valve trays. Theoretical sieve tray efficiency models, which are developed from an improved understanding of the two-phase characteristics and mass transfer on a tray, and a wide range of data, may provide approximations for valve trays.

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Physical properties and tray geometries affect tray efficiencies. However, the physical properties are the most dominant. Early empirical efficiency correlations, such as the O'Connell (1946), were based solely on physical properties. According to Kister (1992), the O'Connell correlation is still the most popular efficiency correlation. The dominant effect of physical properties on tray efficiencies provides another reason to apply sieve models to valve trays.

The hypothesis of this work is that in the absence of theoretical valve tray models, theoretical sieve tray models that capture the effects of physical properties on tray efficiencies are sufficiently accurate for valve tray efficiency predictions.

2. Literature survey

A brief review of the four valve models is presented in this section.

The different databases used to develop the valve models define the extrapolation-ability and the applicability of the different models. The size, scale, and the nature of the different databases are indicated in Table 1. The Todd and Tarat models employed distillation data. The Scheffe and Peytavy models were developed for absorption systems and from absorption data.

The only theoretical model for the prediction of valve tray efficiency was developed by Todd and van Winkle. The data used for the Todd model were collected from a 0.46 m diameter column with three rectangular valve trays using benzene/n-propanol and n-propanol/toluene binaries at atmospheric pressure. The model was developed using 98 data points. Three weir heights (25.4 mm, 50.8 mm, 76.2 mm) and three L/V ratios (0.5, 1.0, 1.5) were studied.

Tarat et al. proposed an empirical model using data collected in a 0.25 m diameter column using the ethanol–water system at total reflux using Glitsch ballast and annular ballast trays. The effect of operating conditions, physical properties, and geometry are considered in terms of dimensionless numbers. The data used for the model span a deck open area range of 7.7–13%, weir heights of 25–70 mm, and liquid rates per bubbling area of 1.5–9.0 m³/m²/h. The model was developed using 42 data points.

Scheffe and Weiland studied the mass transfer characteristics of square trays with 0.372 m² of bubbling area equipped with standard Glitsch V-1 ballast valves. An operating pressure of 100 kPa was chosen to ensure that the resistance to mass transfer was predominantly in the gas phase. The absorption of SO₂ from air into NaOH was used to correlate the volumetric mass transfer coefficient. The model was developed using 140 data points.

Peytavy et al. proposed a model for mass transfer in gas–liquid absorption systems based on data from a 0.45 m diameter column using Glitsch V4R valve trays. The data used for the volumetric mass transfer coefficient were obtained from the absorption of SO₂ from N₂ into NaOH. The model was developed using 72 data points.

The Todd model was based on the two film theory and incorporated heat effects. The key feature of this model is the correlation for predicting the heat transfer across the interface using interfacial and bulk temperatures. However, the inclusion of heat effects increases the complexity of the model. Lockett (1986) observed that including the heat effects does not necessarily provide improvements in efficiency predictions for binary distillation systems. Furthermore, the equations for predicting heat transfer across the interface are empirical and cannot be extended to other geometries or systems.

The interfacial area, clear liquid height, and the vapor contact time expressions used in the Todd model are empirical. Issues and potential implications are described in the following paragraphs.

The constants of the Hughmark (1965) interfacial area correlation used in the Todd model were determined from bubble cap tray data. Fifteen years after the publication of the Todd model, Scheffe and Weiland (1987) reported interfacial areas on Glitsch valve trays that were twice the interfacial areas on bubble cap trays. Consequently, other elements of the Todd model may be overstated to compensate for the underestimated interfacial areas.

The Todd model used an empirical expression to calculate the vapor contact time. The Todd vapor contact time correlation is internally inconsistent because Hughmark's interfacial area correlation used in the vapor contact time correlation already assumes that the vapor contact time is equal to the vapor residence time. Furthermore, the uncertainties in the calculated mass transfer coefficients also affect the back-calculated vapor contact times and consequently the correlation.

The clear liquid height correlation used in the Todd model was regressed from valve tray data. However, Lockett (1986) compared the performance of the various clear liquid height models for the air–water system and found that the predictions using the Todd clear liquid height model for the air–water system do not match well with other valve tray clear liquid height correlations.

In spite of its limitations, the Todd model is the only fundamental valve tray efficiency model available in the literature.

The Scheffe and Peytavy models were developed for predicting volumetric mass transfer coefficients. The vapor phase volumetric mass transfer coefficients predicted by these models must be transformed into efficiencies using a transfer unit relationship. The method of Huml and Standart (1966) was recommended by Scheffe under the conditions of complete liquid mixing and negligible liquid phase resistance. The limitations of the transformation method introduce an additional degree of uncertainty in the model predictions.

Both the Scheffe and the Peytavy models focus on variables representing operating conditions and not on physical properties and valve tray geometries. This may be appropriate for absorption, but it limits the potential applicability to distillation. In general, the efficiencies in absorption are lower than those in distillation, and therefore, the extension of absorption-based correlations to distillation may not be

Table 1 – Valve data used for the four valve tray efficiency models.

Valve model	Column diameter/side (m)	Valve type	Binary system	Database size
Todd (1972)	0.46	Unknown	Benzene/n-propanol; n-propanol/toluene	98
Tarat (1974)	0.25	Glitsch ballast; annular ballast	Ethanol/water	42
Scheffe (1987)	0.61	Glitsch V-1	SO ₂ from air into NaOH	140
Peytavy (1990)	0.45	Glitsch V4R	SO ₂ from N ₂ into NaOH	72

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