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Study of Clear Liquid Height and Dry Pressure Drop Models for Valve Trays

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In this work, literature correlations developed for tray clear liquid height and dry pressure drop are analysed and compared with FRI published data. Four valve trays measured and published by FRI are used in the data analysis. For clear liquid height models, the fundamental Colwell (1979) correlation based on Francis's equation was analysed. The Bennett (1983) model based on air-water data, the Hofhuis and Zuiderweg (1979) model based on spray regime and mixed-froth regime, the Dhulesia (1984) model based on V1 valve and air-water data, the Brambilla (1969) model based on air-water data, and the Glitsch (2013) from Koch-Glitsch Bulletin 4900 were also analysed and compared with each other.

The dry tray pressure drop can be modelled by two ways. For the fixed valve tray and the sieve tray, an orifice type equation is used. The major difference between different researchers is the correlation for orifice constant. For the movable valve/float valve tray, the pressure drop curve is divided into three regions by the valve positions: fully closed region, partially open region, and fully open region. These three regions are determined by the closed balance point (CBP) and the open balance point (OBP). In this work, five literature models were analysed and compared with FRI data. Two of them are based on fixed valve tray or sieve tray (Smith and Van Winkle, Stichlmair), while the other three are based on movable valve tray (Glitsch, Klein, Bolles).

In conclusion, this work studied the two hydraulic parameters for valve trays by analysing literature correlations with FRI measured data. Results show that most of the literature correlations under-predict the clear liquid height for the above four trays. Except for the models based on Francis's theory, the literature correlations cannot predict the trend of the clear liquid height with the bubbling velocity. For the dry tray pressure drop, the three-region models give better prediction than orifice type models for the four valves in FRI database. This work provided a new thought and pathway for future model development.

1. Introduction

Distillation columns can be divided into two divisions based on column internals: packed columns or tray columns. Nowadays, valve trays as column internals are widely used, with the advantages of wide operating range, good turn-down, high capacity, and fouling resistance. The hydraulic performance for valve trays, such as clear liquid height (h_{cl}) on tray decks and dry tray pressure drop (ΔP_{dry}) for vapour through the curtain area, are key parameters for tray design, column operation and troubleshooting.

Fractionation Research Inc., (FRI) has completed more than 15 valve tray tests since 1956, including non-proprietary designs for research projects and commercial valve trays. FRI first developed correlations for tray pressure drop in 1959 (Clarke et al., 1959) and continues to improve the models based on ongoing research. The literature has documented extensive research made in modelling clear liquid height and dry pressure drop over the years. In this work, literature correlations were discussed and applied to predict the hydraulic performance of valve trays tested by FRI, and compared with FRI experimental data in the public domain. The aim was to provide a new thought and pathway for future model development.

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2. Correlations for clear liquid height

The clear liquid height refers to the pressure drop due to passage of gas through the liquid layer on the tray deck. It can be calculated by integration of liquid holdup profiles from γ–ray scan, or can be measured from a manometer at the tray deck.

2.1 Correlations based on Francis's equation

The clear liquid height refers to the pressure drop due to passage of gas through the liquid layer on the tray deck.
The rectangular cross flow of liquid over the exit weir of trays can be seen as water over flow the dam, which is the original assumption of Francis's equation (Francis, 1868). Later on, numerous clear liquid height correlations were developed based on Francis's theory. Colwell (Cowell et al., 1979) proposed a model by assuming the vapour volume fraction in froth flowing over the weir equal to the fraction of two-phase dispersion. The Colwell model can be expressed as follows:

$$h_{cl} = \alpha h_W + 0.73\left(\frac{\alpha^{0.5} Q_L}{C_d W}\right)^{2/3} \tag{1}$$

$$\alpha = \frac{1}{1+\eta} = \frac{1}{1+12.6 Fr_b^{0.4} \phi^{-0.25}} \tag{2}$$

$$Fr_b = 12\left(\frac{\rho_G}{\rho_L - \rho_G}\right)\left(\frac{u_b^2}{g h_{cl}}\right) \tag{3}$$

Where
h_{cl} is the clear liquid height, m;
h_W is the outlet weir height, m;
C_d is the discharge factor, no unit;
Q_L/W is the liquid flow rate per weir length, $m^3/(m^*s)$;
u_b is the bubbling velocity based on tray open area, m/s;
α is the liquid volume fraction, no unit;
η is the dispersion density, no unit;
Fr_b is the Froude number, no unit.

One of the difficulties to apply Colwell model is that iterative calculation is needed to determine α and h_{cl}. To solve this issue, Bennett (1983) proposed a model based on Francis's equation, where the liquid volume fraction α is a function of superficial velocity and liquid/gas densities to avoid the iterative calculation:

$$\alpha_e = \exp[-12.55(u_b(\frac{\rho_G}{\rho_L - \rho_G})^{0.5})^{0.91}] \tag{4}$$

$$h_{cl} = \alpha_e[h_W + C(\frac{Q_L/W}{\alpha_e})^{0.67}] \tag{5}$$

$$C = 0.5 + 0.438\exp(-137.8 h_W) \tag{6}$$

Where
α_e is the effective liquid volume fraction, no unit;
u_b is the bubbling velocity, m/s.

2.2 Empirical correlations not based on Francis's equation

Hofhuis (Hofhuis et al., 1979) proposed an equation that is a function of hole pitch and liquid flow rate per weir length. Hofhuis model can be applied to both froth and spray regimes.

$$h_{cl} = 0.6\psi^{0.25} h_W^{0.5} p^{0.25} \tag{7}$$

$$\psi = \frac{Q_L/W}{u_S}\sqrt{\frac{\rho_L}{\rho_G}} \tag{8}$$

Where
p is the hole pitch, m;

u_s is the superficial vapour velocity based on bubbling area, m/s.
Many researchers also used a generalized correlation for h_{cl}, where the clear liquid height was divided into each influencing factors. Brambilla (Brambilla et al., 1969) proposed a correlation based on this theory:

$$h_{cl} = Ah_W - BF_S + C\frac{Q_L}{W} + D \tag{9}$$

Where
A, B, C, D are empirical constants;
F_S is the superficial F factor, $kg^{0.5}/(m^{0.5}s)$.

Glitsch (2013) model for clear liquid height from Koch-Glitsch Bulletin 4900 was also used in this paper to compare with other models. The Glitsch model is:

$$h_{cl} = 0.4(\frac{Q_L}{W})^{2/3} + 0.4h_W \tag{10}$$

The five correlations introduced above were applied to predict the tray performance tested by FRI. The results were discussed further in Section 4.

3. Correlations for dry pressure drop

The dry pressure drop refers to the pressure drop of vapor going through dry holes/valves when there is no liquid present.

3.1 Orifice type correlations

Besides the clear liquid height, another major contributing parameter in the total tray pressure drop comes from the pressure drop of vapor going through wet holes/valves. For sieve trays and fixed valve trays, the open area is fixed and the model is quite straightforward. In this case, the orifice type equation is used:

$$\Delta P_{dry} = \frac{\xi \rho_G u_h^2}{2g\rho_L} \tag{11}$$

Where
ξ is the orifice coefficient;
u_h is the vapour velocity through the holes, m/s.

The differences between different literature models usually exist in the expression of orifice coefficient. A widely used correlation was proposed by Smith (Smith et al., 1958):

$$\xi = \frac{(1-\phi^2)(p/d_h)^{0.2}}{K_W^2} \tag{12}$$

Where
ϕ is the fractional perforated area (hole area/bubbling area), no unit;
p/d_h is the ratio of hole pitch and hole diameter, no unit;
K_W is the empirical constant, no unit.

Another correlation was proposed by Stichlmair (Stichlmair et al., 1978), where the orifice coefficient had two expressions at different regions:

$$\xi = \xi_0 + \phi^2 - 2\phi\xi_0^{0.5},\ for\ t/d_h < 2 \tag{13}$$

$$\xi = \xi_0 + \phi^2 - 2\phi,\ for\ t/d_h > 2 \tag{14}$$

Where
ξ_0 is the constant that can be read from empirical plots, no unit;
t/d_h is the ratio of tray deck thickness and hole diameter, no unit.

3.2 Three-region correlations

For movable valve trays, the open area changes as hole velocity changes. The valves can have three different positions: fully closed, partially open, and fully open. These three regions are determined by the closed balance point (CBP) and the open balance point (OBP). The point at which the first valve begins to open is the closed balance point (CBP), while the point at which all valves are open for the first time is the open balance point (OBP). The pressure drop models for movable valve tray at fully closed/fully open position are similar with models for sieve tray/fixed valve tray, with the differences in orifice coefficient. For valves at partially open region, the pressure drop is a relative stable curve since the resistance is from the vapour coming through orifice as well as the weight of the movable valves. The equations for the three-region model are:

$$Fully\ closed: \Delta P_{dry} = K_C\left(\frac{\rho_G}{\rho_L}\right)u_h^2 \tag{15}$$

$$Partially\ open: \Delta P_{dry} = Kt_m\left(\frac{\rho_m}{\rho_L}\right) + K_1\left(\frac{\rho_G}{\rho_L}\right)u_h^2 \tag{16}$$

$$Fully\ open: \Delta P_{dry} = K_O\left(\frac{\rho_G}{\rho_L}\right)u_h^2 \tag{17}$$

The three-region pressure drop curve and two balance points (CBP and OBP) is shown in Figure 1. In this paper, three literature correlations (Klein et al., 1982; Bolles et al., 1976; Glitsch et al., 2013) applying this theory were analysed and compared with experimental data.

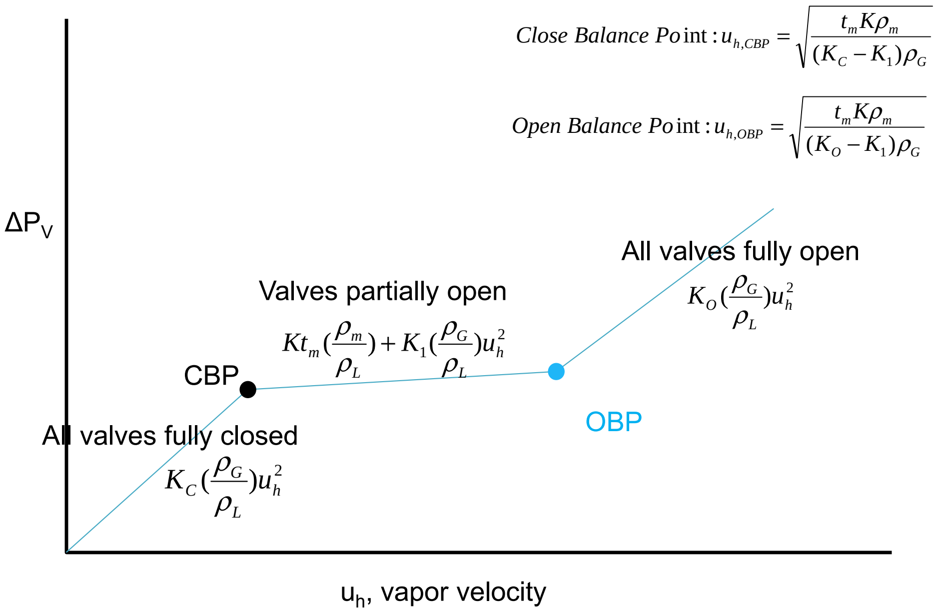
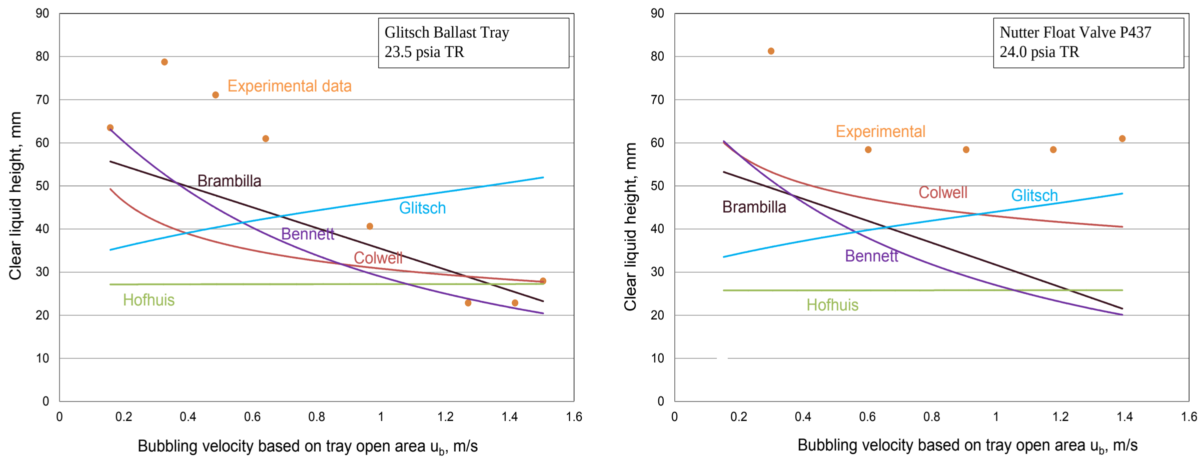


Figure 1: Three-region pressure drop curve for movable valve trays

4. Results and discussion

In this work, four valve trays: Glitsch Ballast Tray, Glitsch V1 Tray, Nutter Float Valve D437, Nutter Float Valve P437, measured and published by FRI were used in the data analysis. The Glitsch V1 Tray was tested in the FRI commercial size High Pressure (HP) Column with diameter of 4 ft, while the other three were tested in the FRI Low Pressure (LP) Column with diameter of 4 ft. The test systems were cyclohexane/n-heptane (C6/C7) and iso-butane/n-butane (iC4/nC4). The correlations for clear liquid height described in Section 2 and for dry pressure drop described in Section 3 were applied to those trays. Data points were taken at total reflux conditions from 4.5 psia to 165 psia (31 kPa to 1138 kPa). Comparison between experimental data and different models for clear liquid height is shown in Figure 2. Results show that most of the literature correlations under-predict the clear liquid height for the above four trays. The models (Bennett model and Colwell model) based on Francis's theory were able to capture the basic trend of experimental data. Bennett model showed a steeper trend than Colwell model, since it used the exponential expression for liquid volume fraction α. The empirical model using a generalized correlation (Brambilla model) also showed a fairly good prediction with experimental data. Other models (Glitsch model and Hofhuis model) cannot predict the experimental data accurately. The results for the other valve trays were similar with the results shown in Figure 2. To save the space of this paper, the repetitive results were not shown.

Based on data analysis and comparison between different correlations, it is recommended to take the format of Francis's theory for future model development on clear liquid height prediction. The empirical constant (C1) and the power dependence (C2) of liquid load per weir length may need to be modified if the operating condition is different from the original condition proposed by Francis. For example, if the flow is not pure liquid, which is common in the froth regime and spray regime. Figure 3 shows the frame diagram for clear liquid height model development. Since Froude number (Fr_b) is a function of h_{cl}, iteration is used in the model development. The constants C1 and C2 can be optimized by data fitting with experimental data.



(a) (b)

Figure 2: Comparison between experimental data and literature models for h_{cl}

$$h_{cl} = \alpha h_W + C_1\left(\frac{\alpha^{0.5}}{C_d}\right)^{2/3}\left(\frac{Q_L}{W}\right)^{C_2}$$

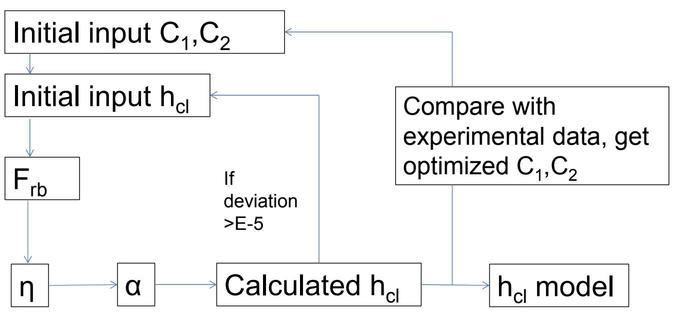


Figure 3: Frame diagram for clear liquid height model development

Comparison between experimental data and different models for dry pressure drop is shown in Figure 4. The dry pressure drop (ΔP_{dry}) is calculated by deducting h_{cl} from total pressure drop. The models (Klein model, Glitsch model) applying the three-region theory (fully closed-partially open-fully open) showed much better prediction than the models (Bolles, Stichlmair, Smith) applying only one expression for all conditions. It can be clearly seen from the experimental data that the pressure drop is relatively steady at the partially open region (u_b from 0.4 to 0.6 m/s), where the vapour force needs to overcome the weight of valves to open them. For most conditions, the orifice type correlations under-predict the dry pressure drop, and cannot successfully predict the trend.

The values of empirical constants (K_C, K, K_1, K_O) in the three-region models were shown in Table 1. The Glitsch model does not have a value for K_C, therefore it only works for the partially open region and fully open region. The Klein model and Bolles model does not have a value for K_1, with the assumption that ΔP_{dry} stay unchanged at partially open region. However, the experimental data show that ΔP_{dry} slightly increases with bubbling velocity (u_b) at this region, indicating that this assumption is over-simplified and K_1 is needed. In conclusion, these models can still be improved for fully closed region by fitting K_C (Glitsch model), or for partially open region by fitting K_1 (Klein model and Bolles model).

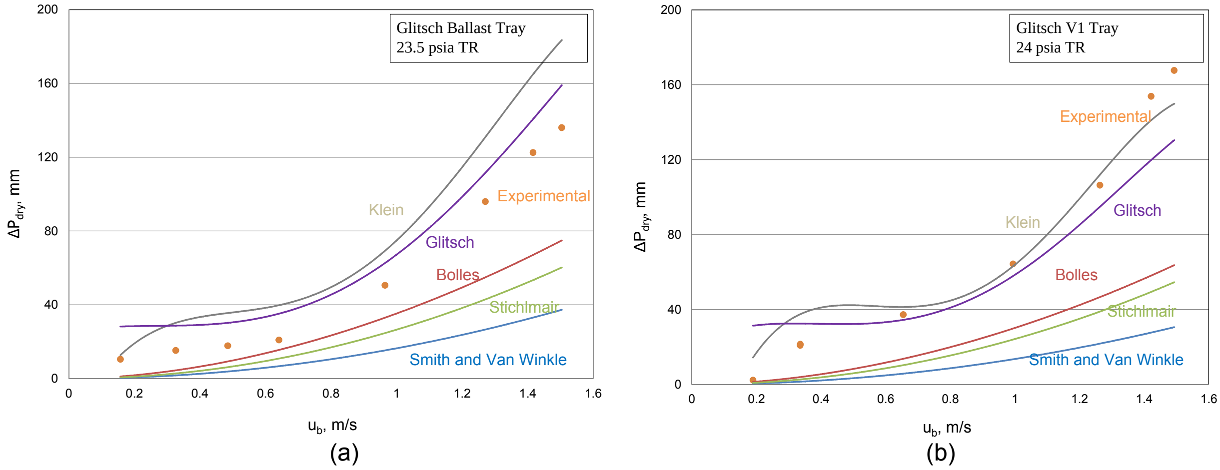


Figure 4: Comparison between experimental data and literature models for ΔP_{dry}

Table 1: Main tower parameters obtained at the selected cases

Coefficient	Klein	Glitsch	Bolles
K_C, $mH_2O/(ft/s)^2$	1.68	-	$1.9(A_h/A_b)^2$
K, no unit	1.3-1.7	1.35	1.2-1.4
K_1, $mH_2O/(ft/s)^2$	-	0.055	-
K_O, $mH_2O/(ft/s)^2$	0.302	0.26	$4/t^{0.5}$

5. Conclusions

In this work, two important hydraulic parameters (clear liquid height h_{cl} and dry pressure drop ΔP_{dry}) for valve trays were studied. Different correlations to predict h_{cl} and ΔP_{dry} based on different theories were analysed and compared with experimental data published by FRI. It is found that clear liquid height models based on Francis's equation and dry pressure drop models based on three-region theory show a good prediction for valve trays. Furthermore, suggestions are given in this paper to improve the existing correlations. The empirical constants in Colwell model can be updated by iteration calculation and data fitting. The omitted parameters in literature ΔP_{dry} models need to be retrieved to make it fit for all regions.

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