

A STUDY ON AN ENERGY-SAVING TRAY DDV WITH NEW STRUCTURES

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A general mathematical model based on the principal of non-equilibrium thermodynamics is proposed for analyzing the energy consumption of trayed column distillation processes related the tray structures, which can be used not only to calculate the energy consuming in different operational conditions, but also, and more importantly, to evaluate the entropy generation rate (EGR) of the different tray structures and different liquid flow patterns on trays of the column. Based on this analysis, an energy-saving tray with novel structures, called diamond-shaped dobble-deck valve tray (simply called DDV tray), was developed and experimentally determined on a pilot column with a diameter of 1000 mm. The results showed that DDV tray have the remarkable advantages in capacity, efficiency and energy-saving, over F1 tray, traditional sieve tray and rectangle-shaped valve tray, etc . . . .

KEYWORDS: DDV tray, energy-saving tray, entropy generation rate

INTRODUCTION

Trays have been the dominant tower internals because of their reliability, good plugging resistance, good corrosion resistance, and higher efficiency at elevated pressure, etc. Traditional trays, however, have some disadvantages as well, such as higher pressure drop, and lower capacity. Based on new designing concepts in the past 10 years, new trays, such as the Nye tray of the Glitsch Company[1] and the MD tray of the UOP Company,[2] have been developed and used successfully in industrial processes.

In our recent research a novel structural tray – DDV was developed based on the numerical calculation of entropy generation rate (EGR)[3]. The performances of this new tray was evaluated on a pilot device. This work will give an overall description of the design criteria of DDV from the calculation of EGR, followed by the further study on its performance, including liquid flow pattern on the tray, temperature profile of the liquid layer, and Murphree tray efficiency, etc.

FUNDAMENTALS OF THE DESIGN CRITERIA OF DDV

Distillation processes with low energy demand have been generated using various kinds of thermodynamic analysis methods[4]. In all these methods, the analysis and calculation of the entropy generation rate (EGR) within a tray and/or a column are the key points to succeed in designing new distillation processes or mass-transfer elements. In our laboratory, a new model was developed, focusing on the effects of structural parameters of a tray on the process EGR.

According to the non-equilibrium thermodynamics, for the case of non-viscous fluids with no chemical reactions and no external forces exerted on a system of N species at constant pressure, the EGR per unit volume, σ, can be written as

$$\sigma = -J_q \frac{\nabla T}{T^2} - \frac{1}{T}\sum_{i=1}^{N} J_i \nabla \mu_{i,T}^{c} \tag{1}$$

where the contribution of temperature variation to the chemical potential gradient ($\nabla\mu$) of component i is neglected. J_q and J_i is the heat and mass fluxes, respectively. By applying the mechanical balance equation and the Gibbs-Duhem equation in Equation (1), a general working equation of EGR for a multi-component system can be derived as[4]

$$\sigma = -J_q \frac{\nabla T}{T^2} - \frac{1}{T}\sum_{i=1}^{N-1} J_i \left[\sum_{k=1}^{N-1}\left(\delta_{ik} + \frac{M_i y_k}{M_N y_N}\right)\nabla \mu_{k,T}\right] \tag{2}$$

where M, y and δ are molecular weight, mole fraction and δ function, respectively. It is very hard to apply equation (2) to calculate the EGR for a multi-component system. However, for a binary system, equation (2) can be simplified, based on the following four assumptions: (1) there is no significant pressure gradient along or across the vapor-liquid interface film and the liquid phase is well distributed on a stage; (2) the temperature and chemical potential gradients are constant in the vapor phase on each stage, and the temperature gradient along the column is small; (3) the thermal contribution to the mass fluxes is negligible; and (4) the dissipation of energy is attributed mainly to the mass transfer across the interface layer with a thickness of Δx ($=D/kc$) and a constant area of a. Thus, by using the linear phenomenological relationship of non-equilibrium thermodynamics and applying the Onsager reciprocity relations to the fluxes J_q and J_i, a simplified expression for the total EGR, P, in a stage was obtained after mathematical derivation:

$$P = \int_0^v \sigma dv = \frac{\Delta\mu_l}{Tm_h} k_c \alpha \Delta c_l \tag{3}$$

where m is the mass fraction, and the subscripts l and h denote the light and heavy components, respectively.

The relationship between the tray parameters and the EGR in a distillation column was simulated for the binary benzene – toluene system based on equation (3) for the calculation of EGR and the AIChE method[5] for the stage efficiency. From the calculations, four important and interesting findings relating the tray structure to the EGR were obtained. (1) Increasing the tray diameter causes a higher EGR on a tray under identical operating conditions, due to the decreased hole velocity and increased active hole area with the increasing tray diameter. The decreased height of the liquid over the weir when increasing the tray diameter can reduce somewhat the EGR on a tray, but it is not a dominant factor. (2) A higher weir height causes higher tray efficiency and higher tray pressure drop that induce both positive and negative effects on the EGR.

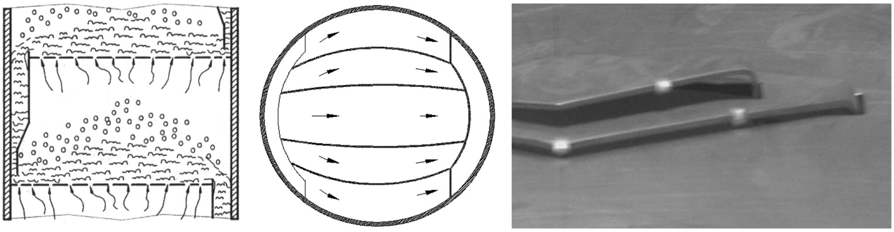


Figure 1. Schematic view of DDV

The calculation showed that the EGR increased with increasing weir height since the increased pressure drop was the primary factor. (3) A decrease in weir length leads to an increasing EGR. EGR profiles change less with variation of weir length than with variation of weir height. (4) Increasing active area of tray can noticeably reduce the EGR, mainly due to the decreased tray pressure drop and the increased mass transfer efficiency that both result from the larger active area.

The above four findings provide a design criteria for the development of new trays. In our laboratory, a novel tray, DDV, was thus designed and shown in Figure 1. This tray consists principally of three parts: a specially designed crescent downcomer[6], sieve or valve tray, and total deflectors. The weir is also in the form of a crescent. This design offers the advantages of (1) a reduction in the hole vapor flow velocity because of the increase in active area, leading to a decrease in entrainment so that the tray spacing can be shortened and the capital investment for the column reduced; (2) decreases in both the pressure drop for these trays and the flooding in the downcomer because of the low vapor velocity; and (3) a lengthening of the fluid flow path and regulated liquid flow pattern because of the tray structure, so that the contacting time for liquid-vapor is longer than that in conventional trays. The liquid backmixing was reduced by the use of the total deflectors. Therefore DDV can have higher efficiency and higher capacity. For revamping, DDV can provide higher capacity without the expense of installing the additional trays that are usually required to compensate for reduced tray efficiency. Even the original tower attachments can most likely be reused. DDV is able to achieve the required capacity and efficiency for a new tower in reduced sizes (diameter and height). A comparison of the EGR on DDV tray and conventional trays of the same sizes (tray spacing and diameter) and weir height was performed showing that DDV is able to remarkblely reduce the EGR and has the characteristics of energy-saving, large capacity and high separation efficiency.

EXPERIMENTAL SECTION

A schematic diagram of the experimental apparatus is shown in Figure 2. Three identical trays were placed in a column with a diameter of 1000 mm. The middle tray served as a test tray, the upper tray functioned as a stabilizing tray, and the bottom tray played a role of

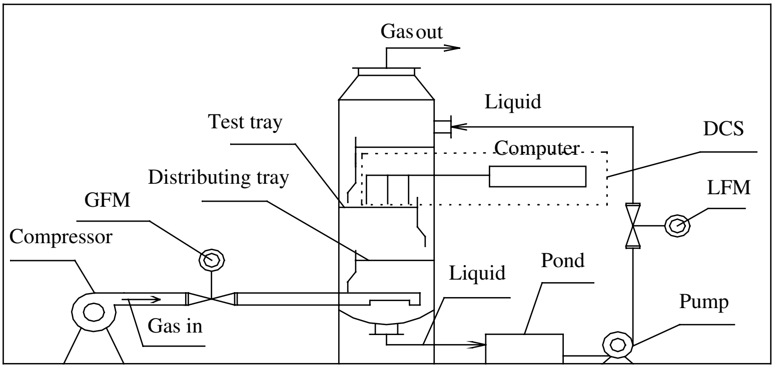


Figure 2. Schematic diagram of the experimental apparatus

evenly distributing vapor. The space between each pair of adjacent trays was 500 mm. The tray structural parameters were as follows: the weir length of 714 mm; weir heights of 45 mm; total hole area over the tray area of 12.0%; and the downcomer exit of 50 mm.

Air/water was taken as the operating system, with a vapor velocity range of 0.6–3.5 m s^{-1} and a liquid flow rate range of 4.0–32 m h^{-1}. The pressure drop for the tray was measured by a "U" pressure differential meter, and the downcomer liquid backup was measured by a liquidometer. The flow pattern was determined with soft colored silks and potassium permanganate as a tracer, the vapor rate was measured with a probe flowmeter of type SY-93 manufactured by EPI company, USA and the liquid with a smart vortex flowmeter 8800C supplied by Fisher-Rosemount Co. Ltd. (Shanghai).

Temperatures within the liquid layer on trays were determined by sensitive platinum resistive thermal detectors (RTDs), specially designed with an accuracy of $\pm 0.01^{\circ}$C. The positioning of the RTDs is shown in Figure 3. Desorption tests of oxygen from the water were carried out to measure E_{ML} (it is unadvisable to measure E_{MV} because the oxygen desorption process is controlled by the liquid film). The oxygen-rich water was prepared by injecting oxygen into the water at the water source. Enough time was needed to let oxygen dissolve sufficiently into the water so that an oxygen content of about 20 mg/L (O_2/H_2O) was obtained. When the testing system reached a steady state, liquid samples were collected from the inlet and outlet of the tray at the same time. Then oxygen contents were titrated by iodometry without delay.

RESULT AND DISCUSSION

FLOW PATTERNS ON THE TRAY

The flow patterns on the tray for various liquid flowrates were studied for liquid-only flow and a liquid-vapor biphase flow with three weir heights (20, 35, 40 mm). The liquid flow on the tray without deflectors can be divided into two parts: (I) an eddy zone and (II) a bulk flow zone. The main reason for the eddy zone is that the liquid outflow from

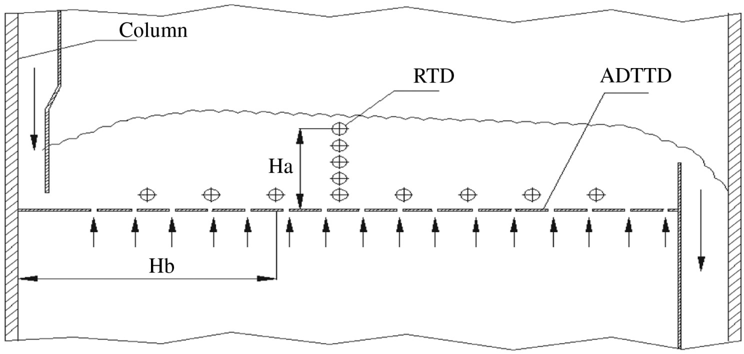


Figure 3. Positions of RTDs; Ha, distance from the testpoint of the RTD to the tray surface, equal to the height of the liquid layer; Hb, distance from the testpoint to the liquid inlet

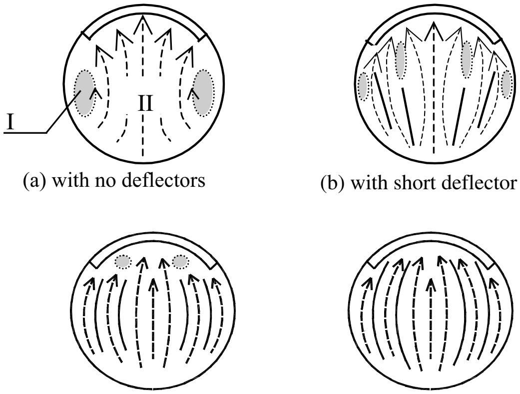
the downcomer has a tendency to flow toward the center of the tray, which results in the maldistribution of the liquid on the tray and an eddy near the column wall. It was found that the overflow rate had a remarkable effect on the liquid flow pattern and that the area of the eddy zone was enlarged with increasing liquid flow rate. The area of the eddy for biphase flow increased slowly with an increment of flux and is smaller than that for single-phase flow. The higher weir height has little influence on the single-phase flow pattern, but remarkably, does influence the eddy area for biphase flow.

To reduce the eddy zone and optimize the flow pattern, deflectors were placed on the tray to regulate and distribute the flow. Figure 4a–d show the flow patterns without and with the deflectors, respectively. The eddy zone can be reduced when deflector #1 is used, but there is some small backflow on the tray. The eddy area almost disappears when deflector #2 is used, and the flow pattern is approximately in an plug state when the deflector #3 is installed. Specifications of the deflectors are given in Table 1.

In the following tests, deflector #3 was adopted and its length was lengthened to achieve a "full-guide" from the inlet to the overflow weir, which was expected to completely divide the tray surface area into several individual channels. Deflectors were arranged like the meridians of the globe on two-dimensional maps. Coming from the inlet, the liquid was evenly guided into these channels. The liquid vortex and backflow were almost eliminated since the velocity gradient of crossflow was basically reduced in each channel. Thus the plug flow, an ideal flow pattern was expected and a multi-plug flow pattern could be set up. The same method can be applied to other round-shaped trays such as valve trays and all conventional sieve trays.

PRESSURE DROP

Compared with conventional trays, the pressure drop for DDV is greatly reduced. As it shown in Figure 5, the per tray pressure drop of DDV is almost one-half of that of a



(a) with no deflectors (b) with short deflector #1;

(c) with longer deflectors #2, (d) with total deflectors #3.

Figure 4. Flow patterns on trays

conventional F1 tray in the range of medium to high vapor flow rates. And the divergence of the pressure drop per tray between the two trays increases with increasing vapor flow rate. This represents that DDV tray has an advantage in energy consumption at on a same duty.

TEMPERATURE PROFILE OF THE LIQUID LAYER

Test results are presented in Figures 6 and 7. Figure 6 shows the vertical temperature profile in the liquid layer of the tray that tends to decrease linearly as the liquid layer height increases. If the flow pattern is plug flow, the theoretical deduction leads to

$$T = -b_1 K h + b_2, \tag{4}$$

where T is the temperature of the liquid layer, h is the height of the same layer, and b_1, K, b_2 are constants. Since the experimental results agree well with equation (4), it can be deduced that the flow pattern on DDV tray is approximately plug flow, the same as what we have seen in flow pattern experiments-Figure 4d. Figure 7 shows the temperature

Table 1. Specifications of deflectors

Number	Length (mm)	Height (mm)	Form
#1	200	40	line
#2	600	50	arc
#3	800	50	arc

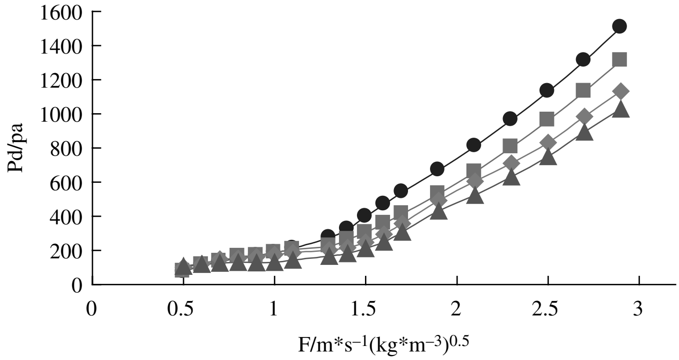


Figure 5. Pressure drop per dry tray at different F-factor (L = 15.5 $m^3 \cdot h^{-1}$) ◆ traditional F1 tray; ■ rectangle-shaped valve tray, ◆ DS tray, ▲ DDV tray

profile along the liquid flow channel in the horizontal direction. At the same height of liquid layer, the temperature also increases linearly from the liquid inlet to the outlet, indicating a plug flow being reached on the tray.

MURPHREE TRAY EFFICIENCIES

The efficiencies of DDV tray and traditional trays are compared in Figure 8. The efficiency of DDV tray is up to 80% higher over the range of medium to high vapor flow rates, while those of traditional trays are 50–70% in the majority of the operational range at the same operating conditions. And more importantly, E_{ML} of the DDV tray is more stable with F

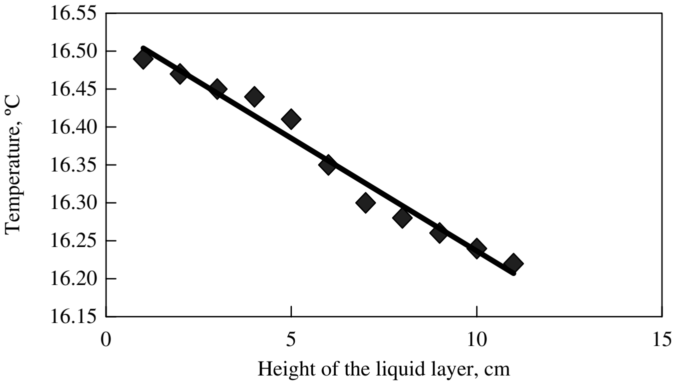


Figure 6. Vertical temperature profile of the liquid layer on DDV tray

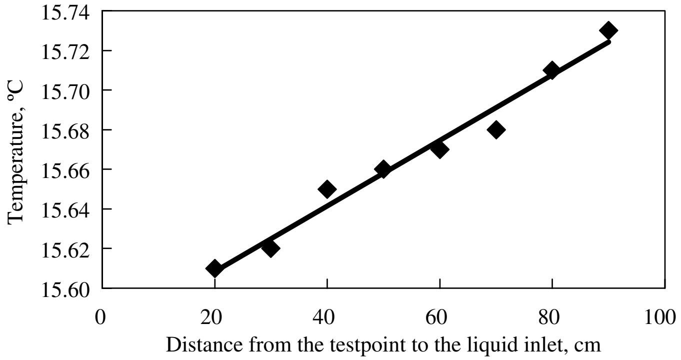


Figure 7. Horizontal temperature profile of the liquid layer on DDV tray

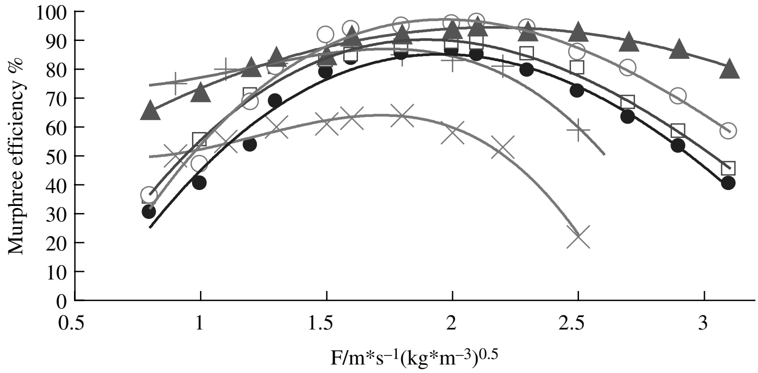


Figure 8. Tray efficiencies of DDV tray and traditional trays 1–DDV tray, 2–DS tray, 3–rectangle-shaped valve tray, 4–F1 tray, 5–deflected sieve tray, 6–sieve tray

factor when it goes from 1.0 to 3.0 or more. This indicates that the DDV tray allows a higher capacity and an operating flexibility than those of other traditional trays.

CONCLUSIONS

The follow conclusions can be drawn from this study:

(1) The DDV tray was designed based on the thermodynamic analysis of the entropy generation rate on the trays; it offers the advantages of a lower pressure drop, larger capacity, higher efficiency, an bigger operating flexibility, than the conventional trays;

(2) The liquid flow pattern on DDV tray is an plug flow and the temperature profiles of the liquid layer are linear in the vertical and the horizontal directions.

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