

# EDDY-DIFFUSION COEFFICIENT IN VALVE TRAY DISTILLATION COLUMNS

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## Introduction

For separation processes, mostly equipment of column type is applied providing intensive mass transfer. In tray distillation columns, material transfer occurs between the steam and liquid phases. As pointed out earlier [1], besides the classical design of bubble cap trays, combined tray structures like valve trays are now increasingly adopted for distillation columns. These tray structures show, however, a significant degree of weeping affecting in turn, the conditions of mixing on the tray, and also the eddy-diffusion coefficient, characteristic of these conditions. The eddy-diffusion coefficient has to be known to determine the number of trays actually required for the separation of a given sharpness.

## Mixing of liquid on a tray

A certain degree of liquid mixing occurs on the tray of a distillation column. Assuming a complete mixing, liquid concentration is uniform all over the tray, i.e. the so-called Murphree tray efficiency is identical with point efficiency [2]. In the other limiting case no liquid mixing occurs at all, this being the so-called plug flow where there is a clean-out correlation between tray efficiency and point efficiency [3]. In practice, some liquid mixing occurs between these limiting cases. The most universally accepted model for describing the mixing of liquid is the so-called eddy-diffusion model [4, 5], according to which the correlation between tray efficiency and point efficiency is

$$\frac{E_{MV}}{E_{OG}} = \frac{1 - e^{-(\eta + Pe)}}{(\eta + Pe) \left(1 + \frac{\eta + Pe}{\eta}\right)} + \frac{e^{\eta} - 1}{\eta \left(1 + \frac{\eta}{\eta + Pe}\right)} \quad (1)$$

where

$$\eta = \frac{Pe}{2} \left[ \sqrt{1 + \frac{4\lambda E_{OG}}{Pe}} - 1 \right]$$

$$\lambda = \frac{mG_M}{L_M}$$

$$Pe = \frac{vZ_l}{D}$$

For determining the tray efficiency, the eddy-diffusion coefficient must be known.

Since the eddy-diffusion coefficient depends only on the flow characteristics, it is influenced to a certain extent by the tray design, decisive for the flow conditions.

Several correlations for calculating the eddy-diffusion coefficient are known from the literature, but these apply only to certain experimental tray designs.

For bubble cap trays, the following correlation has been suggested by GERSTER et al. [4, 5]:

$$D^{0.5} = 0.00378 + 0.0171u_G + 0.00102L^* + 0.0001758h_w \quad (2)$$

Eq. (2) is widely used within the specific range of application. Many general works on this subject also suggest its application [6, 7].

Examining the conditions of liquid mixing on a sieve tray column, Barker and Self have suggested the following equation [8]:

$$D_E = K_1 \cdot L^{*1.44} + K_2 Z_c - K_3$$

where

$$K_1, K_2 \text{ and } K_3 \text{ are constants.}$$

The correlation suggested for sieve trays by FOSS, GERSTER and PIGFORD [9] is:

$$\frac{2D_E}{V^3 Z_c} = C_1 \left[ \frac{Z_c V}{Z_l} \right]^{-C_2}$$

where  $C_1$  and  $C_2$  are constants,

$V$  = rate of foam flow.

Owing to the differences in tray design, these correlations do not apply to valve trays. Weeping through the chimney openings of valve trays affects both the mixing conditions on the trays and the levels of clear liquid and foam.

This study deals with an experiment at work for establishing a correlation suitable for calculating the eddy-diffusion coefficient for valve trays.

The phenomenon of weeping requires the elaboration of a new model different from that used by Gerster, Barker and Self. In the new model, the discretely arranged catch-holes are taken into consideration between the inlet on the tray and the outlet gate.

An approximative model has been produced [1, 10], facilitating analytical and grapho-analytical determination of the eddy-diffusion coefficient.

Analysis of the steady-state concentration profile has been adopted for the tests. The parameters of liquid mixing were determined by analyzing the concentration profile of a so-called indicator which did not take part in the mass transfer process. Writing the differential material balance of the indicator as a dissolved matter for the differential section of the tray [1, 10],

$$D \frac{d^2x}{dz^2} - \frac{1}{A \rho_M} \left( L_{Mbe} - \frac{S_M}{Z_l} z \right) \frac{dx}{dz} = 0 \quad (3)$$

introducing the dimensionless locus co-ordinate  $w$  and performing certain modifications:

$$\frac{d^2x}{dw^2} - \frac{1}{D} \frac{Z_l}{Z_c Z_w} (L - Sw) \frac{dx}{dw} = 0 \quad (4)$$

Solving differential equation (4) and rearranging:

$$\ln \left( \psi \frac{x - x_0}{x_g - x_0} \right) = - \frac{1}{D} \eta \quad (5)$$

where

$$\psi = \frac{b^* - wa^*}{b^* - a^*}$$

$$\eta = (1 - w) \left[ b^* - \frac{a^*}{2} (1 + w) \right]$$

$$a^* = a \cdot D = K \cdot S$$

$$b^* = b \cdot D = K \cdot L$$

$$K = \frac{Z_l}{Z_c Z_w}$$

$$w = \frac{z}{Z_l} \quad \text{dimensionless locus co-ordinate.}$$

With the knowledge of the concentration profile of the indicator, eddy-diffusion coefficient  $D$  is obtained by Eq. (5) for the given operating parameters.

### The steady-state concentration profile as test method

This test method essentially consists of the following steps: the indicator solution is injected into the liquid flow through an injecting network near the outlet gate; maintaining the rate of injection at a constant level, distribution of the indicator concentration is established against the direction of flow.

Under steady operating conditions, the concentration profile does not vary. It can be assumed here that a one-dimension diffusion process takes place on the tray of a tray column between the inlet and outlet gate.

Knowing the concentration profile of the indicator, the eddy-diffusion coefficient corresponding to the extent of mixing on the tray can be established.

### Description of test equipment

Our tests were performed in a dia. 400 mm plexiglass column, illustrated in Fig. 1. Two valve trays and a double-bottom tray of special design were incorporated in the column.

Function of the double-bottom tray was to discharge the liquid weeping from the measuring tray above via an external hydraulic seal.

The tests were carried out in a water-air system. Supply tank marked 4 was constantly supplied with fresh water from the supply mains. Water was fed directly to the inlet segment of the tray located above the measuring tray. The level of the clear liquid established on the tray was measured at several points between inlet and outlet by means of level gauges ( $Z_c$ ).

Air was delivered into the test equipment by the fan marked 7. Rates of flow of air and water could be controlled as shown in Fig. 1. The quantity of liquid weeping through the tray was determined by volume.

The measuring tray is illustrated in Fig. 2. Height of the outlet gate could be varied between  $h_w = 25$  to 80 mm. A constant static hydraulic seal of 15 mm height was maintained during every test. In order to provide identical number of caps in every row, there were also half valves on the tray. The use of half caps is a common method [4]. The injecting network was mounted on the measuring tray 10 mm away from the outlet gate, as shown in Fig. 2. Position of the injecting network could be varied to suit the height of outlet gate.

Number of sampling rows were pointed out on the measuring tray, and the concentrations for the individual rows were obtained by calculating the average of samples taken at several points of each row.

The valve caps used for our tests were of Glitsch type illustrated in Fig. 3.

The indicator solution was prepared in a tank marked 3 in Fig. 1, and transferred into charging tank marked 2. The indicator solution was delivered to the injecting network by a screw pump; the flow rate was controllable continuously at a constant level.

The indicator solution contained sodium chloride, since brine does not take part in mass transfer between the gas and liquid phases, and its concentration can be determined from its conductivity. Concentration and quantity of the brine injected in our tests were established to result in a concentra-

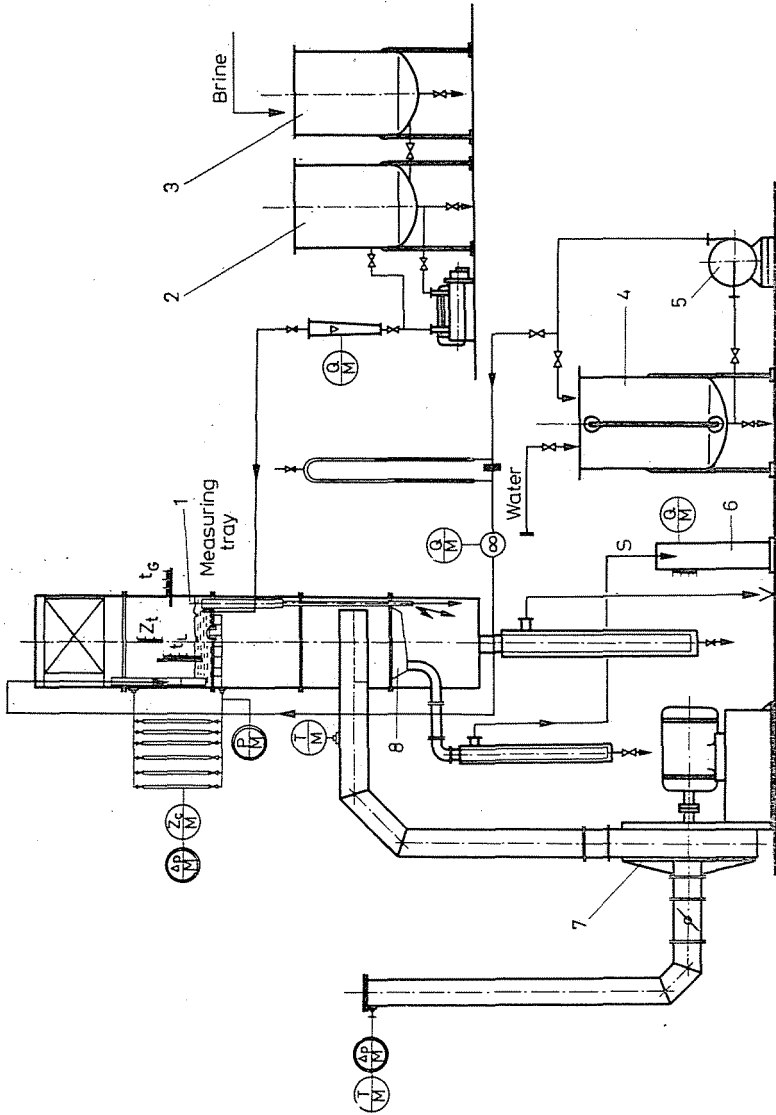


Fig. 1. Circuit diagram of test equipment

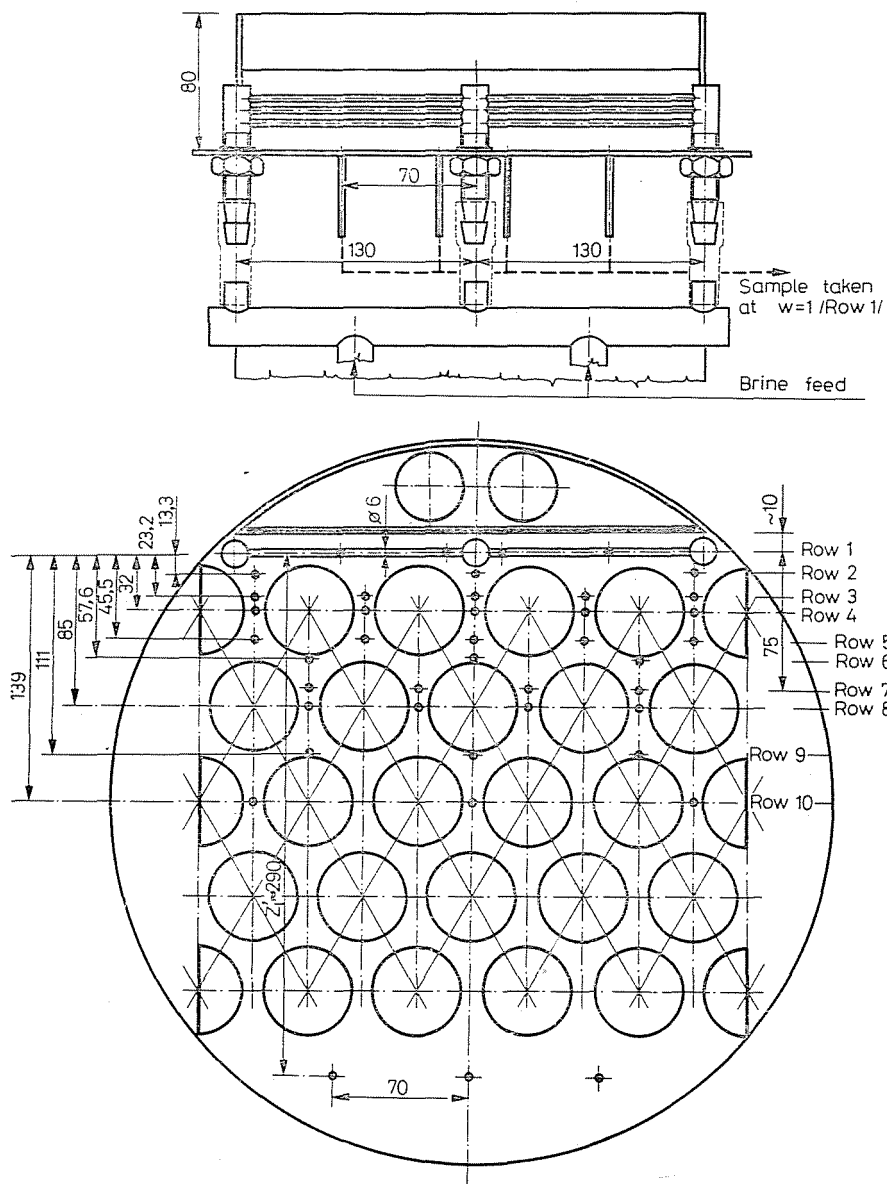


Fig. 2. Design of measuring tray with injecting network

tion not exceeding  $2 \left[ \frac{\text{gram NaCl}}{\text{ou.dm.solution}} \right]$  on the tray, because the conductivity of the brine shows a linear change with concentration up to that limit [10]. The solution samples taken in our tests were thermostated at their original temperature.

In the tests we measured the effect of gas load, liquid load and gate height on the liquid mixing (eddy-diffusion coefficient) and weeping. Having adjusted a fixed gate height and a fixed liquid load, measurements were taken by increasing the gas load.

The following test ranges were used:

$$h_w = 25 \text{ mm}; 40 \text{ mm}; 55 \text{ mm}; 75 \text{ mm} \text{ (gate heights)}$$

$$L = 2; 3; 4; 5 \text{ cu.m./hour (liquid loads)}$$

$$u_G = 0.546 - 1.29 \text{ m/sec (linear gas velocity).}$$

A detailed description of the test equipment and results have been published [10].

### Test results

A significant degree of weeping was observed on the test tray within the above ranges.

The rate of weeping is plotted in Figs 4 and 5. Apparently, at a constant gate height and liquid load, the quantity of liquid weeping through the tray decreases with increasing gas load. Obviously, at loads of e.g.  $F=1 \left[ \frac{\text{m}}{\text{sec}} \right] / \left[ \frac{\text{kg}}{\text{cu.m.}} \right]$  and  $L^* = 8.3 \text{ [cu.m./mh]}$  the percentage of liquid weeping through the tray amounts to 31.7 per cent of the total liquid entering the tray. Although Norman's results [11] have been plotted in Fig. 4, the valve cap design used by him differed so much from that adopted by us that the comparison applies only to the character of changes.

As apparent from Fig. 5, the quantity of the liquid weeping through the tray increased with liquid load.

Based on the literature [1, 10], the eddy-diffusion coefficient was established on a model allowing for weeping.

The quantity  $\ln \left( \psi \cdot \frac{x - x_0}{x_g - x_0} \right)$  is plotted as a function of  $\eta$  on the basis of Eq. (5) (see Fig. 6). It is apparent from the diagram that a straight line can be fitted to between the measurement results, thus verifying the theoretical model. Based on Eq. (5), the eddy-diffusion coefficient can be determined from the slope of the straight line. A total of 60 test runs were completed in the measuring range specified before; the detailed results have been published [10].

For calculating the eddy-diffusion coefficient, a correlation similar to Eq. (2), and applying to bubble trays, has been set up, with the constants established on the principle of parallels and by the method of least squares.

The final correlation obtained is

$$D^{0.5} = 0.0005 + 0.01285 u_G + 0.001755 L^* + 0.000312 h_w \quad (6)$$

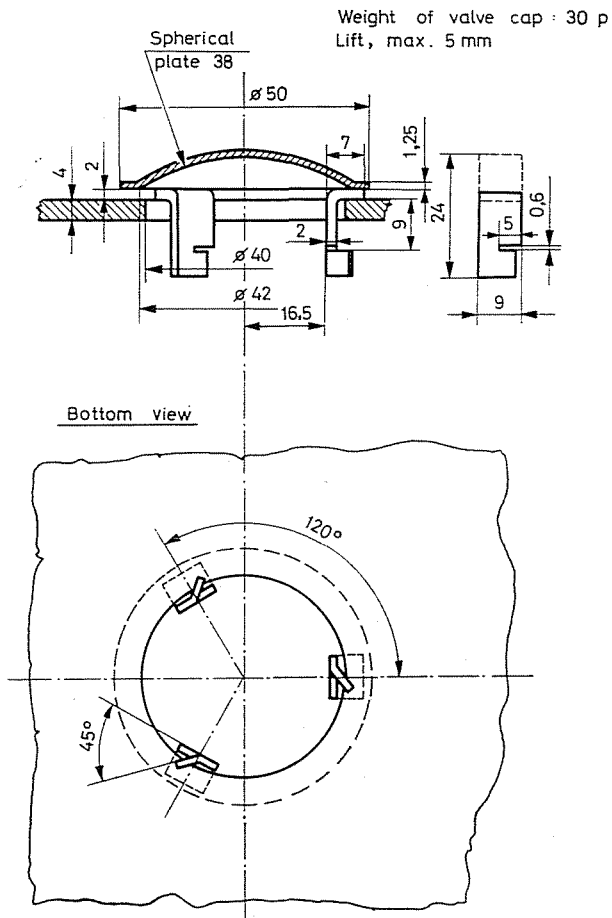
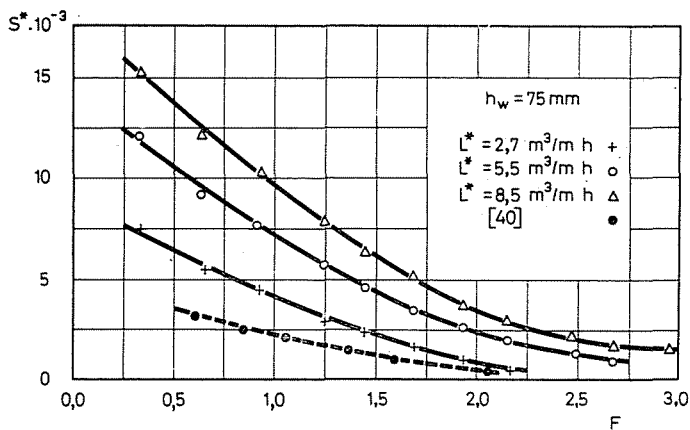


Fig. 3. Type of experimental valve cap



Other than Glitsch-type valve cap

Fig. 4. Rate of weeping vs. gas load factor



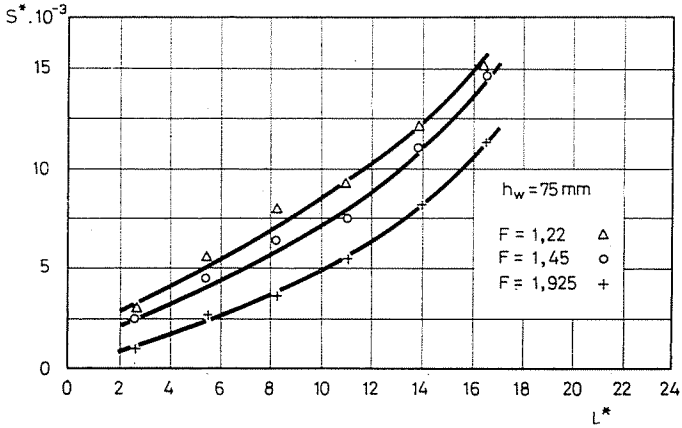


Fig. 5. Rate of weeping vs. liquid load

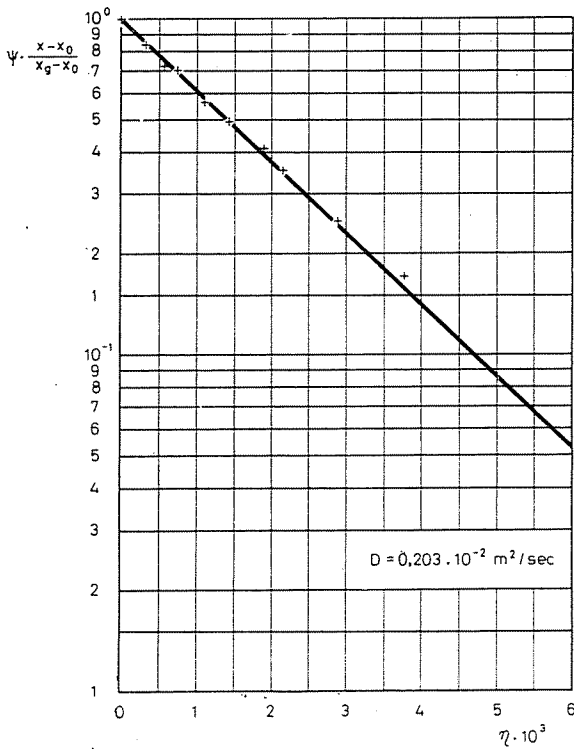


Fig. 6. Determination of eddy-diffusion coefficient

where

$[u_G]$ = m/sec	— linear gas velocity
$[h_w]$ = mm	— gate height
$[L^*]$ = cu.m./mh	— circumferential liquid load
$[D]$ = sq.m./sec	— eddy-diffusion coefficient.

In Fig. 7 the values obtained for the eddy-diffusion coefficient are plotted as a function of the calculated values. The lines marking deviations of 10 per cent plus and minus are clearly visible on the diagram. The suggested correlation (6) can be stated to describe the points of measurement with a fair accuracy.

In Fig. 8 our test results are plotted versus the results calculated by GERSTER et al. [4, 5] for bubble trays according to Eq. (2).

As apparent from Fig. 8, for the range tested and when using valve caps, liquid load and gate height influence the eddy-diffusion coefficient to a higher degree than does gas load — as opposed to bubble cap columns.

It is also apparent from Fig. 8 that Eq. (2) is not valid for valve trays. For the most common operating parameters it can be stated on the strength

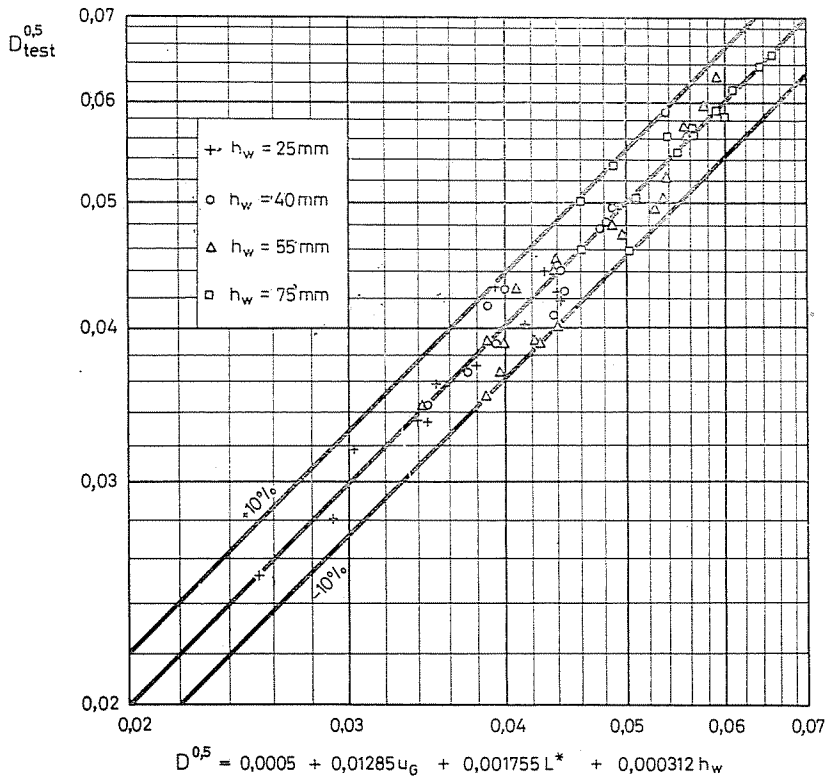


Fig. 7. Test vs. calculated eddy-diffusion coefficient

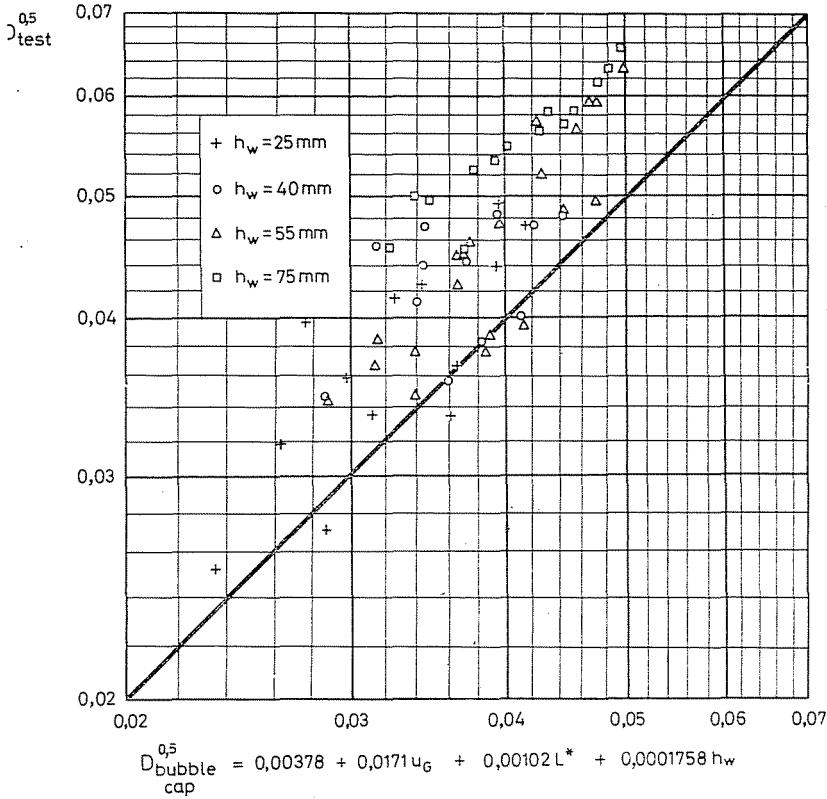


Fig. 8. Test eddy-diffusion coefficient vs. values calculated by the correlation valid for bubble caps

of Fig. 8 that the use of valve trays results in a higher eddy-diffusion coefficient and a more intensive liquid mixing on the tray.

Although Eq. (6) can be used for design purposes, it is advisable to restrict its application to the load limits specified in this study and for the types of valve and tray described before.

**Legend**

- |   |                                   |
|---|-----------------------------------|
| $h_w$ [mm]  | gate height                       |
| $m$   | slope of equilibrium curve        |
| $u$ [m/sec]   | linear gas (steam) velocity       |
| $v$ [m/sec]   | linear phase velocity             |
| $w$   | dimensionless locus co-ordinate   |
| $x$ $\frac{\text{kmol dissolved matter}}{\text{kmol solution}}$ | concentration of liquid phase     |
| $z$ [m]   | co-ordinate                       |
| $A$ [sq.m.]   | flow cross-section area of liquid |
| $D$ [sq.m./sec]   | eddy-diffusion coefficient        |
| $E_{MV}$  | Murphree tray efficiency          |
| $E_{OG}$  | Murphree point efficiency         |

$F = u \cdot \sqrt{\rho_G} \left[ \text{m/sec} \sqrt{\frac{\text{kg}}{\text{cu.m.}}} \right]$	gas load factor
$G_M$ [kmol/hour]	molar gas flow rate
$L$ [cu.m./sec; ou.m./hour]	liquid load
$L^*$ [cu.m./mh]	liquid load referred to the unit length of the gate
$L_M$ [kmol/hour]	molar liquid flow rate
$Pe$	Peclet number
$S$ [cu.m./sec]	rate of liquid weeping through the tray
$S_M$ [kmol/hour]	molar rate of liquid weeping through the tray
$Z_c$ [mm, m]	height of clear liquid on the tray
$Z_l$ [mm, m]	distance between inlet and outlet gate
$Z_w$ [mm, m]	average width of liquid flow on the tray
$\rho$ [kg/cu.m.]	density
$\rho_M$ [kmol/ou.m.]	molar density
$\eta$	marking
$\lambda$	ratio of slopes of the equilibrium curve to the operating straight line
$\psi$	marking
	<i>Subscripts</i>
$be$	inlet
$g$	located at injecting network
$G$	vapour phase
$M$	molar
$o$	located at inlet gate
$w$	gate

### Summary

For determining the number of trays required for tray distillation towers, tray efficiency must be known. There is a correlation between Murphree point efficiency and tray efficiency, depending on the material system and the extent of liquid mixing involved in the process.

For establishing the extent of liquid mixing, the eddy-diffusion coefficient must be known. Since there is some weeping in valve tray columns of a rate depending on tray design, the correlation proposed for static trays does not apply to valve trays. A correlation has been elaborated for calculating the eddy-diffusion coefficient. Evaluation of the test results was made on a model allowing for weeping. This correlation has proved to be suitable for determining the effective number of trays required for tray distillation columns with a fair accuracy.

### References

1. MOLNÁR, K.: *Periodica Polytechnica*, M. E. 17, 4. 301 (1973)
2. TREYBAL, R. F.: *Mass Transfer Operations*, New York, McGraw-Hill Book Company, 1968.
3. LEWIS, W. K.: *Ind. and Eng. Chem.* 28, 399 (1936)
4. "Tray Efficiencies in Distillation Columns", Final Report, University of Delaware, New York, 1958.
5. "Bubble-Tray Design Manual", A I.Ch.E. Manual, New York, 1958.
6. KAFAROV, V. V.: *Az anyagátadás alapjai. (Bases of Mass Transfer.)\** Műszaki Könyvkiadó, Budapest, 1967.
7. PERRY, J. H.: *Chemical Engineers' Handbook*. McGraw-Hill Book Company, New York, 1968.
8. BARKER, P. E.—SELF, M. F.: *Chem. Eng. Sci.* 17, 541 (1962)
9. FOSS, A. S.—GERSTER, J. A.—PIGFORD, R. L.: *A.I.Ch. E. Journal*, 4, 231 (1958)
10. MOLNÁR, K.: *Turbulent diffusion coefficient in valve plate columns.\** (Doctor Techn. Thesis.) 1972.
11. NORMAN, W. S.—GROCOTT, G. J.: *Trans. Inst. Chem. Engers.* 39, 305 (1961)

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