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HYDRODYNAMICS AND MASS TRANSFER OF TEXTILE VIBRATING-VALVE TRAYS

H. MUSTAFA, E. BÉKÁSSY-MOLNÁR* and A. ELHAMOUZ

Chemical Engineering Department, An-Najah National University, West Bank, Nablus, via Israel
**Department of Food Engineering, University of Horticulture and Food, Budapest, Hungary*

New types of vibrating-valve trays with textile valves were investigated to determine their optimal construction. Hydrodynamic and mass transfer measurements were carried out in a pilot plant with different vibrating-valve and conventional valve trays under identical experimental conditions. The total tray pressure drop (Δp), column efficiency (η), volumetric mass transfer coefficient ($K_G a$) and pressure drop per theoretical tray ($\Delta p/N_{th}$) were measured and compared.

The high mass transfer rate, the low investment and operating costs, the corrosion and heat resistance make the vibrating-valve trays attractive for gas absorption and air cleaning in environmental protection.

Keywords: valve trays; vibrating-valve trays; absorption; hydrodynamics; mass transfer

INTRODUCTION

The vibrating-valve tray has tooth-like valves, which vibrate and render the flow cross section adequate to the gas flow rate (Figure 1). At high gas load, the end of the 50 mm long elastic valve can rise 10 ~ 15 mm above the tray surface and around this mean position it vibrates with a frequency of 3 ~ 5 Hz and an amplitude of ± 3 mm.

The textile-valve tray is a new construction patented in Hungary[1]. The textile used as a raw material for the valves, is elastic and corrosion-proof as is the fluorized ethylene-propylene[2] (FEP) version. The advantage of the investigated woven textile (type: SK-IM) is the heat resistance of up to 800°C, while the FEP can be used safely only up to 80°C.

Publications that touch on the hydrodynamics and mass transfer of vibrating-valve trays are very few compared with the literature dealing with conventional valve trays, particularly with Glitsch valve trays[3].

Békássy-Molnár *et al.*[2], Mustafa *et al.*[4] and Annakou *et al.*[5] investigated the hydrodynamic and mass transfer behaviour of vibrating-valve trays. On the basis of experimental results they established that two types of valves proved to be the most useful for high performance: FEP and textile.

Mustafa and Békássy-Molnár[6,7] measured the influence of weeping on mass transfer rate on different types of trays, namely textile-, FEP-, Nutter-, Glitsch-valve, sieve and turbogrid. They realized that all the investigated trays work in the weeping regime with a satisfactory mass transfer rate. Consequently, the operating domain can also be extended towards the weeping regime in case of vibrating-valve trays.

The purpose of this work was to determine the optimal construction of textile-valve trays and to compare the results obtained with those of other tray constructions.

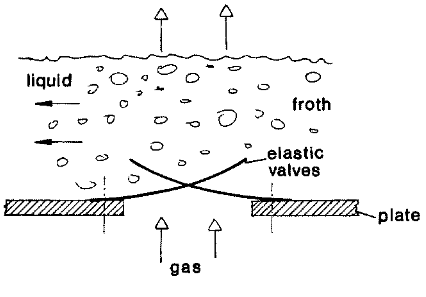

Figure 1. Representation of a vibrating-valve tray.

EXPERIMENTAL

Hydrodynamic and mass transfer experiments were carried out using a pilot plant simulation column of 400 mm inside diameter and 350 mm tray spacing with four trays (Figure 2). Different types of tray constructions were investigated and compared (Table 1). The optimized textile vibrating-valve tray with rectangular valves is shown in Figure 3.

Hydrodynamic parameters were measured using the air/water system. Liquid load was varied between $L_w = 0.12$–$15\,\mathrm{m^3\,m^{-1}h^{-1}}$, while the gas capacity factor (related to active area of tray) was $F_a = 0.3$–$2.6\,\mathrm{Pa^{0,5}}$.

Some measured total pressure drop data (Δp) and pressure drop across the froth (Δp_f) are shown in Figure 4. The working domain of the textile-valve tray and that of the Nutter-valve tray with moving valves is shown in Figure 5.

The mass transfer was measured by the absorption of acetone from air into water. The point of introduction of acetone into the column can be seen in Figure 2. Gas concentrations above the trays were measured continuously by means of an FID analyser and liquid concentration was determined by red-ox titration. Only points with a mass balance deviation below 15% were included in the data base.

Typical concentration profiles are shown in Figure 6. The range of gas content was $Y = 20$–$3000\,\mathrm{mg\,m^{-3}}$, and liquid

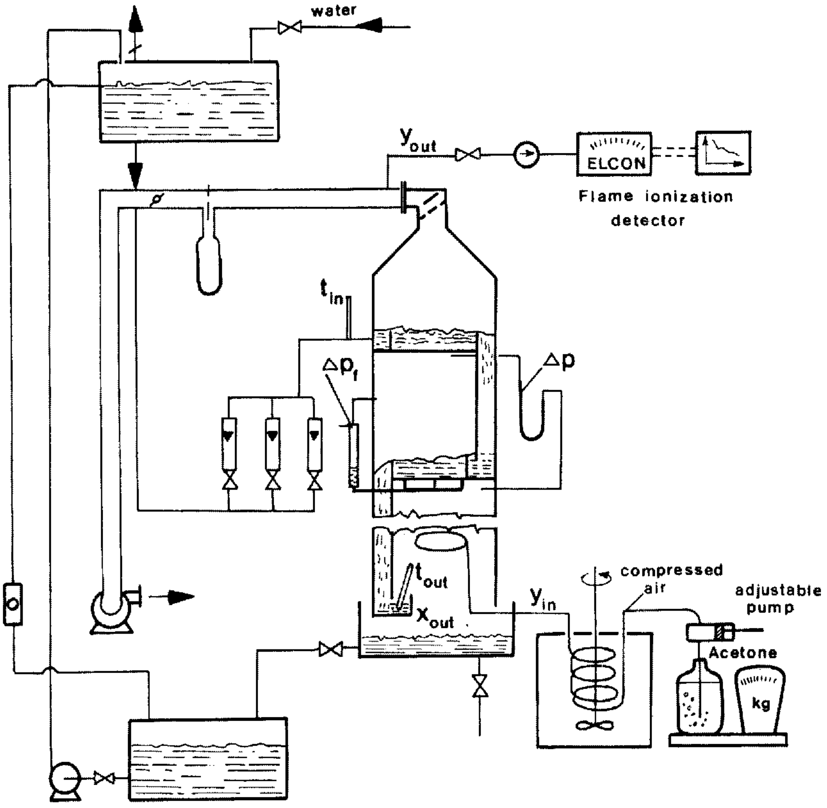

Figure 2. Experimental apparatus.

concentration was X =300–1300 mg dm^{-3} at a column temperature of 8–15°C and pressure of 1 bar. The slope of the equilibrium curve (m) was determined by using the formula[6]:

$$m = 0.3 + 0.04t$$

CHARACTERISTIC PARAMETERS TO EVALUATE DIFFERENT TRAYS

To determine the optimal tray construction and to compare different types of trays, the following characteristic parameters were measured under the same conditions in a

Table 1. Comparison of mass transfer for different tray constructions. Absorption factor $A \approx 2$.

No	Tray type	Weir height h_w (mm)	Free cross section f_a (%)	Valve size or hole size (mm)	Gap between valves (mm) or valve weight (g)	$K_G a$ (1 s^{-1})	$\Delta p/N_{th}$ (Pa)
1	Textile vibrating valve	50	36	20*60^{x}	2 mm	1.70	1120
2		70	36	20*60^{x}	2 mm	1.67	1150
3		60	36	20*60^{x}	3 mm	2.00	950
4		50	36	20*60^{x}	4 mm	1.60	930
5		70	36	20*60^{x}	4 mm	1.91	920
6		60+R*	36	20*60^{x}	3 mm	1.92	1100
7		60	36	(15–20)*60^{xx}	3 mm	1.15	1391
8		60	36	(15–20)*60^{xx}	5 mm	1.51	920
9	FEP vibrating valve	50	36	(3–10)*20^{xx}	6.2 mm	1.80	1150
10		70	36	(3–10)*20^{xx}	6.2 mm	2.00	1460
11		70+R*	36	(3–10)*20^{xx}	6.2 mm	1.90	1300
12	Nutter	50	18.5	15–62	20 g	1.90	1180
13		70	18.5	15–62	20 g	1.70	1500
14	Glitsch	50	17.4	Ø40	31.1 g	1.70	1298
15	Sieve	50	4.5	Ø4.3		1.70	1500
16		50	14.4	Ø6.0		1.57	1010
17		50	9.6	Ø4.9		1.78	1000
18		70	9.6	Ø4.9		1.83	1140

R*: droplet reflector for the case of very low liquid load, $L_w < 1\ \mathrm{m^3 m^{-1} h^{-1}}$
x: the shape of the valves is rectangular (Figure 2.)
xx: the shape of the valves is trapezoid (Figure 2.)

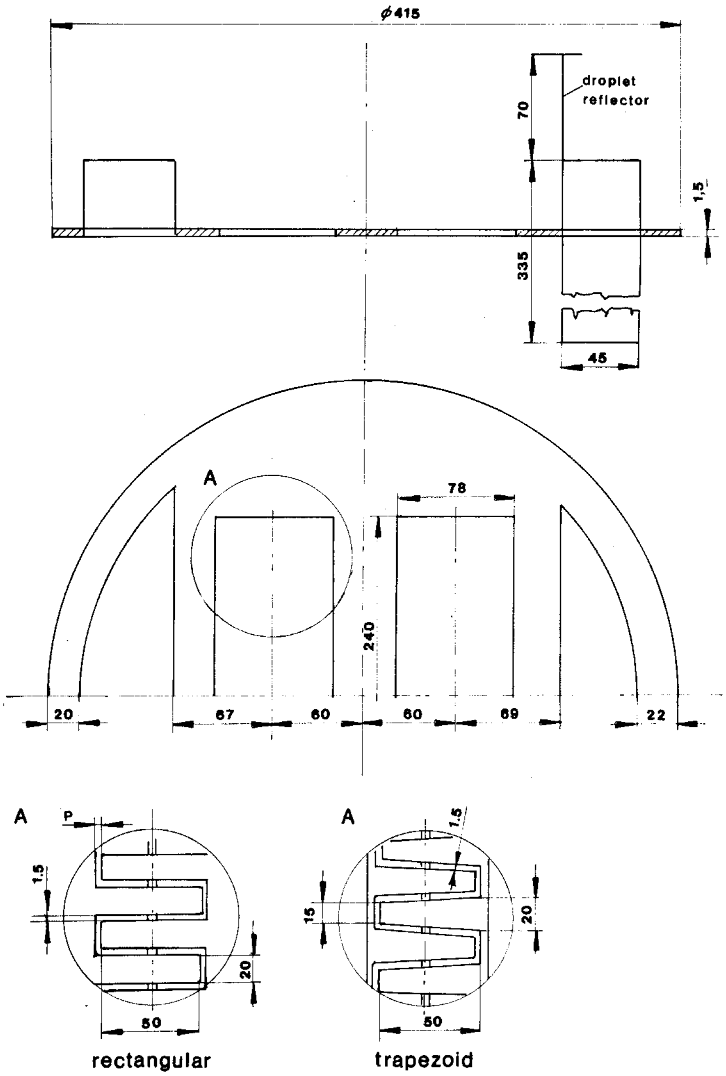

Figure 3. Textile vibrating-valve trays with rectangular and trapezoid valves.

four tray column:

- Total pressure drop of one plate: Δp (Pa)
- Column efficiency measured by acetone-air/water absorption:

$$\eta = \frac{N_{th} \times 100}{N} = \frac{N_{th} \times 100}{4}$$

- Overall volumetric mass transfer coefficient[8]: $K_G a$ ($1\ s^{-1}$)
- 'Energy consumption' of one theoretical tray $\Delta p / N_{th}$ (Pa)

EXPERIMENTAL DESIGN

Five types of vibrating-valve trays with rectangular shaped valves were prepared and investigated. The material of the valves was an elastic and heat resistant woven textile type. Two independent geometrical factors: the weir height (h_w) and the gap between valves (p) were varied systematically, using the method of 2^n factorial design:

- Weir height levels were 50 mm and 70 mm.
- The gap between the valves was 2 and 4 mm.

The experiments were carried out according to a matrix shown in Table 2 and Table 3. The central point corresponds to the mean value of the factors and these were $h_w = 60$ mm and $p = 3$ mm. The characteristic parameters: Δp, η, $K_G a$ and $\Delta p / N_{th}$ were determined as a function of h_w and p.

The results at two operational conditions are summarized in Tables 2 and 3:

$v_a = 1\ \mathrm{m\,s^{-1}}$ $L_w = 2.5\ \mathrm{m^3\,m^{-1}h^{-1}}$ $A = 1.85$ (Table 2)
$v_a = 1.2\ \mathrm{m\,s^{-1}}$ $L_w = 5\ \mathrm{m^3\,m^{-1}h^{-1}}$ $A = 2.35$ (Table 3)

The value of the absorption factor of about $A = 2$ is in line with that recommended in the literature[8].

RESULTS AND DISCUSSION

It was found that for the central point at $h_w = 60$ mm and $p = 3$ mm, the effectivness (η and $K_G a$) have a maximum (Tables 2 and 3). This indicates that the geometrical ranges were well chosen. Since the characteristic parameters cannot be measured with high precision and the variation of the weir height was only ± 10 mm, and that of the gap was ± 1 mm, there was no need for further, more precise optimization: Hence, $h_w = 60$ mm and $p = 3$ mm were chosen as optimal construction data.

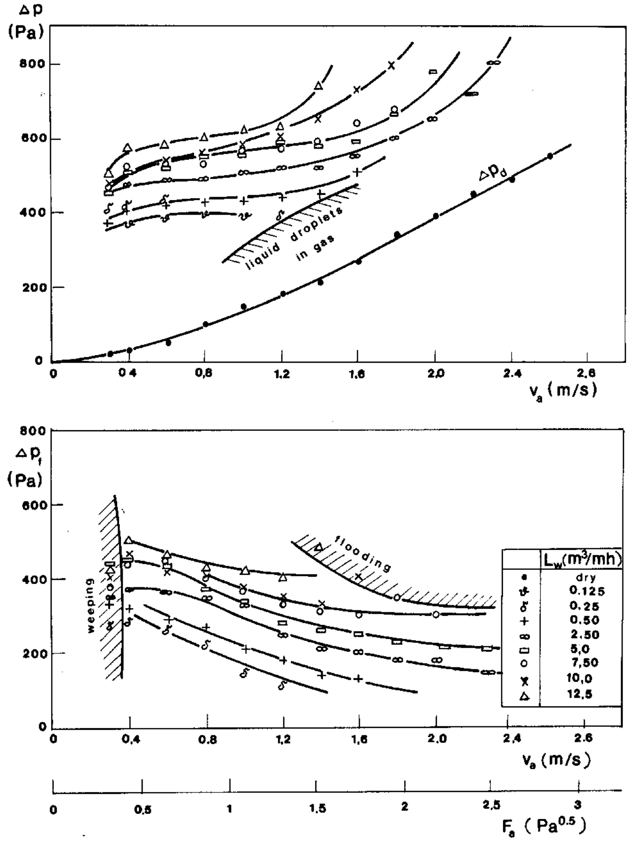

Figure 4. Total pressure drop (Δp), dry tray pressure drop (Δp_d) and pressure drop of froth (Δp_f) as a function of gas velocity relative to the active area of the tray (v_a) and with liquid load relative to the weir length (L_w) for a textile vibrating-valve tray (weir height h_w =60 mm, gap between valves p = 3 mm).

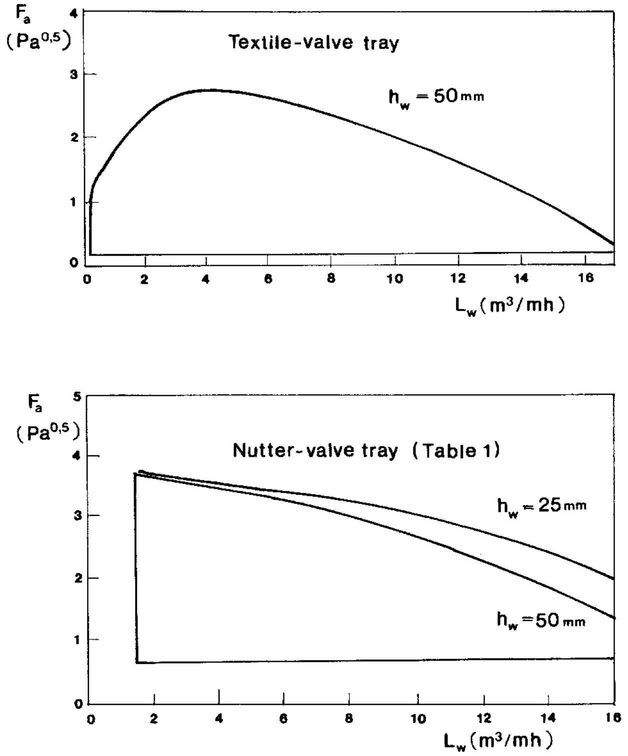

Figure 5. Comparison of the domains of good performance.

Hydrodynamics

The total pressure drop (Δp) is the sum of the dry plate resistance (Δp_d) and the pressure drop of the froth (Δp_f). It can be seen that excluding the weeping and flooding regions, the pressure drop barely increases with an increase in the gas velocity. This indicates the hydrodynamic flexibility of the textile vibrating-valve tray (Figure 4).

Table 2. Matrix I. of experimental design textile-valve tray with rectangular valves. $v_a = 1\ \mathrm{m\ s^{-1}}$; $F_a = 1.1\ \mathrm{Pa^{0.5}}$; $L_w = 2.5\ \mathrm{m^3 m^{-1} h^{-1}}$; A = 1.85.

Exp.	h_w (mm)		p (mm)		$\Delta p/N_{th}$ (Pa)	K_Ga (1/s)	Δp (mm)	η (%)
1	−1	50	−1	2	1069	1.81	54	50.3
2	−1	50	+1	4	913	1.57	42	42.1
3	+1	70	−1	2	1244	1.67	56	45.0
4	+1	70	+1	4	865	1.91	45	52.0
5	0	60	0	3	952	2.00	49	56.6
6	0	60	0	3	945	1.78	52	54.9
7	0	60	0	3	1019	1.68	53	52.0

Table 3. Matrix II. of experimental design textile-valve trays with rectangular valves. $v_a = 1.2\ \mathrm{m\ s^{-1}}$; $F_a = 1.3\ \mathrm{Pa^{0.5}}$; $L_w = 5\ \mathrm{m^3 m^{-1} h^{-1}}$; A = 2.35.

Exp.	h_w (mm)		p (mm)		$\Delta p/N_{th}$ (Pa)	K_Ga (1/s)	Δp (mm)	η (%)
1	−1	50	−1	2	1269	2.16	59	46.6
2	+1	50	+1	4	946	1.96	44	46.3
3	−1	70	−1	2	1289	2.07	58	46.0
4	+1	70	+1	4	948	2.28	46	48.0
5	0	60	0	3	938	2.47	53	56.3
6	0	60	0	3	939	2.37	54	57.3
7	0	60	0	3	1029	2.26	54	52.7

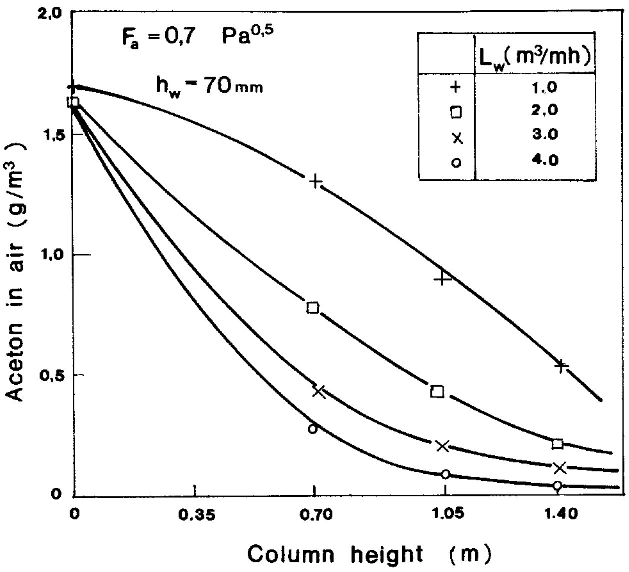

Figure 6. Concentration profiles in a column with four vibrating-valve trays at identical inlet gas concentration and different liquid loads for absorption of acetone from air by water.

The pressure drop across the froth increases with an increase in the liquid flow rate and decreases with an increase in the gas velocity (at higher gas velocity the foam density is lower which causes a lower pressure drop).

An important advantage of the textile valve tray is that the minimum liquid load is nearly one order of magnitude less than that of traditional trays or packed columns. This is illustrated in Figure 5, where the working domain of the textile valve tray is compared with that of the Nutter-valve tray, with moving valves (Table 1).

Mass Transfer

The efficiency is shown in Figure 8 as a function of liquid flow rate. For an F-factor of $F_a = 0.7\,\mathrm{Pa}^{0.5}$ and a liquid load of $L_w = 2\,\mathrm{m}^3\,\mathrm{m}^{-1}\mathrm{h}^{-1}$ the efficiency of vibrating valve trays (FEP and Textile) ranges between 40–55%, while the efficiency of traditional trays is 35–40%. The efficiency of the optimum construction textile-valve tray is about 55% at the same conditions.

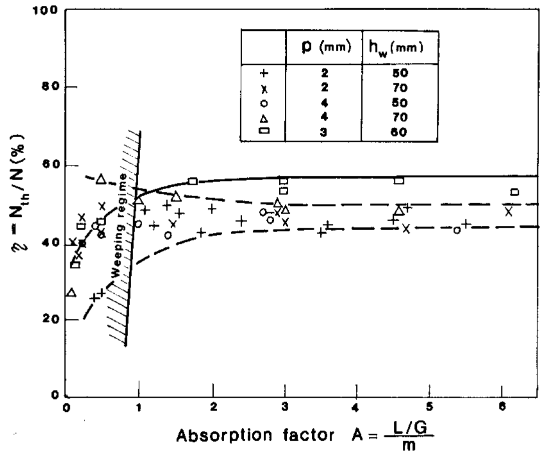

Figure 7. Column efficiency of different textile vibrating-valve trays measured for absorption of acetone from air into water.

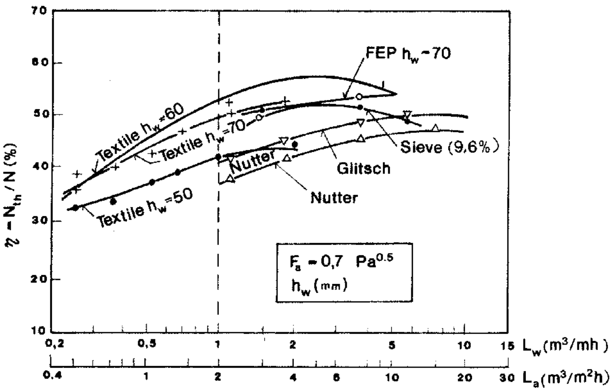

Figure 8. Comparison of the column efficiency of different vibrating-valve trays and conventional trays as a function of liquid flowrate.

In the domain of low liquid flow rate ($L_w < 1\,\mathrm{m}^3\,\mathrm{m}^{-1}\mathrm{h}^{-1}$) only vibrating valve trays operate under hydrodynamically stable conditions with adequate mass transfer rates. At higher liquid flow rates the mass transfer performance of some traditional trays is less than that of vibrating-valve trays.

According to our measurements, the volumetric mass transfer coefficient ($K_G a$) of vibrating-valve trays is 10–20% higher than that of traditional trays (Table 1).

Pressure Drop per Theoretical Stage

Table 1 shows that the value of $\Delta p/N_{th}$ decreased with an increase in the gap between valves and was only slightly affected by the weir height.

The column efficiency (η) is almost independent of the absorption factor shown in Figure 7.

Industrial Applications

Textile vibrating-valve tray columns have been used in industry for the absorption of waste gases. Examples of some successful applications are briefly as follows:

In a refinery plant, warm corrosive vacuum gas containing H_2S is absorbed by mono-ethanol-amine/water solution in a 900 mm diameter absorber with 10 trays.

In a plastics factory, air containing dimethyl-formamide is removed from a fibre cell and led to an 8 tray absorber of 1600 mm diameter. The solvent is deionized water. The outlet DMF concentration is below $100\,\mathrm{mg\,m}^{-3}$ in the air and 18–19% in the water. The high concentration water is recycled to the fibre cell as a solvent. The textile valve tray has also been successfully applied for dust washing from dirty gases.

CONCLUSIONS

A new type of vibrating-valve tray, the textile-valve tray, has been introduced for absorption. Using an experimental design method, the optimum construction of that tray occurred at a weir height of 60 mm and a gap of 3 mm. An important advantage of the textile-valve tray is that the minimum liquid load is nearly one order of magnitude less than that of traditional trays. The vibrating-valve tray gives high mass transfer effectiveness while the pressure drop per stage, or energy consumption, changes moderately due to the valve effect. Another advantage of the textile-valve tray is that there are no friction elements, since the valves do not touch each other. There is no need to use raw materials of high mechanical strengths. Therefore, both the investment cost and the operational costs are fairly low. Textile valves have been used successfully in industrial applications. The heat resistance of textile-valves makes the tray attractive for thermal separation processes also.

NOMENCLATURE

A	absorption factor, $A = \frac{L/G}{m}$, – (L – $\mathrm{l\,h^{-1}}$ water, G – $\mathrm{m^3h^{-1}}$ air)
F_a	gas capacity factor related to the active area of tray, $\mathrm{Pa^{0.5}}$
h_w	weir height, mm
K_Ga	overall volumetric mass transfer coefficient, $\mathrm{1\,s^{-1}}$
L_a	liquid load relative to the active area of tray, $\mathrm{m^3m^{-2}h^{-1}}$
L_w	liquid load relative to the weir length, $\mathrm{m^3m^{-1}h^{-1}}$
m	slope of equilibrium line, $(\mathrm{g\,m^{-3}}$ air$)/(\mathrm{g\,l^{-1}}$ water$)$
N	number of trays in the column, –
N_{th}	number of theoretical trays, –
p	gap between valves, mm
t	mean temperature in the column, °C
v_a	gas velocity relative to the active area of tray, $\mathrm{m\,s^{-1}}$
Δp	total pressure drop of the tray, Pa
Δp_d	pressure drop of dry tray, Pa
Δp_f	pressure drop across the froth, Pa
η	column efficiency, %

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ADDRESS

Correspondence concerning this paper should be addressed to Professor E. Bekassy-Molnar, Department of Food Engineering, University of Horticulture and Food, H-1118 Budapest, Menesi str 44, Hungary. (E-mail: bmolnar@hoya.kee.hu).

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