THE EFFICIENCY OF THE VERTICALLY ARRANGED EXPANDED METAL SHEETS FOR EVAPORATIVE COOLING AND AIR HUMIDIFICATION*

Z. BROŽ and G. P. PASCALEV**

Institute of Chemical Process Fundamentals, Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchdol

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The paper deals with experimental determination of the efficiency of the vertical plane packing made of expanded metal sheets for cooling water by air. The results are compared with the data found in the literature and the correlation of Gilliland and Sherwood for diffusion of vapour into a turbulent stream of air.

Water applied as a coolant in chemical industry and power plants usually circulates in a closed loop and must be therefore cooled at some point before returning into the process. Various types of direct and indirect heat exchangers are used for cooling water. The most widely used type is a tower where water cools by direct contact with air giving up part of its sensible heat and evaporating partially. Depending on the type of the packing and auxiliary equipment the tower works under either natural or forced convection of the air. Another application of towers with direct gas–liquid contact is the drying or humidification of industrial gases.

Since the involved amounts of gases in contact with liquid are frequently large it is desirable that the packing of the cooling tower have a minimum pressure drop. This is very well met by the packing made of vertical expanded metal sheets. This packing has been shown in experimental studie, to have also a very good efficiency for absorption[1,2] and rectification[3] and permits high through-puts of the phases per unit area of tower cross section.

This paper deals with the results achieved on this type of packing for direct contacting of cooled water and air.

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** Present address: Central Laboratory of Chemical Engineering, Bulgarian Academy of Sciences, Sofia, Bulgaria.

EXPERIMENTAL

The packing was made of carbon-steel expanded metal sheet with 16×6 mm openings: the thickness of the sheet was 1·215 mm. The spacing of the sheets was 10 mm leaving 7·6 mm wide gap between the sheets. The overall length of the irrigated edge of the sheets was 1·26 m. The sheets within the tower were arranged vertically and proper spacing of the sheets was ensured by strips of corrugated metal sheet welded to the expanded metal sheet. The distance between individual spacers along the height of the tower was 400 mm. The packing was mounted in a glass tube 133 mm in diameter insulated at its outside by polystyrene foam and strips of wool. Tap water was fed onto the packing through an area distributor. The temperature of the circulating water was kept at 45°C by pneumatic regulation of a steam heater. The flow rate of water driven by a centrifugal pump was metered by a rotameter and orifices. Having set the flow rate of water a ventilator was switched on and the flow rate of air was adjusted so as to reach the state just below flooding. Reaching the steady state after approximately 15 minutes the flow rates, the pressure drop and the inlet and outlet temperatures of water and air were recorded. The temperatures were measured by calibrated mercury thermometers to an accuracy of 0·2°C. The humidity of the inlet and the outlet air was assessed from the reading of the dry and the wet-bulb thermometers. As a next step the flow rate of air was gradually decreased keeping the flow rate of water constant.

The flow rates of water employed correspond to the following values of the density of irrigation, L: 8080, 15600, 25900, 43200 and 86400 kg m^{-2} h^{-1}. The velocities of air related to empty column cross section amounted to 1·1, 1·6, 2·2, 3·2, 4·2 m s^{-1} plus the value bringing about flooding. The densities of irrigation per unit length of the irrigated edge of the packing (linear density of irrigation), Γ, were: 0·0248, 0·0478, 0·0793, 0·132, 0·265 kg m^{-1} s^{-1}. The experimental measurements extended over a period of about one year leaving considerable time span between individual replica measurements. This should reveal eventual long-term effects of the surface of the packing (oxidation, precipitation of insoluble deposits, *etc.*).

RESULTS

Experimental data were evaluated in two ways. The first method utilized the difference of enthalpies under local conditions and that of the saturated air as a driving force. The height of a transfer unit was computed from

$$H_G = l \bigg/ \int_{I_b}^{I_t} \mathrm{d}I \bigg/ (I^* - I) . \qquad (1)$$

The integral on the right hand side of Eq. (*1*) was evaluated numerically. The enthalpy corresponding to the bottom of the column, I_b, was computed from the psychrometric equation and the data of the dry and wett-bulb thermometers. The enthalpies, I, along the height of the column as well as the enthalpy corresponding to the column top, I_t, were computed from the equation of the operating line, the enthalpy of the saturated air, I, from temperature and corresponding equilibrium humidity. The thermal balance for air and water was within 7%.

The dependence of the height of a transfer unit on the velocity of air with the density of irrigation as a parameter is shown in Fig. 1. At higher densities of irrigation HTU becomes independent of the velocity of air or slightly decreases and falls between 0·6 and 0·7 m. At very low densities of irrigation it is likely that the interfacial area diminishes considerably and HTU grows. The terminal points of all curves represent states just before formation of gas–liquid mixture at the inlet end for air and this state will be refered to as the flooding. (The value of the velocity of flooding depends strongly on the design of the air entrance region.) Nevertheless, the packing can be operated above this point (the velocity of flooding) but a foam forms, the hold up and pressure lossess increase, and small droplets of water are being entrained by air. The height of a transfer unit under such conditions decreases. This phenomenon has been observed for all densities of irrigation employed in this work; for the densities 8080, 43200 and 86400 kg m^{-2} h^{-1} the phenomenon is depicted in Fig. 1 by a broken line.

The other way of processing experimental data obtained on the vertical expanded metal sheets packing compares the results with those of Gilliland and Sherwood[4] corresponding to the evaporation of various liquids into streaming air in a 2·67 cm in diameter wetted wall column. The authors describe evaporation by means of a correlation for the thickness of the diffusional film, x, expressed as a fraction of the column diameter, d, *versus* the Reynolds and the Schmidt numbers for gas in the form

$$d/x = 0{\cdot}023(du\varrho/\mu)^{0.83}\,(\mu/\varrho D)^{0.44}\,. \tag{2}$$

The ratio d/x was expressed from the equation for the flux of the diffusing vapour per unit area of interface, N_A

$$N_A = DP\,\Delta p_A/(RTxp_{BM})\,. \tag{3}$$

Multiplying both sides of Eq. (3) by the diameter of the column, d, and after some

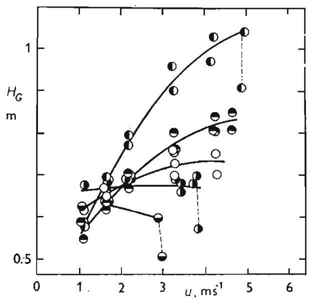

FIG. 1

HTU as a Function of Air Velocity with the Density of Irrigation as a Parameter

◐8080, ⊖ 15600, ○ 25900, ◑ 43200, ⊖ 86400 kg m^{-2} $hour^{-1}$.

arrangement we obtain

$$d/x = dRTp_{BM}N_A/(DP\,\Delta p_A)\,. \qquad (4)$$

In our case, when we deal with a column of rectangular cross section, the equivalent diameter for gas was defined in the usual manner as

$$d_e = 4F/0 = 2bh/(b + h) \approx 2b\,, \qquad (5)$$

where b stands for the spacing of the expanded metal sheets and h designates the width of a strip. A comparison of the results, achieved during experiments with expanded metal sheet packing, with Eq. (2) valid for a wetted-wall column can be seen from Fig. 2. From the figure it is apparent that the dependences separate according to the densities of irrigation. Low values of the density of irrigation exhibit low d_e/x. For intermediate densities, the straight lines approximate Eq. (2) (broken line) and for the densities above about 35 000 kg m^{-2} h^{-1} the experimental values of d_e/x are higher. Judging the comparison one should bear in mind the tenfold range of the densities of irrigation (with a maximum $L = 86\,400$ kg m^{-2} hour^{-1}) covered in our study with the expanded metal sheet packing in contrast to the Gilliland and Sherwood's correlation representing a single density of irrigation 84 660 kg . . m^{-2} h^{-1}. For this reason d_e/x deviate toward lower values at low densities of irrigation as a result of diminished interfacial contact area which is thus less than twice the geometrical surface of the sheets. High values of d_e/x for the maximum densities of wetting may on the contrary be accounted for by higher degree of turbulence of both the gas and the liquid stream caused by the spatial structure of the expanded metal sheets. Formation of additional interfacial area on the corrugated metal strip spacers and waves on the surface of the film may also contribute to the increased

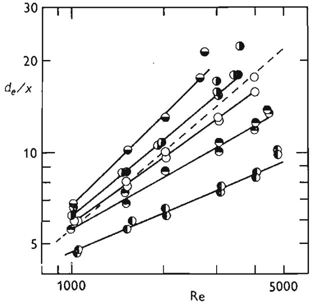

FIG. 2

d_e/x as a Function of the Reynolds Number ◐ L = 8080, ◓ 15600, ○ 25900, ◑ 43200, ◒ 86400 kg m^{-2} hour^{-1}.

d_e/x in comparison to Eq. (2) at the same value of the Reynolds number. The straight lines for individual densities of irrigation display a certain increase of the value d_e/x for the flooding points as these have been discussed in connection with Fig. 1. Expressing the slope of these straight lines (exponent over gas Reynolds number) as a function of the density of irrigation, which could have been done, was regarded as merely formal and meaningless in view of the above mentioned reason for this phenomenon. The course of these straight lines in Fig. 2 is thus to some extent indicative of the magnitude of the interfacial area and at some densities of irrigation the equation of Gilliland and Sherwood can be used to give sufficiently close estimates for the expanded metal sheet packings.

The above experiments represent a single diameter of the column, single size of the openings of the expanded metal sheet and a single spacing of the strips of the sheet. It can be therefore assumed that these parameters could be optimized with the aim to obtain higher efficiency for the cooling of liquids or evaporation of liquids. In the monograph Cooling towers, Jackson[5] have published minimum densities of irrigation by water for various types of packings (Table I), the number of gas velocity heads lost per meter of the packing, economic gas rates and the corresponding velocities in the empty tower. The height of a transfer unit pertains to the mean flow rate of gas, G_m, of the above limits. For this mean value also the pressure losses per meter of packing were computed. In order that we might compare the results for individual packings under equivalent conditions, we took the ratio L/G equal 1·1 as this value ensures that the minimum density of irrigation is at least reached

TABLE I

Comparison of Various Packings for $L/G = 1{\cdot}1$

Number	Packing	L_{min} kgm^{-2} h^{-1}	n m^{-1}	Economic air mass velocities kgm^{-2} h^{-1}	Corresponding superficial velocities m s^{-1}
1	1 in plain grids	5 300	29·5	6 210—9 890	1·5—2·4
2	2 in serrated wooden grids	2 854	9·8	8 625—13 570	2·1—3·4
3	3 in stacked rings	5 300	59	4 738—6 095	1·2—1·5
4	3 in dumped rings	4 480	262	2 875—5 474	0·6—1·2
5	expanded metal sheet packing[3]				

Notes. 1 For packings 1—4 the mean value of the economical air mass velocity G_m, 2 For packings

or exceeded for all types of listed packings. The density of irrigation, L, was then computed from the mean flow rate of gas, G_m, and the ratio $L/G = 1{\cdot}1$. The ratio $L/G = 1{\cdot}1$ represents the maximum of the interval $L/G = 0{\cdot}4 - 1{\cdot}1$ encompassing usually the economic optimum water cooling.

Table I indicates that the density of irrigation L and the flow rate of gas per unit volume of the tower, G/H_G, are maximum for packings made of expanded metal sheet. For the process of cooling water by air the pressure loss of the packing becomes important from the economy point of view. This quantity has been incorporated into the group $Gl/H_G \, \Delta p$ which, for the expanded metal sheet packing also takes a maximum value. The value of this group can be further increased by more sparse spacing of the sheets as may be apparent from the course of the lines in Fig. 2 and the pertaining discussion.

A similar comparison for the loading point is shown in Table II. For the packings 1–4 Jackson reports the data about the loading point only for two ratios L/G. For the expanded metal sheet packing the air velocity of the loading point was defined as that corresponding to 80% of the velocity of flooding. The remaining quantities were interpolated to this value and appear also in Fig. 3 as functions of the density of irrigation. The region applicable to water cooling is at low densities of irrigation. This follows from the ratio L/G and the cooling temperature difference, Δt, achieved on the height of the sheets equalling 1·215 m. For gas humidification or cooling of gases by water, the L/G ratio may take higher values.

TABLE I

(*Continued*)

G^1 kgm^{-2} h^{-1}	U m s^{-1}	$H_G{}^2$ m	$\Delta P/l$ Nm^{-3}	L kgm^{-2} h^{-1}	G/H_G kgm^{-3} h^{-1}	$Gl/H_G \, \Delta p$ kgh^{-1} N^{-1}
8 050	1·9	0·73	64	8 855	11 030	172
11 100	2·7	1·52	41	12 211	7 300	178
5 420	1·3	0·98	58	5 961	5 530	95
4 170	1·0	0·67	153	4 591	6 230	40·7
14 180	3·4	0·78	75	15 600	18 180	242

1–4 the HTU corresponds to G_m, 3 Interpolated from experimental data for $L/G = 1{\cdot}1$ (for the density of irrigation $L = 15600$ kg m^{-2} hour^{-1}).

TABLE II

Comparison of Various Packings at Loading

Notes: 1 u(loading) = 0·80u (flooding) for the expanded metal sheet packing, 2 The effect of the density of irrigation was neglected in the calculation of the pressure drops for packings *1–4* from velocity head lost per meter of packing and air velocity (Table I). 3 HTU for packings *1–4* were corrected for air velocity by the relation $H_G = H_{Gm}(G/G_m)^{0.25}$ where H_{Gm} and G_m are given in Table I.

Number	Packing	L kgm^{-2} h^{-1}	G kgm^{-2} h^{-1}	L/G —	U^1 m s^{-1}	$\Delta P/l^2$ Nm^{-3}	$H_G{}^3$ m	G/H_G kgm^{-3} h^{-1}	$Gl/H_G \Delta p$ kg h^{-1} N^{-1}
1	1 in plain grids	8 970	11 400	0·79	2·8	130	0·80	14 250	110
		17 940	9 860	1·82	2·3	96	0·77	12 800	133
2	2 in serrated wooden grids	4 480	12 380	0·362	3·0	51	1·55	7 990	157
		8 970	6 840	1·31	1·7	15	1·34	5 100	340
3	3 in stacked rings	8 970	10 140	0·89	2·5	200	1·14	8 890	445
		17 940	9 610	1·87	2·3	180	1·13	8 500	472
4	3 in dumped rings	8 970	7 960	1·13	1·9	560	0·79	10 080	180
		17 940	7 580	2·37	1·8	510	0·78	9 720	190
5	expanded metal sheet packing	8 070	16 340	0·49	4·0	100	0·99	16 500	165
		15 600	15 180	1·03	3·7	80	0·79	19 220	240
		25 900	13 850	1·87	3·4	68	0·72	19 240	283
		43 200	12 340	3·5	3·1	62	0·67	18 420	297
		86 400	9 480	9·1	2·4	60	0·61	15 540	259

The quantities G/H_G and $Gl/H_G\,\Delta p$ from Table II are therefore plotted as functions of the L/G ratio in Fig. 4. From the figure it is apparent that the expanded metal sheet packing exhibits considerably higher or comparable values $Gl/H_G\,\Delta p$ in the whole range of the used ratios L/G.

The equation (2) of Gilliland and Sherwood for the wetted wall column and our data for the expanded metal sheets enable a comparison to be made of heat and mass transfer for the two geometries. The values to be compared are the data on the interfacial area per unit volume of the column, the magnitude of the mass transfer coefficient, the overall rate of mass (heat) transfer per unit volume of column corresponding to a unit driving force, pressure drop, price, *etc.* From the standpoint of design it is clear that a bundle of closely spaced tubes can be wetted only on their inner walls. For tubes arranged in a triangular pitch the pitch amounts to usually $1{\cdot}25d$ to $1{\cdot}5d$. The specific interfacial area is maximum for the $s = 1.25d$ pitch, namely $a = 2{\cdot}32/d$. Substituting $d = 0{\cdot}0267$ (Gilliland and Sherwood) we obtain $a = 86{\cdot}7\,\mathrm{m}^{-1}$. For the expanded metal sheet packing with the 10 mm spacing the corresponding a is 200 m^{-1}. For our purposes it is more suitable not to use the definition of the equivalent diameter of the packing and write the Nusselt number as

$$\mathrm{Nu} = Kd/D = d/x\,. \tag{6}$$

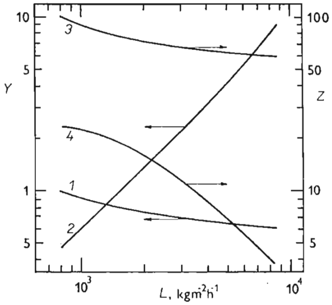

FIG. 3

HTU, L/G, Pressure Drop and Cooling Range as Functions of the Density or Irrigation at Loading

Y: *1* H_G (m), *2* L/G; Z: *3* $\Delta p/l$ (Nm^{-3}), *4* Δt (°C).

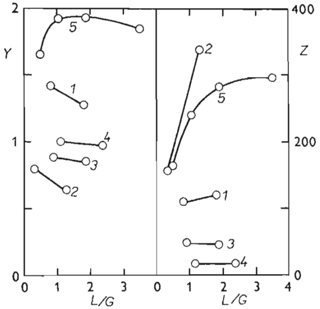

FIG. 4

The Groups G/H_G (kg m^{-2} hour^{-1}) and $Gl/H_G\,\Delta p$ (kg hour^{-1} N^{-1}) as Functions of L/G at Loading

Y G/H_G 10^{-4}, Z $Gl/H_G\,\Delta p$. The figures on individual curves agree with those in Table II.

For the mass transfer coefficient we then get

$$K = (d/x) . (D/d) . \tag{7}$$

The experimental data of Gilliland and Sherwood for the counter-current flow of water and air were recalculated in accord with Eq. (7) and compared with our experimental data. This comparison is furnished in Fig. 5 showing the data in dependence on the velocity of air. This figure shows also by the broken line the dependence computed from Eq. (2).

The mass transfer coefficient, K, corresponding to the expanded metal sheet packing is by 30% higher than that for the wetted wall column. With the density of irrigation decreasing by a factor of more than ten, K is by 10–45% less than that for the wetted wall column. This is probably due to the decreased interfacial area at low densities of irrigation. The dependence on the density of irrigation cannot be compared because Gilliland and Sherwood in their wetted wall column did not vary the flow rate of water.

Naturally, the maximum velocity of air for the expanded metal sheet packing is lower owing to the thick spacing of the sheets. However, comparing the data for the rate of mass (heat) transfer per unit column volume at a unit driving force we obtain for the velocity $u = 3 \text{ m s}^{-1}$ the following values: for the wetted wall column $Q = Ka = 0{\cdot}0215 \times 86{\cdot}7 = 1{\cdot}86 \text{ s}^{-1}$; for the expanded-metal-sheet-packed column $Q = 0{\cdot}031 \times 200 = 6{\cdot}2 \text{ s}^{-1}$. On taking $u = 6 \text{ m s}^{-1}$ we obtain for the wetted wall column $Q = 0{\cdot}038 \times 86{\cdot}7 = 3{\cdot}3 \text{ s}^{-1}$ which is still almost one half of that for the expanded metal sheet. If we ensure wetting of both surfaces of the tubes of the wetted wall column we reach the same Q as that for the expanded metal sheet. However, such construction has not been made so far technically feasible. Further improve-

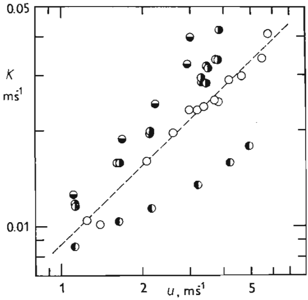

FIG. 5

Plot of K (ms^{-1}) *versus* Velocity of Air (ms^{-1})

Broken line — Eq. (2) of Gilliland and Sherwood[4] wetted wall column[4]: ○ $L = 84\,600$ kg m^{-2} hour^{-1} expanded-metal-sheet-packed column: ◒ $L = 86\,400$, ◑ 43 200, ◐ 8 080 kg m^{-2} hour^{-1}.

ment could be achieved by smaller diameter tubes. This, of course, would increase their number and hence the capital and running costs and pressure drop.

LIST OF SYMBOLS

a	specific interfacial area
b	spacing of the strips of expanded metal sheet
d	tube diameter
d_e	equivalent diameter of packing
D	diffusion coefficient
F	area of cross section of a rectangular duct for the flow of gas
G	mass velocity of gas
h	width of the strips of expanded metal sheet
H_G	height of a transfer unit
I	enthalpy of air per unit mass of dry air
I^*	enthalpy of saturated air per unit mass of dry air
K	overall coefficient of mass transfer
l	length of the strips of expanded metal sheet
L	density of irrigation
n	number of velocity heads lost per meter of packing
N_A	flux of diffusing species across interface
$Nu = Kd/D$	Nusselt number
O	wetted perimeter of rectangular duct for gas flow
P	absolute pressure
$\Delta p/l$	pressure drop per meter of packing
p_{BM}	long-mean partial pressure of inert (air)
Δp_A	mean difference of partial pressure of liquid and vapours in streaming air
Q	rate of mass (heat) transfer per unit volume of column for a unit driving force
R	gas constant
$Re = ud\varrho/\mu$	Reynolds number
s	pitch of tubes
T	Kelvin temperature
Δt	cooling range, temperature difference between inlet and outlet
u	velocity of air in an empty column
V	superficial velocity of gas
x	thickness of diffusional film
Γ	linear density of irrigation related to the length of irrigated edge
μ	viscosity
ϱ	density

Subscript

b	bottom
e	equivalent
t	top
min	minimum
m	mean

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