The Investigation of Cooling Tower Packing in Various Arrangements

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Abstract

The effect of form with corrugated packing on heat transfer and pressure drop characteristics in   atmospheric cooling towers has been studied experimentally. The results showed that the heat transfer coefficient decreased with increase in packing pitch and increase in the ratio of rib pitch to rib height. Friction factors were expressed by a dimensional equation which included pitch and distance between the packings, for both smooth and rough surface. From these results, the relationship between packing heat transfer coefficient and pressure drop was deduced. The correlations were verified with additional experimental data taken with $1.1 < P/D < 1.70$ and $1 \leq p/e \leq 5$. This provides a useful Semi experimental relation, in the area generally lacking in design and performance data.

Symbol

a	Pack density (surface area per unit volume)	m^{-1}
D	Distance between the cooling tower packing (rib)	mm
e	Height of roughness element,	mm
G	Flow rate (air),	kg/s
G'	Mass flux (air),	kg/m^2s
E	Height of corrugation,	mm
L	Flow rate (water),	kg/s
L'	Mass flux (water),	kg/m^2s
k	Mass transfer coefficient,	kg/m^2s
Nu	Nusselt Number	dimensionless
p	Distance between repeated ribs,	mm
P	Pitch of packing, (see Figures 3 & 4)	mm
Pr	Prandtl Number,	dimensionless
Z	Packed height,	m
Δp	Pressure drop,	Pa
Re_w	Water Reynolds number $= 2\,L'\,D/\mu_w$	dimensionless
ρ_a	Air density,	kg/m^3
u_a	Air velocity inside the packing,	m/s
u_w	Water velocity inside the packing,	m/s
θ	Angle of inclination of cross ribbing with the horizontal,	°

Introduction

In general, the design of an efficient, compact mass transfer pack for gas/liquid applications is based on the optimisation of the passage diameter and passage length. Also from a number of recent studies it is apparent that the choice of material plays a major role in packing design, the ideal material being highly formable in order to provide a high specific surface area.(Egberongbe 1990). Heat and mass transfer between a falling liquid film along a vertical wall and upward flowing air contacting directly with the film is an important and interesting phenomenon in industrial apparatus such as cooling towers. While 96% of the cooling towers use PVC packing with smooth and cross ribbing, no data on the flow of liquid over a flat vertical wall with cross ribbing have been published. Only some of the features of their operation in contact heat exchangers have been investigated. (Bukowski 1995, Nabhan 1994, Kranc 1993, Marselle 1991). Major aspects that remain to be studied include: the geometry and layout of the main corrugation with and without the cross ribbings, the pattern of flow of the liquid film and interaction between phases. In this paper the mass transfer and pressure drop characteristics of many types of corrugated packing, including smooth and rough surface corrugated packings, are investigated, and the relationship between packing mass transfer coefficients and pressure drops are discussed. Mass transfer performance of rough corrugated packing is increased by 1.5 to 2.5 times the smooth packing values, but the pressure drop of packings also increases with the increase in heat transfer performance.

Experimental Apparatus and Procedure

The experimental apparatus for the heat transfer experiments, consisted of a counterflow forced draft cooling tower, as shown in Fig. 1. Water stored in a tank at the base was pumped into the spray nozzles. The supply water velocity was regulated by a valve. The cross sectional test area was A= 0.15 x 0.15 m. Inlet and outlet air and water temperatures were measured by mercury in glass thermometers with a range of 0-50°C and an accuracy of 0.2 K. Packing pressure drop was measured by an APM 2000 (0 to 2000 Pa) micromanometer with an accuracy of ±1% (i. e. maximum of 1.2 pa error in our measurements). Measurements of mass transfer and pressure drop were carried out in the steady state. The mass transfer coefficients and pressure drops were measured for a range of L/A (L') from 0.45 to 2.22 kg/m²s and G/A (G') 0.20 to 1.50 kg/m²s. A series of perimeter deflector plates as shown in Fig 1 was installed around the inner perimeter of the column, made in the laboratory of clear Poly Carbonate plastic to allow observation of the water flow. These deflector plates removed the water film from the wall of the tower's column and redistributed the water in the packing zone. As a result of deflection, most of the water was transferred to the packing surface from the outer wall, forming descending thin films, while air was blown vertically upward, counter current to the water by a fan at the base.

The packings tested were of two types, smooth and ribbed, both of PVC. The smooth packing had horizontal corrugations and the ribbed had horizontal corrugations with ribbing set at an angle to the main corrugations. The cross ribs were separated by distance

p, ranging from 2 mm to 10 mm, for the six sample packings, and the height e of the ribs ranged from 1 mm to 3 mm. The main corrugation pitch, P, ranged from 30 mm to 70 mm. The thickness of packing was negligible. The forms of corrugated packings used in the experiments are listed in Table 1, and typical shapes are shown in Figs. 3 and 4. The column packed height, Z, was 160 cm and the water level in the sump was about 1.2 m below the top of the packing. Water inlet and outlet temperatures were 37 °C and 27 °C respectively.

Table 1: shapes of corrugated packing used for experiments

Test Group	Type of corrugation	Surface area per unit volume (m^{-1})	Pitch (mm)	Spacing (mm)	P/D	Type of surface	p/e	θ deg)
C1	sinusoidal	200	70	50	1.40	rough	1	45
C2	sinusoidal	250	65	40	1.65	rough	3	0
C3	triangular	300	45	40	1.13	smooth	-	-
C4	triangular	350	50	35	1.43	rough	4	0
C5	hexagonal	470	40	25	1.32	rough	5	0
C6	sinusoidal	500	30	20	1.50	rough	4	45
C7	triangular	500	30	20	1.50	rough	5	0

* All corrugations are parallel to each other and normal to the flow direction.
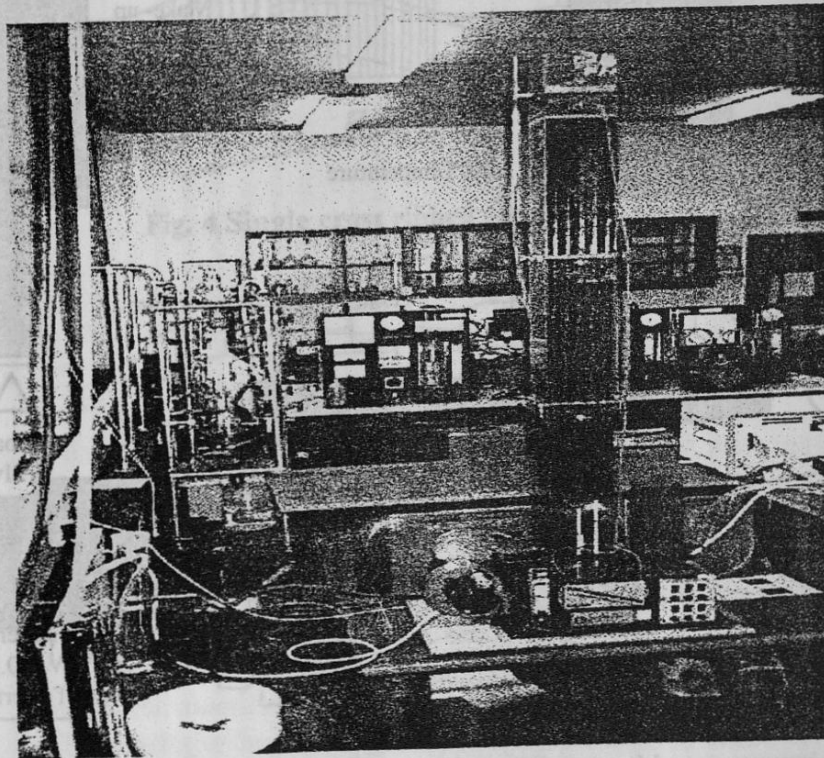
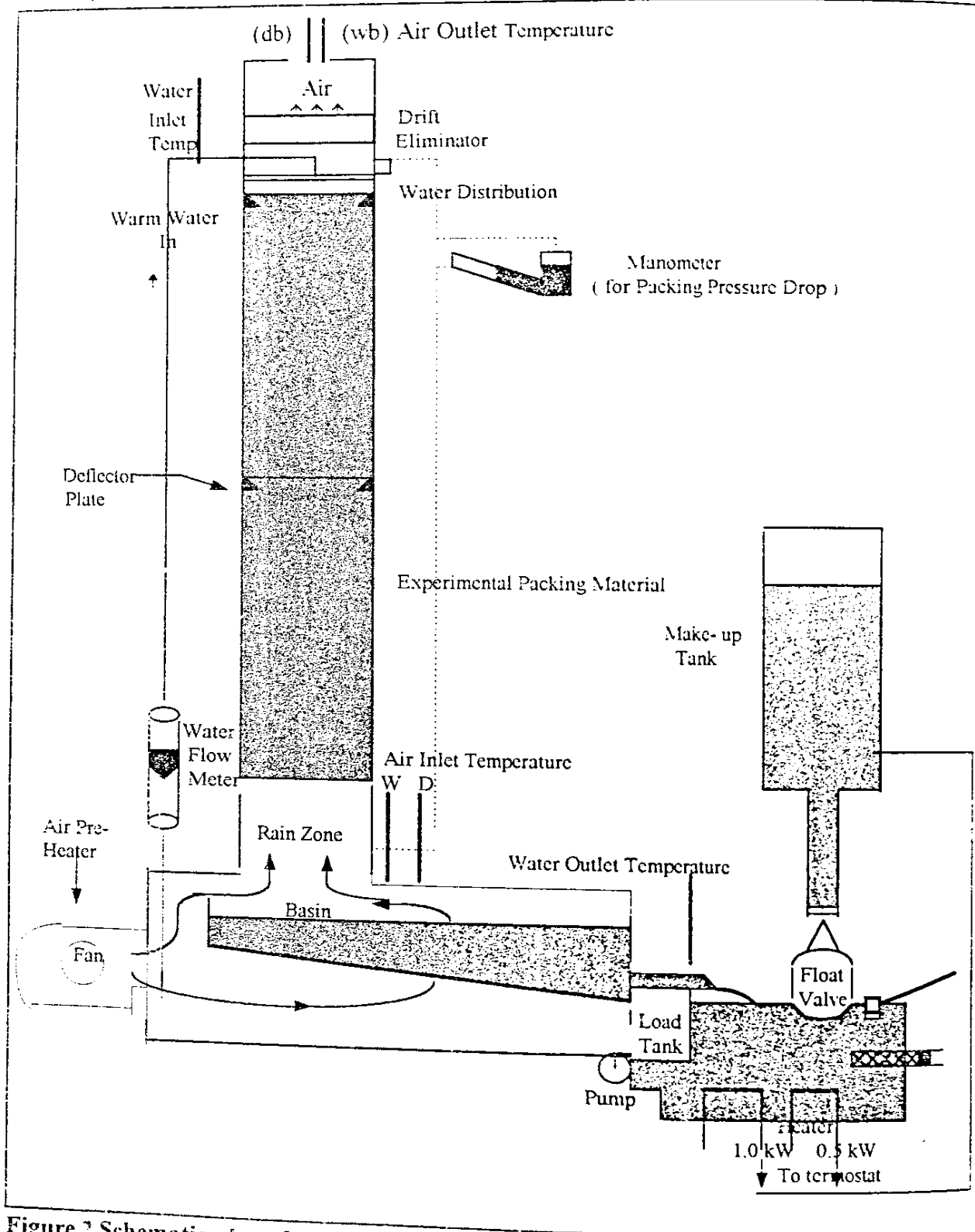**Fig. 1 Outside view of forced draft cooling tower in transport phenomena laboratory.**

(db) | | (wb) Air Outlet Temperature

Water Inlet Temp

Air

Drift Eliminator

Water Distribution

Warm Water In

Manometer (for Packing Pressure Drop)

Deflector Plate

Experimental Packing Material

Make-up Tank

Water Flow Meter

Air Inlet Temperature
W D

Air Pre-Heater

Rain Zone

Water Outlet Temperature

Basin

Fan

Float Valve

Load Tank

Pump

Heater

1.0 kW   0.5 kW

To termostat

Figure 2 Schematic plan of our experimental counterflow forced draught cooling tower.

4
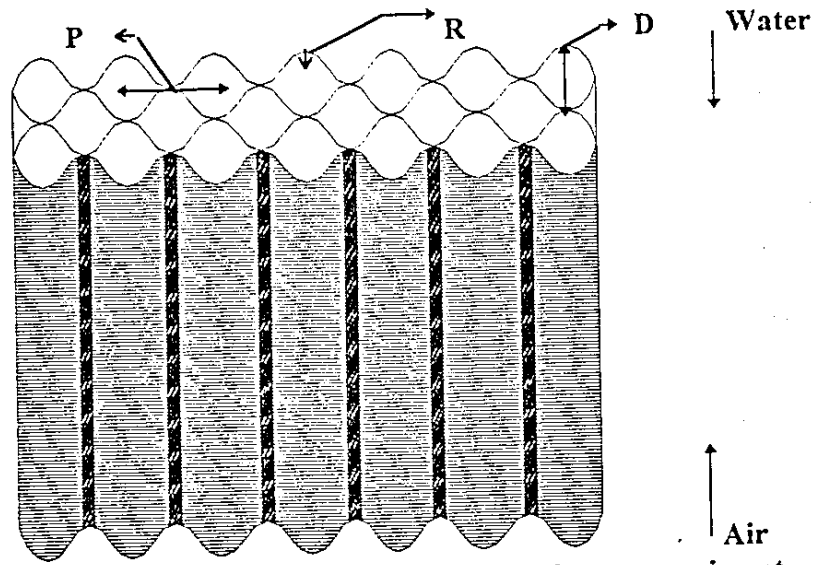
Fig. 3 Typical shape of smooth corrugated packing used in our experiment
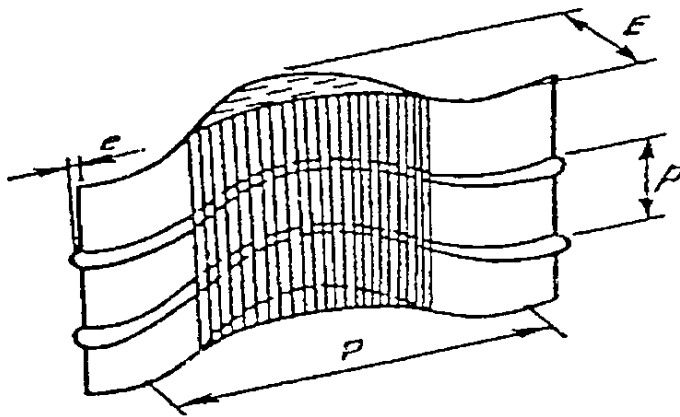
Fig. 4 Single cross ribbed sheet
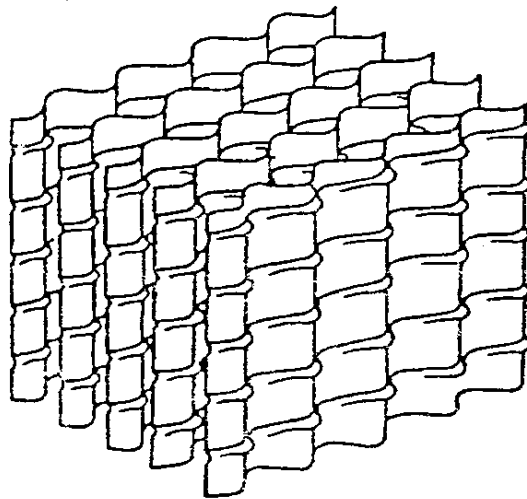
Fig. 5 Typical shape of rough corrugated packing used in our experiment.

5

Experimental Results

Heat Transfer Characteristics

Cooling tower packings typically have quite complex surface geometries, for which the mass transfer co-efficient, k, cannot be analytically predicted. Because manufacturers treat such data as proprietary, the k relation should be derived from test data, specific to the packing geometry.

Fig. 6 shows values of measured mass transfer coefficient k, plotted against the ratio of water flow rate to air flow rate (L/G) for existing packings. The values of k for corrugated packing were 1.5 to 2.5 times higher than comparable smooth packing k values when the water to air ratio was 1.0. The k values for rough and smooth corrugated packings decreased with the increase in pitch, and had a maximum value when P/D = 1.5 and the ratio of distance between repeated ribs to height of rib was 4, and the angle, θ, 45°. (Packing C6)
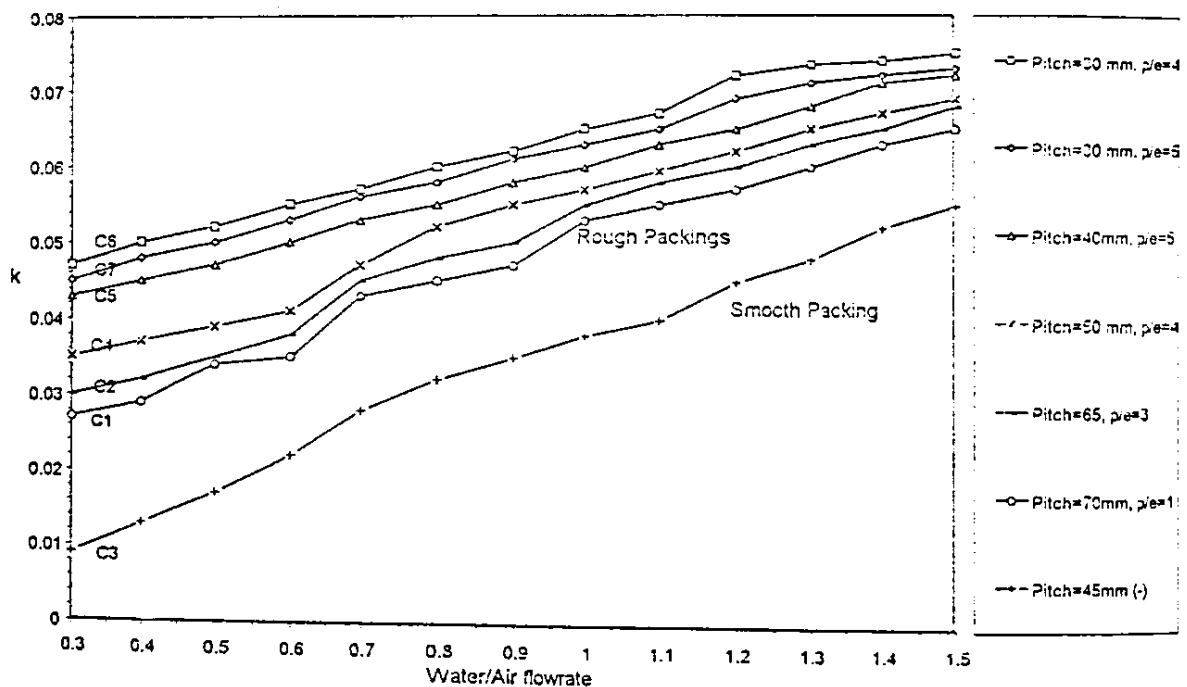

Fig. 6 Heat transfer characteristic of packing with different spacing and surface roughness.

As it can be seen from Fig. 6, k increases with
(i) decrease of the spacing between the sheets, all other parameters being constant.
(ii) increase in the value of L', for G' = constant.
(iii) increase in the ratio of the pitch of the corrugation to the of the spacing. P/D should be of the order of 1.5 and p/e should be of the order 5 to have maximum heat transfer.
(iv) decrease of the ratio of distance between repeated ribs and height of the rib.
(v) decrease in θ.

It can see that mass transfer increases with the decrease in spacing, but higher mass transfer in packing C6 compared with C7 and C5 is likely to be due mainly to the difference in the effect of the packing wall roughness[factors (iv and v) above].

6

The volumetric overall mass transfer coefficient based on enthalpy difference, which expresses the thermodynamic performance of a cooling tower, changes not only with the mass flow rate of air and water and temperature conditions but also with the dimensions, shape and arrangement of the cooling tower packing. Since the air and water flow in a cooling tower is complicated, the relationships between k, G and L have been found only by individual experiments for each cooling tower.

The resultant correlation ka of the Nos 1 to 7 was determined from these experiments with the most susceptible to error of ±4% by:

$$k = c_1 (L')^{0.45} (G')^{0.6} \tag{1}$$

c_1 is an experimental constant. The constant for type No. 3, (smooth surface), is 1.20 while for type Nos 1, 2, 4, 5, 6, 7 the constant is 1.75, 1.83, 190, 1.98, 2.20, 2.10 respectively. Using the smooth sample, No 3 as reference, the relative increases due to ribbing were, for No. 1 = 1.45, for No. 2 = 1.52, for No, 4 = 1.58, for No. 5 = 1.65, for No. 6 = 1.83, and for No 7 = 1.75 respectively.

Convective heat transfer data are usually correlated by an equation of the Dittus Boelter type; (Grigule 1969)

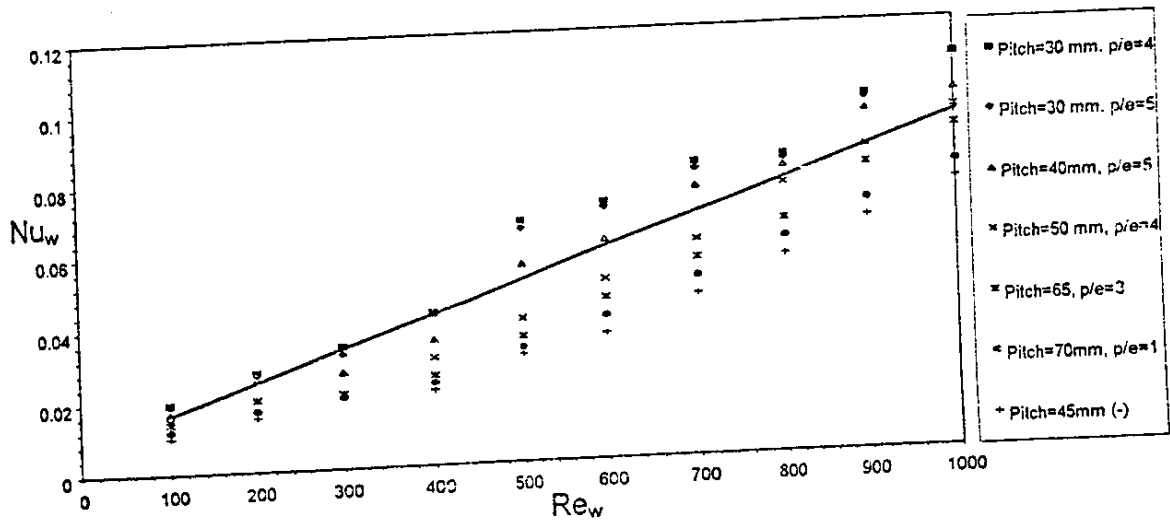$$Nu_w = A \, Re_w^m \, Pr_w^n \tag{2}$$

Fig. 7 Correlation of liquid phase heat transfer data.

The value of Nu_w can be evaluated based on empirical correlations found in the literature. In this paper, the value of Nu_w is evaluated using the Dittus - Boelter equation.(Bernier 1995) Thereafter the dimensionless correlation of data is shown in Fig. 7, where a solid line gives approximations to Nu_w.
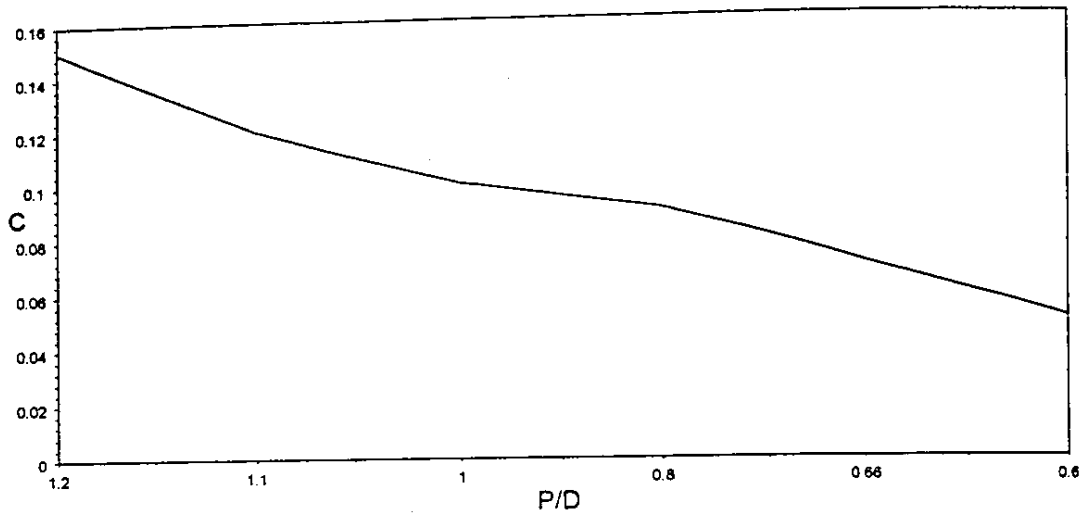
Fig. 8 Plots of C against the ratio of pitch to diameter.

From Fig.7 and 8 packing heat transfer coefficients were finally expressed as follows;

$$Nu_w = C \, (P/D)^{-0.15} \, Re_w^{0.8} \, Pr_w^{0.4} \tag{3}$$

The constant C is a function of surface roughness and varies with ratio of distance between repeated ribs and height of roughness element. (Pr_w assumed to be constant)

Pressure drop characteristics

Another aspect of the investigation of the performance of packings concerned pressure drop characteristics.

As it can be seen from Fig. 9 ΔP increases with

(i)   decrease in spacing between the sheets when all the other parameters being constant.

(ii) increase in L', for G' = constant.

(iii) increase of the ratio of distance between repeated ribs and height of rib.

(iv) decrease in θ.

The resultant of pressure drop for the packing No. 1 to No.7 is expressed with the most susceptible to error of ±3% by;

$$\Delta P = c_2 \, (L')^{0.35} (G')^{0.55} \tag{4}$$

c_2 is an experimental constant. The constant for type No. 3 having a smooth surface is 17.7 while those for types Nos. 1, 2, 4, 5, 6, 7, are 20.5, 22.6, 25.6, 27.8, 30.7, 32.5, 35.2, respectively.
The result in figure 9 shows that the pressure drop of packing C7 is about 70% higher than that of C1. This difference appears to be caused by difference in the height of the corrugations and the different surface created by the ribs.
The only exception is for C6 of the present investigation (spacing of 20 mm). The pressure drop is lower by about 15% than the pressure drop for the C7 (spacing of 20m). This difference can be attributed to the difference of the turbulent flow condition caused by the wall roughness of the packing created by the lower distance between the plates.
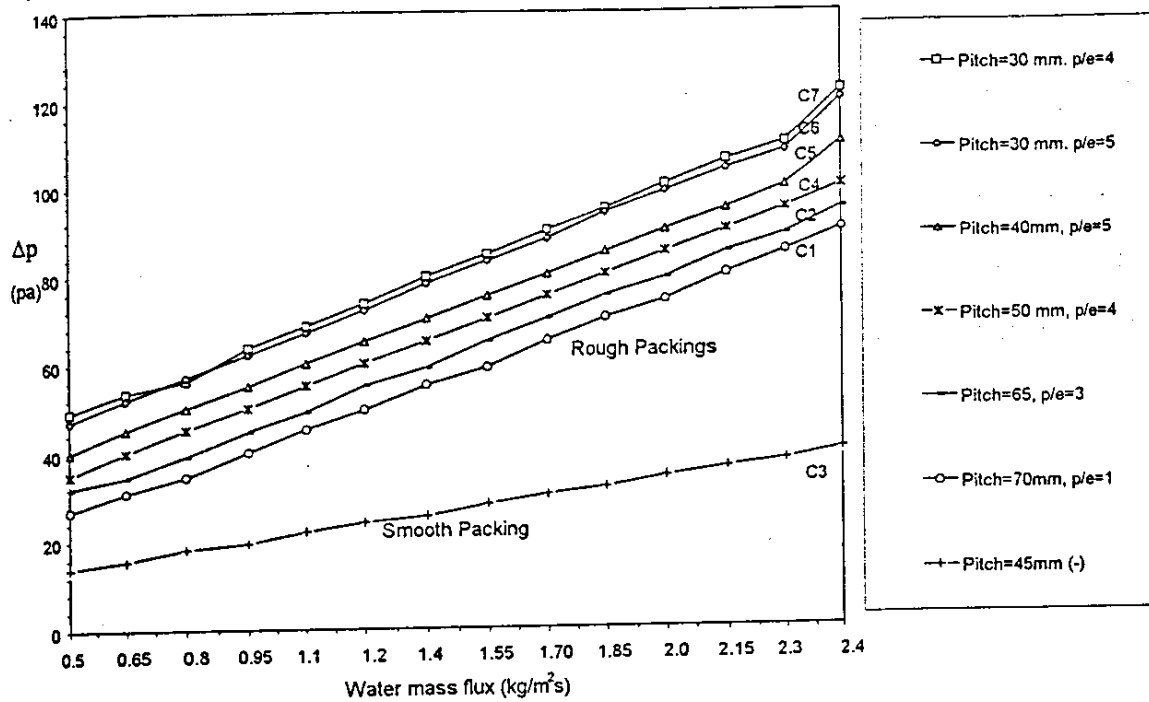
Fig. 9 Pressure drop characteristic with different spacing and surface roughness.

Friction factor f was derived using the following equation (Tezuka 1980)

$$f = \frac{1}{4} \cdot \frac{D}{Z} \cdot \frac{\Delta P}{\rho_a \dfrac{(u_a + u_w)^2}{2}} \tag{5}$$
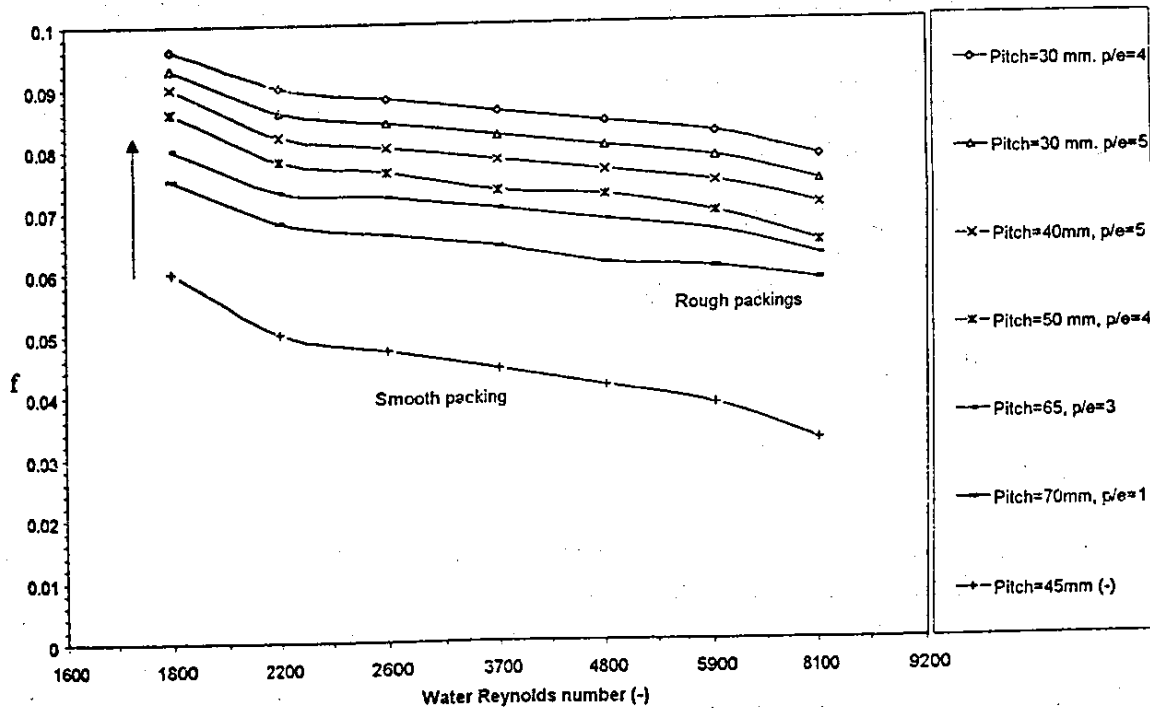

Fig. 10 Typical friction factor

9

Fig. 10 shows typical plots of friction factor f against the Reynolds Number Re. As it can seen from the graph, the friction factor of corrugated packing was affected by pitch, depth and also surface roughness.

The friction factor curve for packing C3 investigated in the present test, lies below the curves for packing C1 to C7. This can be expected because the height of the corrugation and the condition of the surface are dominating, the mean overall height of corrugations for packing C3 is 2.0 cm.

Therefore friction factors f was expressed by the following equation for the smooth packing;

$$f_{smooth} = C_f (P/D)^m \qquad (6)$$

And friction factor for the rough packings were expressed by the following equation;

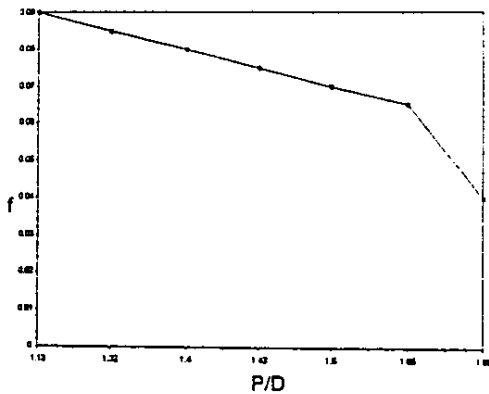$$f_{rough} = C_f (P/D)^m (p/e)^n \qquad (7)$$
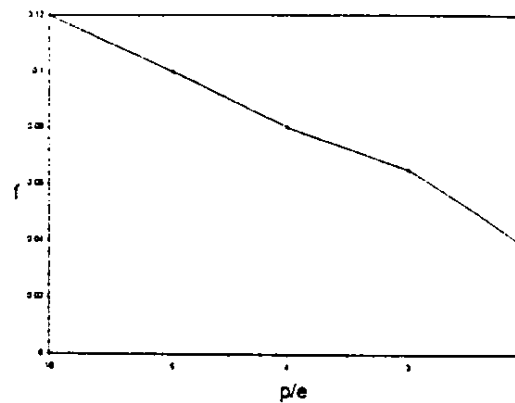

Fig. 11 Friction factor against P/D

Fig. 12 Friction Factor against p/e

Fig 11 and 12 show plots of friction factor of packing against P/D and d/e respectively. From these figures the exponents m and n were obtained and friction factors of smooth and rough packings were expressed by the following equations;

$$f_{smooth} = C_f (P/D)^{-1.32} \qquad (8)$$
$$\&$$
$$f_{rough} = C_f (P/D)^{-1.52} (p/e)^{-0.94} \qquad (9)$$

As an example, if m = -1.52 and n = -0.94, $C_f = 1.48$ is obtained for P = 30mm and D = 35 mm.

Discussion

When a fluid flows through a channel containing a solid system, various resistances to fluid flow (or friction factors) occur, according to the shape of the solid system. The conditions, which result in high friction factors, produce strong eddies in the fluid and thereby increase the rate at which heat may be transmitted from the fluid to the solid system. In other words, the friction and heat transfer properties of the system are correlated, so that it is generally impossible to achieve high heat transfer properties with low friction factor.

In relatively wide packings, the fluid stream is almost completely separated from the walls, and a large proportion of the packing is filled with recirculating fluid. (e.g. Packing C1)

In relatively narrow, corrugated packings flow separation takes place near the ridge of every corrugation, and flow re-attachment takes place upstream of the next ridge in the flow directions. The troughs of the corrugations are partly filled with re-circulating fluid. It was found that a packing of particular interest was the packing C6, which has a vertical main corrugation with the cross ribbing making an angle of 45°. Flow separation enhances the turbulence of the flow (compared with corresponding flow between smooth, straight wall) and thereby increases mass transfer rate and pressure drop. (e.g. Packing C6)

A packing with high turbulence in combination with a relatively low fluid velocity is more economic than a fairly smooth and straight packing in combination with a high fluid velocity. The results showed that mass transfer performance of the corrugated packing is increased by up to 1.5 to 2.5 times compared to the smooth packing, C3. In order to have the maximum mass transfer, the ratio of the pitch to spacing of the corrugation, P/D should be of the order of 1.36 to 1.50.

In this study packing mass transfer coefficients, k, of corrugated packings were expressed by Eq. (1). It was found that, for the effect of pitch on the Nusselt number, the value C was approximated to by $(P/D)^{-0.15}$. In fact the value C decreased with increase in P/D. Eq (3).

Finally, in order to compare the mass transfer performance of smooth packing with that of rough corrugated packing, the packing mass transfer coefficient (k) was correlated to pressure drop per unit length (ΔP/L) from experimental results (see Fig 13). It was found that at a given pressure drop, the maximum mass transfer coefficient for the corrugated packing can be obtained when $\frac{P}{D}$ = 1.5 and $\frac{P}{e}$ = 4 with an angle of 45° to the horizontal. For all corrugated packings, (ΔP/L) and k were correlated by the following equation;

$$k \propto (\Delta P/L)^{0.41} \tag{10}$$

It has been found that mass transfer coefficients of rough corrugated packing are in proportion to the pressure drop raised to the power 0.41. This value of 0.41 is smaller than the value for smooth packing, 0.46.
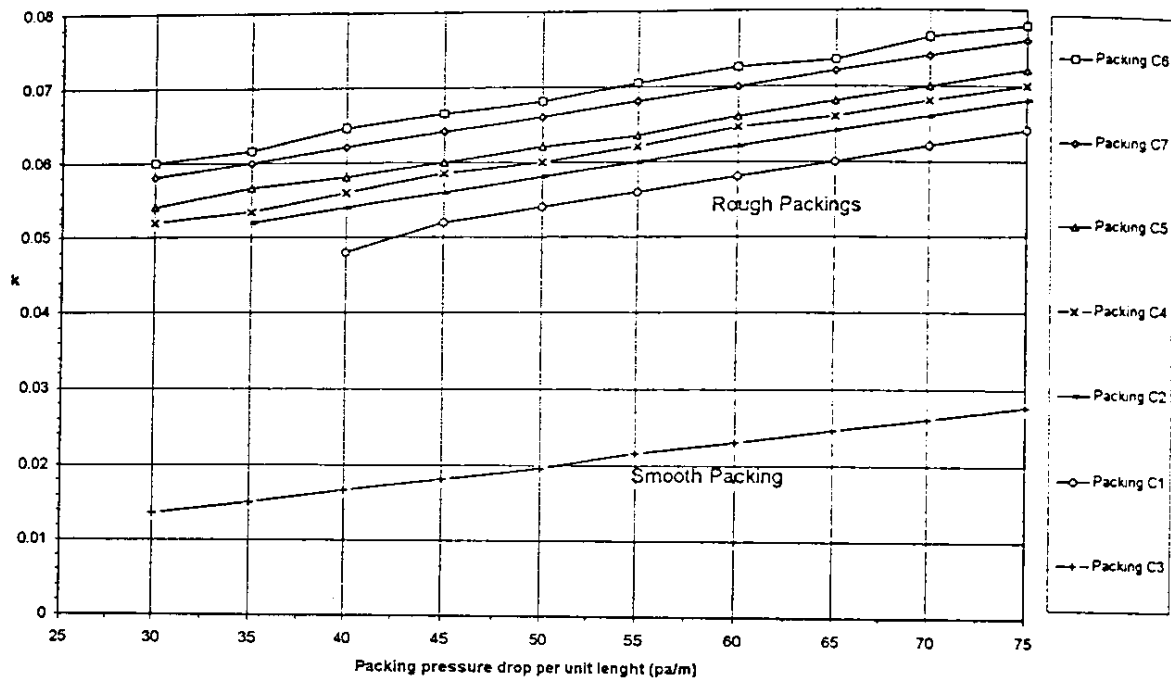
Fig. 13 Relation between packing mass transfer and pressure drop per unit length

Conclusions

Experiments were conducted to investigate the effect of the spacing and surface roughness on the heat transfer and pressure drop in PVC packing for which no comprehensive investigations had previously been reported. The experiments were carried out for comparative types of packing in a counterflow cooling tower. From the experimental results and discussion on the performance characteristic of seven vertical parallel packings arrangement in forced draft counterflow cooling tower the following conclusions may be drawn;

(1) Overall heat transfer coefficients and pressure drops of ribbed corrugated packings increase considerably compared with smooth packing and are affected by spacing of the packing and the distance between the ribs.

(2) It was found that a packing of particular interest was the packing C6 , which had a horizontal main corrugation with the cross ribbing making an angle of 45°.

(3) Packing heat transfer coefficients vary in proportion to $(P/D)^{-0.15}$ and C the value decreased with increase in P/D.

(4) Friction factors of corrugated packings vary in proportion to $(P/D)^{-0.94}$ and $(p/e)^{-1.52}$

(5) Mass transfer coefficients of corrugated packing vary in proportion to the 0.41 power of pressure drop per unit height. This value of 0.41 is smaller than smooth packing value 0.46.

12

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