Chapter III

Heat Transfer by Forced Convection

Introduction

The problem of heat transfer by convection seems to have attracted the attention of Physicists both from the theoretical and experimental points of view since the time of Bossinesq (1903) and Rayleigh (1915). More systematic ~~and~~ and accurate measurements on heat transfer by forced convection were made by J.A. Hughes (1916). He measured the heat losses from cylinders and tubes placed in a tunnel 3 ft. wide and 10 ft. long. From his measurements he concluded (i) that at all velocities of wind, the heat transfer per unit length is proportional to $d^{0.87}$ where 'd' is the diamter of the tube, and (ii) that the heat loss H varies as v^n, where v is the wind velocity and where n increases from 0.55 for the smallest cylinder to 0.98 for the largest one. If however the wind velocities were low, n appears to tend to the value 0.6. Davis (1921 to 1934) has made a careful study of convection from wires in a stream of air and has extended the agreement of the similitude equation with published data on heat transfer from cylinders and its relation with resistance due to dynamical effect. By combining Hydrodynamical theory with dimensional analysis, he suggested the following formula for forced convection.

$$\frac{hl}{k} = F\left(\frac{\rho l}{\mu} V\right)$$

where h is the heat transfer coefficient, l the characteristic length, k the coefficient of thermal conductivity, ρ the density of the fluid, μ the coefficient of viscosity and V is the velocity of the fluid. Experiments of A.H. Gibson (1924) and and J. Small (1935) also yield similar relations. Hilpert's data (1933) surveys a very wide range of Reynolds number $\left(Re = \frac{\rho l}{\mu} V\right)$ for cylinders and he concludes from his experiments that the index power 'm' in the relation $Nu = C(Re)^m$ increases steadily from 0.33 to 0.805 as Re. increases from $(1.0-2.5) \times 10^5$ where Nu is Nusselt number $\left(\frac{hl}{k}\right)$ and Re. the Reynolds number $\left(\frac{\rho l}{\mu} V\right)$. He has investigated the dependance ~~of~~ on temperatures of heat transfer coefficient and has found it to be about 6 % only.

Hilpert has also investigated the relation between Nu and Re for tubes of non-circular cross section and has found that for tubes of rectangular cross section the value of m = 0.675 for the range of Reynolds number, 5.0×10^3 to 1.0×10^5

Recently Kapadnis and Gogate (1952) and Kapadnis (1953, 1955) have investigated the variation of convective heat losses from vessels of different shapes and sizes and have tried to determine the shape constants (convection constants) for differently shaped vessels. They have found that the convective heat loss depends largely upon the shape of the vessel and varies approximately as the square root of the air velocity. Kapadnis studied the effect of fluid motion ~~of~~ on heat transmission and determined the convective heat losses from vertical cylinders. He has shown as a result of his experiments that the rate of heat transfer is proportional to 0.52^{th} power of the air velocity. He has also studied the heat losses due to forced convection from cylindrical, spherical and rectangular vessels and has tried to establish a quantitative relation between the Nusselt number and Reynolds number on the basis of his experimental data.

We have investigated the heat losses by forced convection from vessels of different shapes and sizes, particularly for two ranges of Reynolds number, the lower range (4×10^3) to (3×10^4) with air velocities below 240 cm/sec. and the upper range $(2 \times 10^4$ to $1.5 \times 10^5)$ with air velocities above 300 cm/sec. This was done with a view to find out how far the shape constants (convection constants) retained their constancy within these ranges and also to determine the variation of C and m in the general relation $Nu = c\,(Re)^m$ in these ranges. [redacted] This chapter deals with the experiments on forced convection for the lower range of Reynolds numbers while the investigations in the upper range of Reynolds numbers are described in the next chapter which also gives an account of the work in connection with the friction drag coefficient.

Study of Heat Transfer in the lower range of Reynolds numbers

Theory

We know that in dealing with problems of thermal convection, the heat transfer H can be conveniently represented by a relation of the form:

$$\frac{Hl}{k\Delta\theta} \propto \left(\frac{\rho l}{\mu} V\right)^{x_1} \left(\frac{c_p \mu}{k}\right)^{x_2} \left(\frac{\beta g l^3 \rho^2 \Delta\theta}{\mu^2}\right)^{x_3}$$

Where the Nusselt number $Nu = \frac{Hl}{k\Delta\theta}$ is the dependent variable and the quantities within the three brackets on the right hand side are the independent variable — dimensionless groups known as the Reynolds number Re, the Prandtl number Pr. and the Grashof number Gr. respectively. Here V denotes the forced velocity of the fluid, l the linear size of the vessel, $\Delta\theta$ the temperature difference between the fluid and the surface of the vessel, μ viscosity, k thermal conductivity, ρ density, c_p specific heat of the fluid at constant pressure, $(\beta \times g)$ - the product of coefficient of thermal expansion and acceleration due to gravity and x_1, x_2, x_3 are unknown indices. For convection in gases, Pr. may be taken as constant as it is nearly the same for all gases and over a wide range of temperature. For air, Pr.= 0.72. Again in the case of forced convection, the effects of buoyancy being negligible, the variable $(\beta \times g)$ may be dropped out since gravity no longer affects the problem. Putting $x_3 = 0$ in the above relation, the Grashof number is eliminated and Nu. becomes dependent upon Re. and Pr. only or in the case of gases, upon Re. only. Thus we have,

$$Nu = B\,(Re)^m$$

where B is a constant and $m = x_1$

Experimental arrangement

A spherical vessel of copper V, with a clean, white and uniform aluminium paint on its outer surface, was filled with some hot water and was placed at a distance of 40 cm. from a electric fan F (Fig.I). A stream of air proceeding from the fan was directed on to the vessel

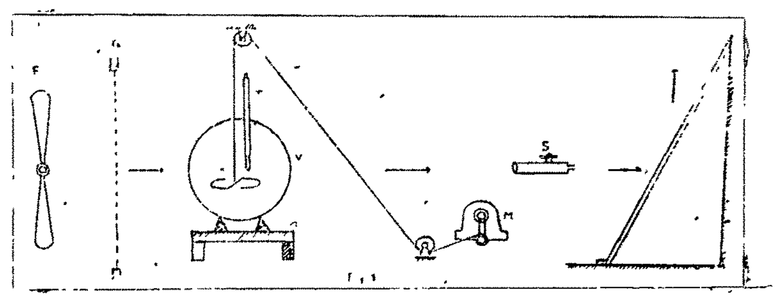

FIG. 1

after allowing it to pass through a wire grid G situated at a distance of 15 cm. from the fan. The grid G served to render the divergent stream of air from the fan into a uniform, and nearly, parallel stream. The top of the vessel was closed with a lid having two holes in it. Through one of the holes, passed a sensitive thermometer and through the other a stirrer was kept working up and down in the vessel so that a uniform temperature was maintained throughout the whole mass of water at any instant.

A very thin layer of oil was spread on the surface of water inside the vessel to help in preventing evaporation. The speed of the air stream proceeding from the fan could be varied by changing the strength of the current in the circuit of the fan and the air velocity was measured by means of a sensitive three-cup anemometer. The latter was so sensitive that it was possible to measure quite easily, air-velocities within the range 15 to 300 cm/sec., with sufficient accuracy. Special care was taken to avoid reflected air streams from the front wall by using various tilted screens at different angles. These screens helped in diffusing and directing upwards, the oncoming air streams. The temperature of the water in the vessel was measured by focussing a small telescope S on the vertical thermometer T passing through the lid of the vessel. This procedure eliminated the possibility of affecting the temperature of the vessel by the breath of the observer. The stirrer was moved vertically up and down in the vessel by connecting it to a string passing over a pulley as shown in fig. I. The other end of the string was passed round a pulley and then connected to an eccentric arrangement attached to the shaft of a low speed electric motor M. The air-velocity was measured by placing the sensitive anemometer exactly in the place of the vessel before and after every set of readings for the rate of cooling. The usual precautions were taken to minimize the heat losses due to conduction, radiation and evaporation. Losses due to natural convection were determined by separate experiments in still air and all subsequent observations were corrected for losses due to natural convection and radiation. The heat losses from the vessel, under these circumstances, were due to forced convection alone.

Different values of air-velocity ranging from 47 to 293 cm./sec. were used thus obtaining a number of corresponding cooling curves for the vessel. From these cooling curves, the rate of fall of temperature $(d\theta/dt)$ for any mean temperature θ could be calculated. The values of $\left(\frac{d\theta}{dt}\right)$ are then used to calculate the total heat losses by the vessel at various temperatures and air-velocities.

Results & Discussion

The values of Re. and Nu. were determined for several values of the air velocity at different mean temperatures of the vessel. These are recorded in table I. The value of H, the heat loss due to convection alone, required for the evaluation of the Nusselt number was obtained by subtracting the heat loss H_2 by radiation

$$H_2 = 1.73\times10^{-9} \times E \times \left(T_1^4 - T_2^4\right)$$

from the total heat loss H_1 given by

$$H_1 = \left(M + M_0\right)\left(\frac{d\theta}{dt}\right)$$

Here M is the mass of the hot water in the vessel, M_0 the water value of the containing vessel, E - the emissivity of the surface taken as 0.55 for aluminium paint, T_1, the absolute temperature of the vessel and T_2 is the absolute temperature of the surroundings. For a temperature difference $\Delta\theta$ between the vessel and the surroundings, we therefore have $H = H_1 - H_2$.

The values of Re. and Nu. were determined for several values of the air velocities at different mean temperatures for vessels of three different shapes viz. spherical, cylindrical and rectangular. These values are recorded in table 1 given below:-

Table I.

Shape of the vessel.	Characteristic length 'l' cm.	Air velocity in cms./sec. V	Nusselt Number Nu.	Reynolds Number Re.
Sphere		47.6	48.5	4468
		75.6	63.0	7106
		109.7	70.9	8191
	15.8	157.3	106.0	14790
		185.3	112.0	17390
		219.0	131.0	20270
		248.0	142.0	23320
		293.0	154.0	27560
		48.0	56.5	5916
		94.5	88.0	11470
		121.0	99.0	14640
	20.8	137.0	113.0	16640
		166.0	128.0	20180
		205.0	141.0	24890
		277.0	152.0	27550
		256.0	163.0	31060
		276.0	170.0	33540

Shape of the vessel.	Characteristic length 'l' cm.	Air velocity in cm./sec. V	Nusselt Number Nu.	Reynolds Number Re.
Cylinder		155	71.1	12900
		242	89.7	20100
		326	111.7	27100
		405	123.0	33700
	15.0	487	134.6	40500
		563	147.9	46800
		644	157.8	53600
		721	196.0	59900
		805	173.0	66900
		882	180.0	73300
		186	135.0	24690
		239	163.0	31780
		311	201.0	41300
		354	230.0	46970
	20.8	390	248.0	51820
		484	282.0	64370
		509	293.0	67670
		558	301.0	74090
		697	304.0	79360
		655	326.0	87040
Rectangular Vessel		173	64.5	10020
		299	96.8	17590
		216	90.4	12750
		421	117.0	25080
	9.2	427	123.0	25130
		451	134.0	26570
		521	156.0	30690
		564	169.0	33210
		640	175.0	37690
		665	171.0	39130
		723	186.0	42530
		764	188.0	45050
		204	142.0	27340
		259	171.0	34680
		370	203.0	42430
		381	244.0	51000
	20.8	437	260.0	58350
		472	279.0	63240
		530	306.0	70990
		579	303.0	77540

Sphere. l=15.8 cms.

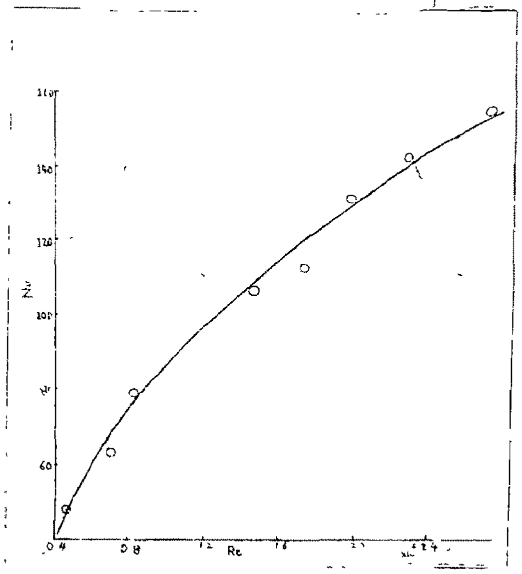

Fig 2

Sphere. l=20.4 cms.

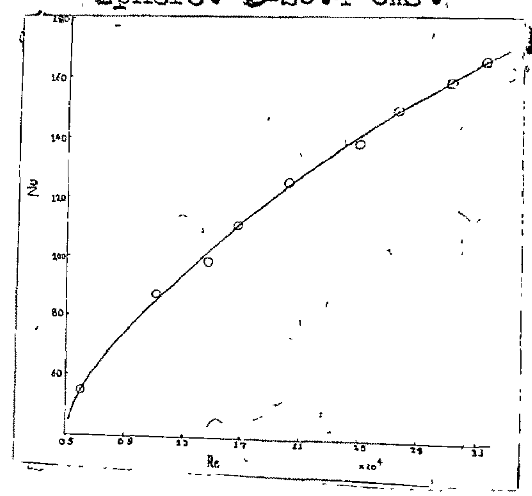

Fig 3

The plots of Nu. against Re. for the different shapes of vessels are given in figures 2 to 7. They all are curves convex towards the Nu-axis. As we have already shown

Cylinder. l=15.0 cms.

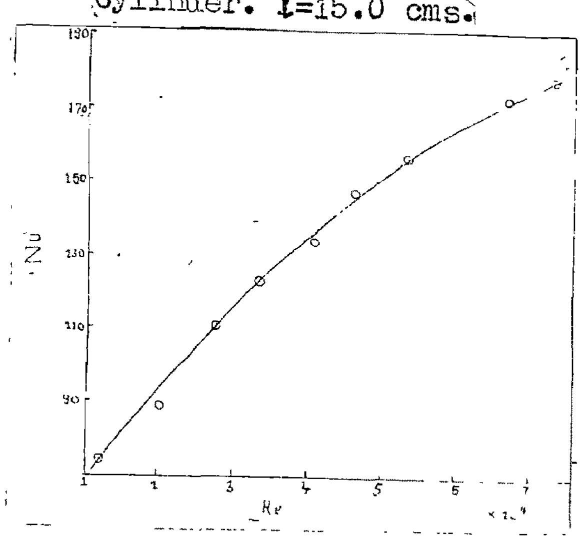

Fig 4

Cylinder. l=20.8 cms.

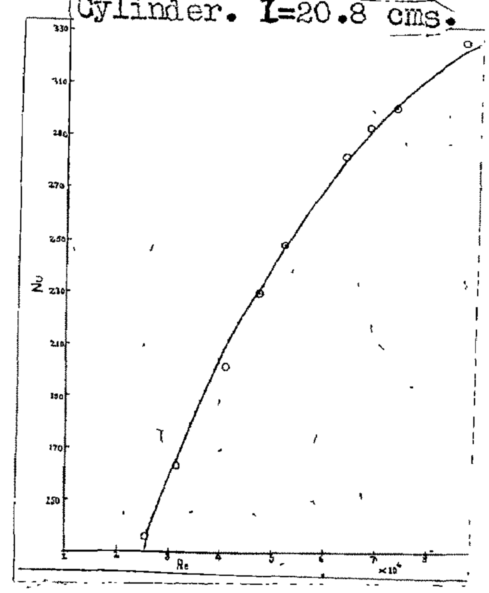

Fig 5

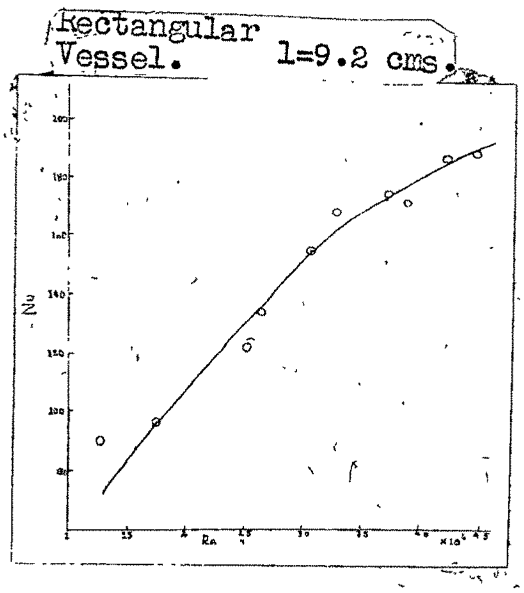

Fig 6

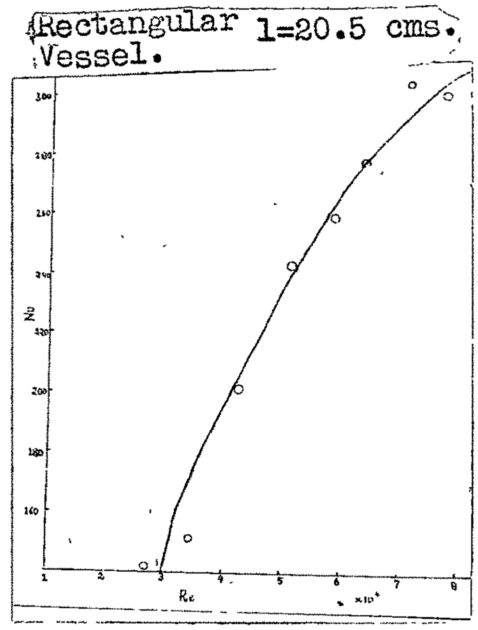

Fig 7

(page 38) in the case of heat transfer by forced convection, Nu. and Re. are connected by the relation:

$$Nu = B\,(Re)^{m}$$

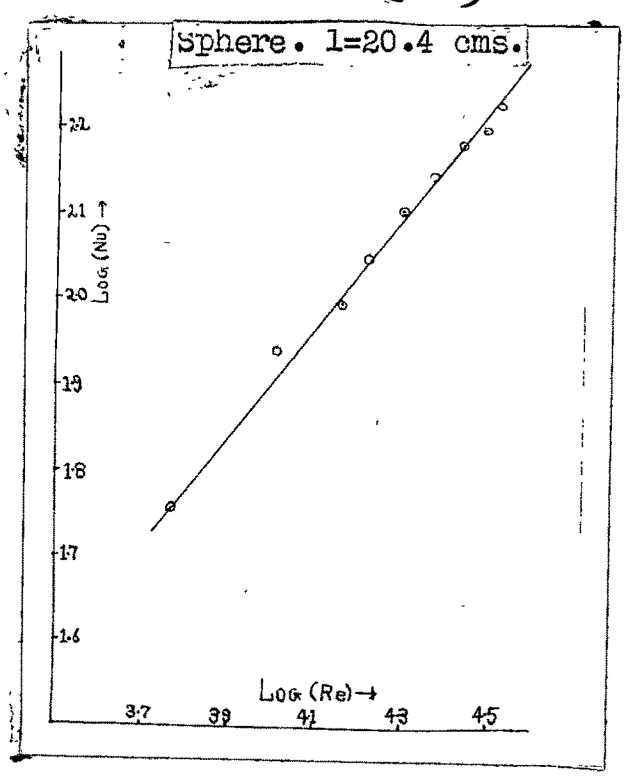

Fig 8

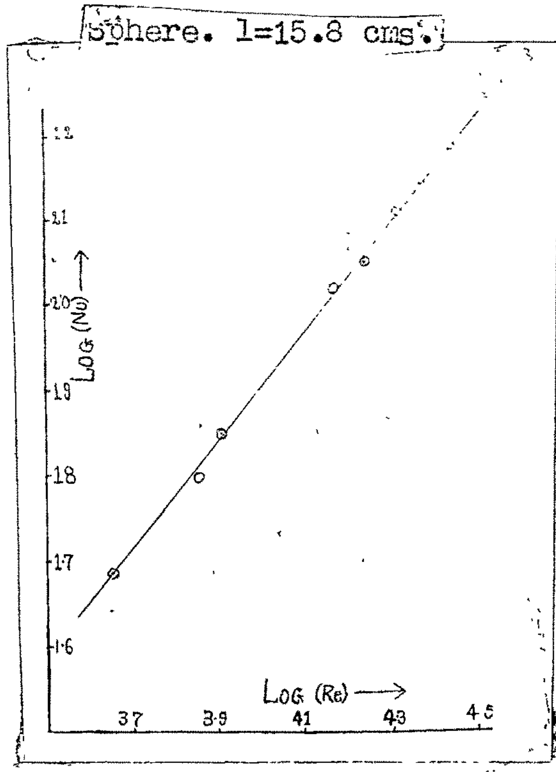

Fig 9

where B and m are constants which can be easily determined from the data given in Table 1 above. A graph of log Nu. against log Re. is found to be linear in every case.

Table II.

Shape of the vessel.	Author.	Range of Re.	m	B.
Spherical	H.S.Desai	4.5×10^{3} to 3.3×10^{4}	0.61	0.296
	McAdams.	50 to 1.5×10^{5}	0.60	0.340
	Kapadnis & Gogate	4.7×10^{4} to 1.1×10^{5}	0.65	0.203
Cylindrical	H.S.Desai	1.2×10^{4} to 8.7×10^{4}	0.61	0.205
	Hilpert	4.0×10^{3} to 4.0×10^{4}	0.618	0.174
	Kapadnis	4.0×10^{3} to 1.3×10^{5}	0.62	0.185
Rectangular	H.S.Desai	1.0×10^{4} to 7.7×10^{4}	0.66	0.15
	Hilpert	5.0×10^{3} to 1.0×10^{5}	0.675	0.092
	Kapadnis	2.7×10^{3} to 1.4×10^{5}	0.654	0.12

The slope of this straight line graph gives the value of m while the intercept on the log Nu-axis gives the value of log B. (See figures 8 & 9). A comparison of the values of the constants B & m determined from the results of our experiments with those obtained by others is given in Table II. Considering the uncertainties involved in experiments of these types, the agreement between our values and those of other workers appears to be fairly satisfactory.

Shape constants.

The shape (convection) constant C may be defined by the relation:

$$H = C A V^{n} \Delta\theta$$

(see Gogate and Kapadnis 1952. Ind. Jour. Phy. XXVI P.173).

Where H = the amount of heat lost in Kilo-Calories per hour.

A = Area of the surface in square metres.

$\Delta\theta$ = Temperature difference between the surface of the vessel and the air stream surrounding it.

C = Shape constant.

Assuming n = 0.5 in the above equation i.e. assuming that the heat transfer varies as the square root of air velocity, as has been done by Gogate & Kapadnis (1952) & others, for lower range of Reynolds numbers, we can determine the

the value of C by using the data of table I. This has been done for the different shapes of vessels used and the results are exhibited in table III. (given below).

Table III.

Shape of the Vessel	Characteristic length 'l' cm.	Range of velocity in cm/sec. 'v'	Range of Reynolds Number 'Re'	Index n	Shape constant C
Sphere	15.8	47-293	4.5×10^3 to 2.8×10^4	0.5	1.33
"	20.4	48-276	5.9×10^3 to 3.3×10^4	0.5	1.31
Cylinder	15.0	155-882	1.2×10^4 to 7.3×10^4	0.5	1.12
"	20.8	185-655	2.5×10^4 to 8.7×10^4	0.5	1.15
Rectangular Vessel	9.2	173-764	1.0×10^4 to 4.5×10^4	0.5	1.32
"	20.8	204-579	2.7×10^4 to 7.7×10^4	0.5	1.12

A glance at the above table shows that amongst the different shapes of vessels employed in our experiments, the shape constant C has the lowest value for cylinders. Hence the convective heat loss appears to be least in the case of vessels having a cylindrical shape. Our experiments have shown that the value of the index m in the relation

$$Nu = B\,(Re)^m$$

in the different ranges of Reynolds numbers covered by our experiments is generally higher than 0.5 and ~~vales~~ varies between 0.5 and 0.7 depending upon the intensity of turbulence.

A redetermination of the shape constants was therefore undertaken using the different values of the index 'm' as determined from the plots of log Nu. against log Re. These values of the shape constants redetermined for the higher values of index 'm' are shown in table IV.

Table IV.

Shape of the Vessel	Characteristic length 'l'	Range of Velocity cms/sec. V	Range of Reynolds Number 'Re'	Index 'm'	Shape constant C
Sphere	15.8	47-293	4.5×10^3 to 2.8×10^4	0.61	0.75
"	20.4	48-276	5.9×10^3 to 3.3×10^4	0.61	0.68
Cylinder	15.0	155-882	1.2×10^4 to 7.3×10^4	0.61	0.41
"	20.8	185-655	2.5×10^4 to 8.7×10^4	0.65	0.46
Rectangular Vessel	9.2	173-764	1.0×10^4 to 4.5×10^4	0.66	0.50
"	20.8	204-579	2.7×10^4 to 7.7×10^4	0.66	0.45

It is obvious from the above table that the value of the shape constant C is again minimum for cylindrical vessels and that ~~there~~ here also (i.e for higher values of m) the convective heat loss is minimum in the case of vessels having a cylindrical shape. The values of shape constants appearing in tables III and IV also indicate that the convective heat loss is greater for rectangular vessels than for cylindrical vessels and it is maximum for vessels of spherical shape.

References on pages 64 & 65