Chapter IV

Study of Heat Transfer in the upper range of Reynolds numbers.

The work described in this ~~section~~ chapter is an extension to higher Reynolds numbers, of the work described in the previous one. The main point that emerges from the present study is that the rate of heat exchange undergoes a relatively sudden change in the region of Re = 10^5, this being the region where the nature of flow undergoes a change.

Experimental.

The apparatus used in this investigation was a slight modification of that used in the previous experiments (Kapadnis and Gogate 1952). A copper vessel V (figure 10) containing hot water was placed in a small wind tunnel at a distance of about 34 cm.

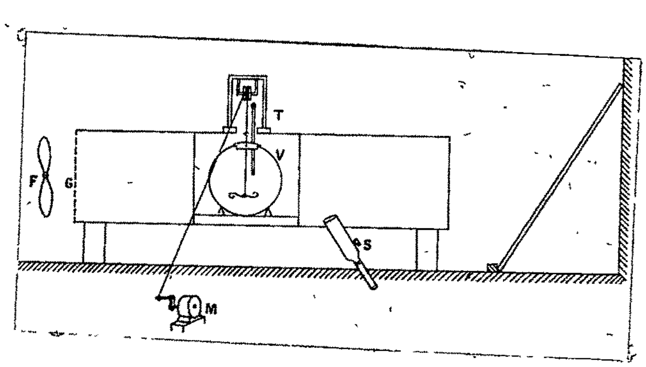

Fig. 10

from an electric fan F and a stream of air proceeding from the fan was directed on to this vessel through a wind tunnel after allowing it to pass through a wire grid G situated at a distance of about 9 cm. from the fan. The wind tunnel consisted of a rectangular wooden case 165 cm. long with a square cross section 38 cm. X 38 cm. and open at both ends. The top of the vessel was closed with a lid having two holes in it. Through one hole passed a sensitive thermometer T and through the other a stirrer was kept working up and down by means of a string connected to an eccentric arrangement attached to the shaft of a low speed electric motor. The speed of the air stream could be varied by changing the strength of the current in the circuit of the d.c. fan F and the air velocity was measured by means of a sensitive three cup anemometer. The latter was placed exactly in the place of the vessel V before and after every set of observations for the rate of cooling of the vessel. Special care was taken to avoid reflected air stream from the front wall by using 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 focusing 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 usual precautions were taken to minimize the heat losses due to conduction, radiation and evaporation. Losses due to natural convection were determined separately in still air and all subsequent observations were corrected accordingly.

Results.

A number of cooling curves were obtained for the vessel using different values of air velocity and the

Table V.

Shape of the vessel.	Characteristic dimension of vessel in cm. l	Air velocity cm/sec. V	Nusselt Number Nu.	Reynolds Number Re.	Drag Coeff. C_f
		158	122	20690	0.0146
		226	180	29940	0.0127
		274	195	35810	0.0125
		329	221	42970	0.0127
		396	252	51720	0.0121
Sphere	20.4	472	278	61670	0.0111
		591	299	77200	0.0096
		622	307	81170	0.0093
		649	324	84760	0.0094
		725	338	94710	0.0088
		773	374	100900	0.0092
		783	380	102300	0.0092
		817	452	106600	0.0101

Shape of the vessel	Characteristic dimension of vessel in cm. l	Air velocity cm/sec. V	Nusselt Number Nu.	Reynolds Number Re.	Drag Coeff. C_f
		174	153	28330	0.0133
		260	200	42250	0.0107
		305	214	49710	0.0107
		479	252	78030	0.0079
Sphere	25.5	531	275	86480	0.0078
		564	303	91950	0.0077
		662	332	107800	0.0072
		674	346	109800	0.0078
		735	364	119800	0.0075
		753	382	122700	0.0077
		771	429	125700	0.0084
		186	135	24690	0.0136
		239	163	31780	0.0127
		311	201	41300	0.0121
		354	230	46970	0.0121
		390	248	51820	0.0118
Cylinder	20.8	485	282	64370	0.0108
		509	293	67670	0.0107
		558	301	74090	0.0106
		687	304	79360	0.0095
		655	326	87040	0.0093
		744	374	98790	0.0094
		786	402	104400	0.0095
		198	122	32510	0.0093
		259	151	42230	0.0088
		287	158	47010	0.0083
		320	184	52520	0.0087
Cylinder	25.5	381	207	62520	0.0082
		482		79030	0.0081
		646	315	106000	0.0074
		677	304	111000	0.0068
		716	312	117600	0.0066
		771	330	126600	0.0064
		799	354	131000	0.0067

Shape of the vessel	Charac-teristic dimension of vessel in cm. l	Air velocity cm/sec. V	Nusselt Number Nu.	Reynolds Number Re.	Drag Coeff. C_f
		204	142	27340	0.013
		259	171	34680	0.012
		317	203	42430	0.0119
		381	244	51000	0.0118
Rect-angular	20.8	436	260	58350	0.011
		472	279	63240	0.0109
		530	306	70990	0.0107
		379	303	77540	0.0097
		628	361	84070	0.0106
		777	454	104000	0.0108
		177	105	29900	0.0906
		257	127	42650	0.00740
		333	141	55340	0.00631
		387	219	64480	0.00848
		454	220	76650	0.00724
		506	245	84280	0.00721
		582	262	96940	0.00672
		640	278	108600	0.00647
		673	291	113500	0.00647
		472	335	123600	0.00658
		708	373	129900	0.00714

rates of fall of temperature $\left(\frac{d\theta}{dt}\right)$ for different mean temperatures θ were calculated. These values of $\left(\frac{d\theta}{dt}\right)$ were used to calculate the total heat losses by the vessel at different temperatures and air velocities. To study the relation between heat transfer and the velocity of the air stream, a graph was plotted between the dimensionless quantity $\frac{Hl}{k\Delta\theta}$ known as the Nusselt number (Nu.) and another dimensionless

Sphere. l=20.4 cms.

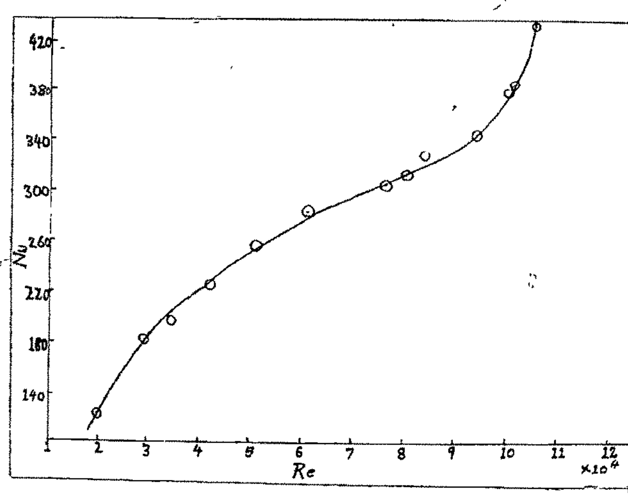

Fig. 11

Sphere. l=25.5 cms

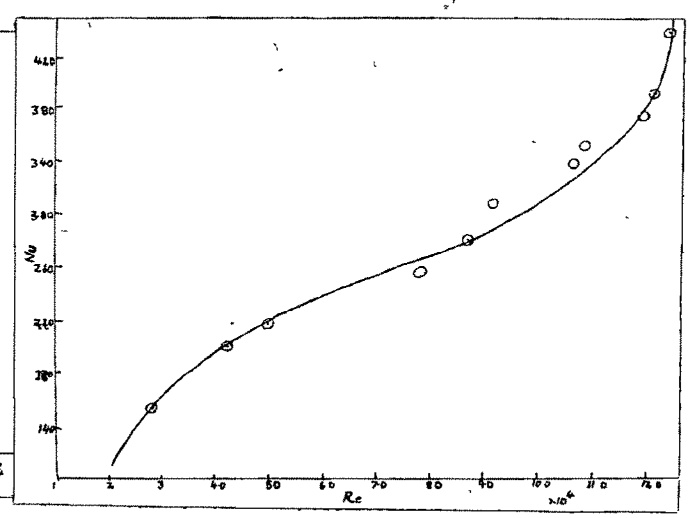

Fig. 12

variable $\left(\frac{\rho l}{\mu} v\right)$ known as the Reynolds number (Re.) where H is the total heat loss due to forced convection, l the linear dimension of the vessel used, K the thermal conductivity of air, $\Delta\theta$ the temperature difference

Cylinder. l=20.8 cms

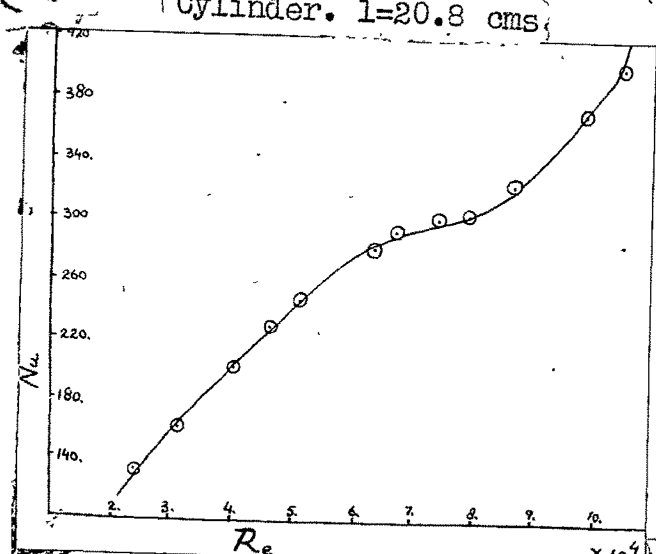

Fig. 13

Cylinder. l=25.5 cms

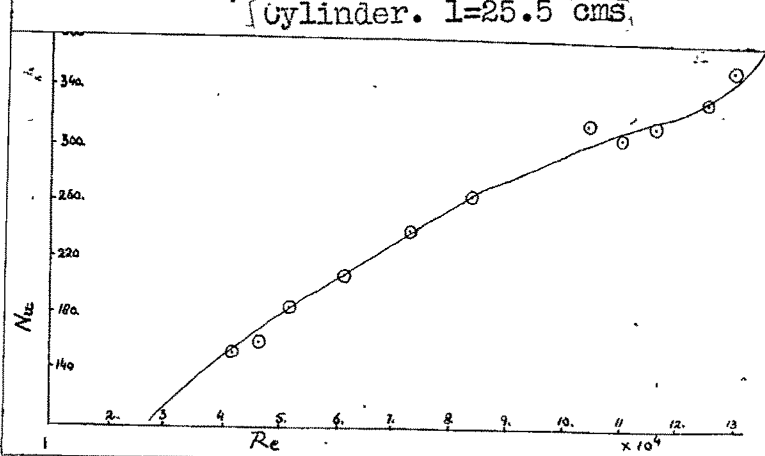

Fig. 14

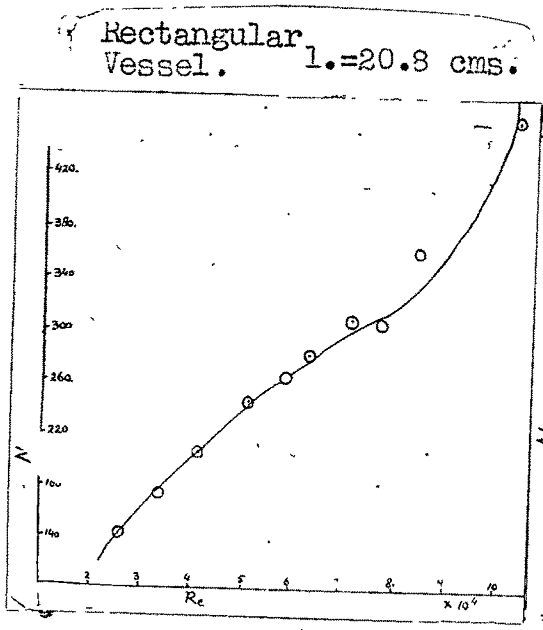

Fig. 15

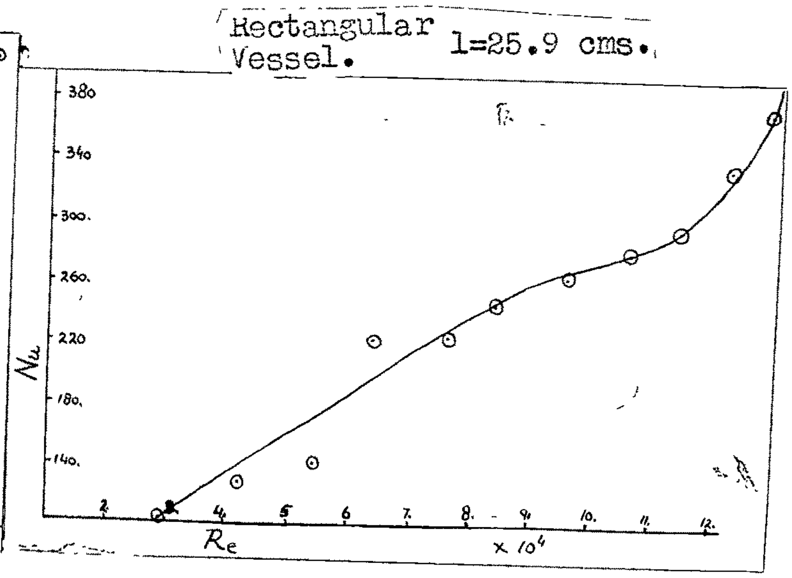

Fig. 16

between the vessel and the surroundings, ρ the density and μ the viscosity of air at the temperature of experiment. It is clear from figures (11 & 12) that for value of (Re.) up to nearly 8 X 10^4 the curve is concave to the (Re.) axis but as we approach the value of (Re.) near about 10^5, the curve changes its form and becomes convex towards the (Re.) axis. This change from concavity to convexity towards the (Re.) axis of the curve giving the relation between (Nu.) and (Re.) has been confirmed by experiments with ~~shpheres~~, spheres, cylinders & rectangular vessels of different sizes. This can be easily seen from the curves given in figures 11 to 16. This shows that the convective process of heat exchange undergoes a relatively sudden change near (Re.) = 10^5.

Discussion.

Let us now consider the mechanism of fluid flow and try to understand the relation between heat transfer and momentum transfer near a solid surface over which a fluid at a different temperature is moving. Let a fluid particle of mass M move from the main fluid stream having velocity V to the surface of a solid at which it is reduced to rest. The momentum conveyed to the solid surface by the fluid particle is mV. If we assume that the particle remains long enough in contact with the solid surface to attain the surface temperature, then the heat transfer from the fluid to the surface will be mc θ where θ is the temperature difference between the surface and the main stream and c is the specific heat of the fluid at constant pressure. The ratio of the heat transfer to the momentum transfer will thus be $\frac{c\theta}{V}$. Taking into consideration all the particles moving between the fluid and the solid surface and applying this reasoning to them, we have, for the ratio of heat transfer, per second, H, to the friction drag force F tangential to the surface,

$$\frac{H}{F} = \frac{c\theta}{V} \quad ----(1)$$

If we take into consideration the thermal conductivity of the fluid, the above relation is modified (Fishendon, M. & Saunders, O.A. 1950) to

$$\frac{H}{F} = \frac{c\theta}{V} \frac{1}{1+a(Pr-1)} \quad ---(2)$$

where 'a' is a constant less than unity and Pr. is the Prandtl number $\left(\frac{c\mu}{K}\right)$. Since Pr. is very nearly equal to unity for gases, equation (2) reduces to (1) in the case of gases. $\frac{H}{c\theta\rho V}$ is known as stanton number which is obviously equal to $\frac{Nu}{Re\cdot Pr.}$. The skin drag-coefficient C_f which is defined in aerodynamics as $\frac{2F}{\rho V^2}$ is given by (Fishendon M. & Saunders O.A. 1952)

$$C_f = \frac{2F}{\rho V^2} = \frac{2HV}{\rho V^2 c\theta} = 2\,(\text{Stanton Number})$$

where H represents the amount of heat-transfer per second, F is the friction drag force, θ the temperature difference between the surface of the vessel and the main fluid stream, C the specific heat of the fluid at constant pressure, V the velocity of the fluid stream, ρ its density at the temperature of the experiment. We have plotted C_f against the Reynolds number (Re). It will be observed from the curves given in figures 17 to 22 that the value of C_f goes on decreasing rather rapidly with

1

Sphere. l=20.4 cms.

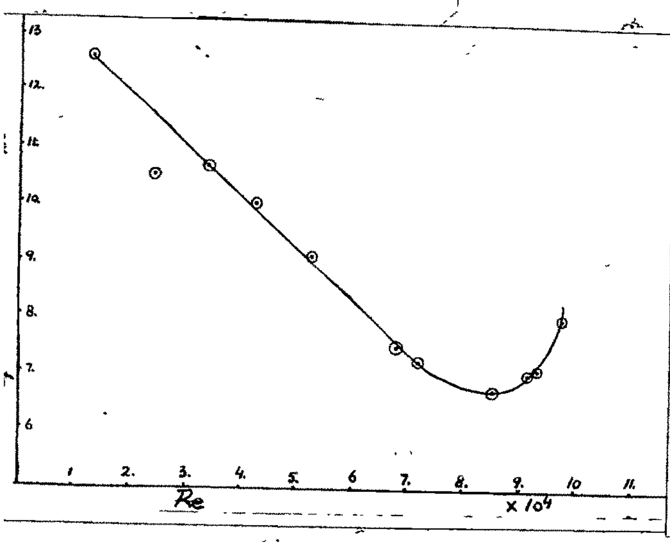

Fig 17

Sphere. l=25.5 cms.

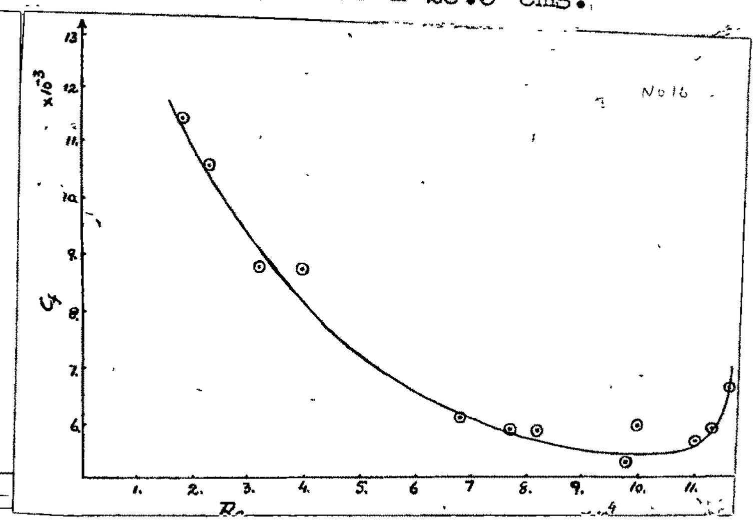

Fig. 18

increasing (Re), attains a minimum value at (Re) $\sim 10^5$ and then it begins to increase again with increasing (Re). This behaviour of C_f as a function of (Re) is associated, as is well known (Goldstein 1938), with a change

Cylinder. l=20.8 cms.

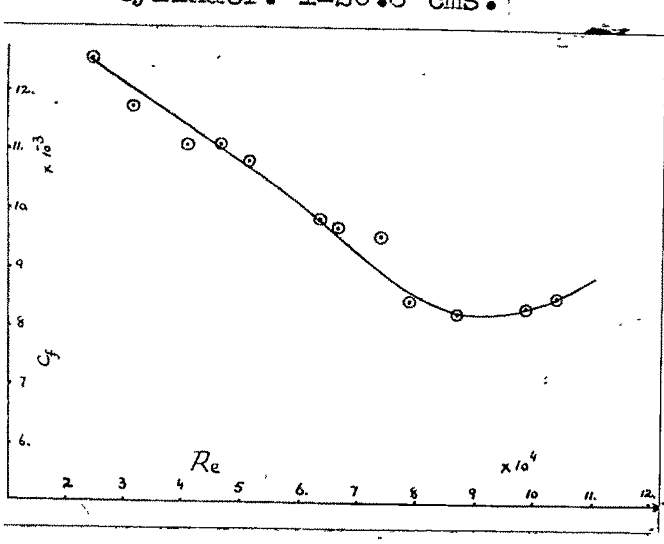

Fig. 19

Cylinder. l=25.5 cms

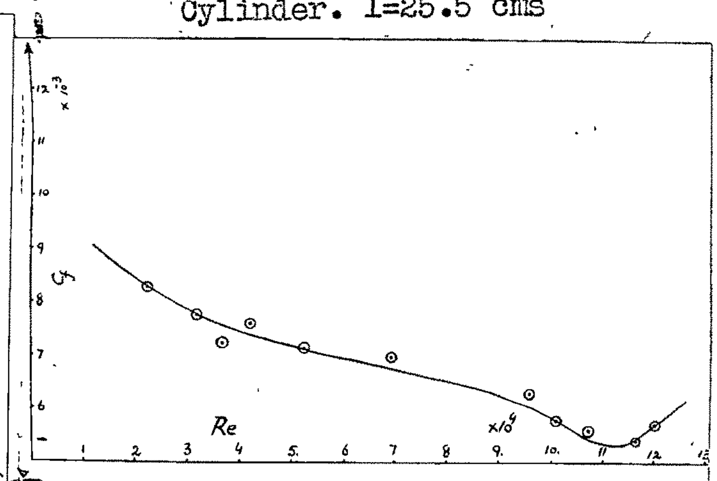

Fig. 20

Rectangular Vessel. l=20.8 cms.

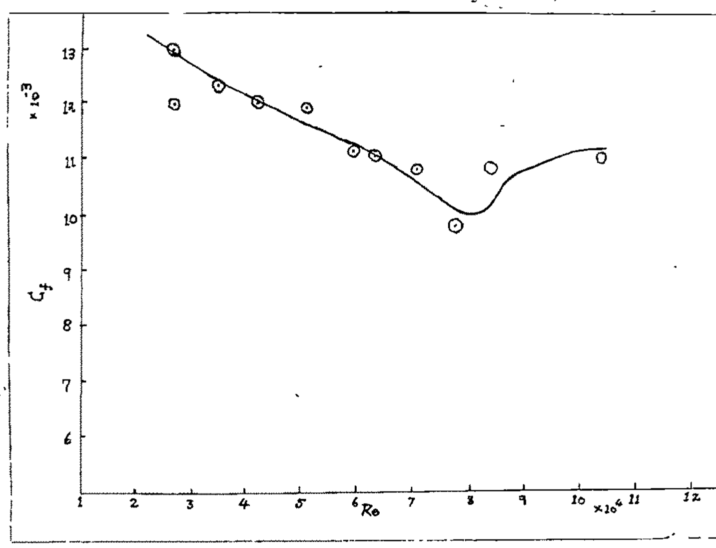

Fig. 21

Rectangular Vessel. l=25.9 cms.

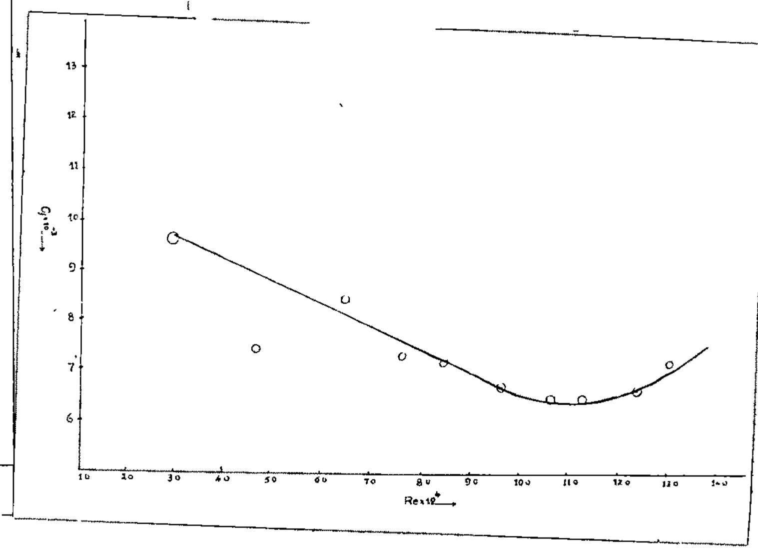

Fig. 22

in the nature of the flow pattern as Re. approaches its critical value which is, in general, of the order of 10^5; by the critical value of (Re) we refer to the value for which C_f is minimum.

Table VI

Shape of the vessel	Characteristic length 'l'	$(Re)_{critic.}$	$C_{f\,minimum.}$
Sphere	20.4	9.3×10^4	8.85×10^{-3}
	25.5	1.1×10^5	7.35×10^{-3}
Cylinder	20.8	9.4×10^4	9.2×10^{-3}
	25.5	1.25×10^5	6.25×10^{-3}
Rectangular	20.8	8.2×10^4	10.2×10^{-3}
	25.9	1.1×10^5	6.2×10^{-3}

The foregoing table gives the critical value of Re. and the minimum value of C_f for vessels of different shapes and sizes. The decrease in the value of C_f with increasing Re. is due to the fact that upto the critical value of Reynolds number, the heat transfer coefficient does not increase as fast as the wind velocity. Vortices, while separating alternately from the sides of the vessel wash the surface of the rear half of the vessel. The intensity of this washing increases with increasing Re. Again the slow increase in the value of C_f after the critical value of Re. is reached, can be explained by the fact that, the laminar flow in the boundary layer changes into turbulent flow before it separates from the surface. The critical value of Re. where the transition takes place depends upon (1) Intensity of turbulence in the tunnel, (2) Pressure drop across the tunnel (3) curvature of the surface and (4) Degree of roughness of the vessel.(A.Fage, Report on Progress in Physics 1939). Experiments on the direct determination of the drag coefficient of a sphere placed in wind tunnels have shown (Goldstein 1938) that in the case of a sphere the critical Reynolds number is comparable with $(2 — 5) \times 10^5$.

We thus find, as is to be expected from the correspondence between the mechanisms of drag and convective heat loss, that the phenomenon of critical (Re). also finds expression in heat exchange through the process of convection. It would be of interest to extend the experiments described in this ~~note~~ chapter to the case of heat exchange between a solid body and a flowing liquid.

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