**THE INFLUENCE OF 90° AND 180°
PIPE BENDS ON HEAT TRANSFER
FROM AN INTERNALLY FLOWING
GAS STREAM**

Thesis submitted for the Degree of Doctor of
Philosophy in the Faculty of Engineering of the
University of Surrey.

by

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ABSTRACT

An investigation has been made into the effect of 90° and 180° bends, of 2 in internal diameter and varying diameter ratio, on the rate of heat transfer from a fluid flowing through the bend.

The test section, immersed in water which acted as a heat sink, consisted of a pipe bend with upstream and downstream lengths of straight pipe. Hot air was blown through the test section and Reynolds numbers in the range 10,000 to 50,000 were studied.

Local heat transfer coefficients were computed from a knowledge of local heat flux values along the pipe system. This enabled equations predicting heat transfer coefficients for a system containing a bend to be produced.

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LIST OF SYMBOLS

a	internal area of small section of pipe (ft^2)
a_r	surface area of pipe/ft run (ft^2)
A	area (ft^2)
C_p	specific heat of air at constant pressure ($\text{Btu/lb } ^\circ\text{F}$)
d	internal diameter of pipe (ft)
D	diameter of curvature of bend (ft)
f_c	friction factor for curved pipe
f_s	friction factor for straight pipe
	$\left. \begin{array}{l} f_c \\ f_s \end{array} \right\} \frac{8R}{\rho v_m^2}$
	$R = \text{shear stress}$
g	gravitational constant (ft/s^2)
G	mass flow rate (lb/hr ft^2)
h	internal heat transfer coefficient ($\text{Btu/hr ft}^2\text{ }^\circ\text{F}$)
h_{av}	average heat transfer coefficient downstream from the beginning of a bend ($\text{BTU/hr ft}^2\text{ }^\circ\text{F}$)
h_c	internal heat transfer coefficient for a curved pipe ($\text{Btu/hr ft}^2\text{ }^\circ\text{F}$)
h_{pm}	peripheral mean heat transfer coefficient ($\text{Btu/hr ft}^2\text{ }^\circ\text{F}$)
h_s	internal heat transfer coefficient for a straight pipe ($\text{Btu/hr ft}^2\text{ }^\circ\text{F}$)
h_T	internal heat transfer coefficient for a system containing a bend ($\text{Btu/hr ft}^2\text{ }^\circ\text{F}$)
h_w	film coefficient of heat transfer for water ($\text{Btu/hr ft}^2 \text{ }^\circ\text{F}$)
H	enthalpy of fluid (Btu/lb)
k	thermal conductivity ($\text{Btu/hr ft}^2\text{ }^\circ\text{F/ft}$)
kt	total bend loss coefficient
l	distance downstream from beginning of test section (ft)
l_b	axial length of pipe bend (ft)
l_c	axial length of curved pipe (ft)
l_s	length of straight pipe (ft)
l_T	length of system containing a bend (ft)

L_H	length of straight pipe equivalent to amount of heat transferred (ft)
L_P	length of straight pipe equivalent to head loss feet
L_S	length of straight pipe equivalent to system containing a bend (l_T) (ft)
p	pressure (lb/ft ²)
p_w	head of water (in)
P	loss of head in a straight pipe (ft)
P_b	loss of head caused by straight pipe of length l_b (ft)
P_c	loss of head in a curved pipe (ft)
P_t	total loss of head caused by a bend (ft)
q	rate of heat transfer through small section of pipe (Btu/hr)
Q	amount of heat transferred (Btu/hr)
r	radius of pipe (ft)
R	radius of curvature of bend (ft)
t	temperature (°F)
t_{am}	bulk mean temperature (°F)
t_g	air temperature (°F)
t_w	water temperature (°F)
Δt	temperature difference (°F)
Δt_m	logarithmic mean temperature difference (°F)
U	overall heat transfer coefficient (Btu/hr ft ² °F)
v	fluid velocity (ft/s)
v_m	mean fluid velocity (ft/s)
V	volume/unit mass of fluid (ft ³ /lb)
W	mean weight flow (lb/s)
x	distance downstream from beginning of bend (ft)
z	distance in vertical direction (ft)
b_1, b_2	constants
b_3, m, n	
α	numerical coefficient
β	coefficient of thermal expansion (/°F)

θ	bend angle (radians)
ρ_{am}	density of air at bulk mean temperature (lb/ft ³)
ρ	density of air (lb/ft ³)
ρ_w	density of water (lb/ft ³)
μ	viscosity of fluid at bulk mean temperature (lb/ft s)
μ_s	viscosity of fluid at surface of pipe wall (lb/ft s)
Gr	Grashof Number ($\frac{\beta \cdot g \cdot \Delta t \cdot d^3 \cdot \rho^2}{\mu^2}$)
Nu	Nusselt Number ($\frac{h \cdot d}{k}$)
Pr	Prandtl Number ($\frac{C_p \cdot \mu}{k}$)
Re	Reynolds Number ($\frac{v_m \cdot d \cdot \rho}{\mu}$)

Subscripts 1 and 2 refer to upstream and downstream stations

Subscripts ABCD refer to positions on the pipe wall with respect to local coefficients

Note: Equation numbers run within each chapter.

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CHAPTER 1

HISTORICAL INTRODUCTION

In industry, pipe bends are often used to connect straight lengths of pipe in heat transfer equipment. Thus 180° bends are commonly met in trombone coolers, and shell and tube exchangers using hairpin tubes, whereas 90° bends find widespread use in the gas industry in the immersion tube heating of liquids. It is known that imparting a directional change in fluid flow increases the quantity of heat transferred from such an installation. Despite the obvious importance of the problem, the design and performance assessment of such heat exchangers is impaired at the present time by lack of detailed information concerning the degree of increase in heat transfer caused.

The present research was carried out to furnish the engineer with more accurate equations for calculating the heat transfer coefficient for pipe systems containing bends.

1.1. Literature Survey

Numerous correlations are available to predict heat transfer coefficients for fluid flow through straight tubes. The streamline region has lent itself to both the mathematical treatment of heat transfer and to experimental investigations when correlation has been by means of a plot of $\ln Nu$ versus $\ln (Gr.Pr.)$ (1). (A list of symbols appears on page 7).

The mechanism of fluid flow in the turbulent region is more complicated than that assumed for stream line flow, and although progress is being made on an analytical basis, most of the attempts to solve the heat transfer problem in this region are made either by way of analogies or semi-empirical equations based on correlations of experimental data. These equations have generally been of the type

$$Nu = \phi (Re)^m (Pr.)^n \quad (2)(3)(4)(5)(6)(7)$$

although additional groups, such as μ/μ_s and l/d , have been added to account for heating and cooling (8) and the length of the tube. (9).

Colburn (10) has proposed a method for the correlation of forced convection heat transfer data which consists of plotting $(h/C_p G)$ multiplied by $(C\mu/k)^{2/3}$ against Reynolds number. The resulting plot was found to coincide with data on fluid friction plotted in the usual manner as

$$\frac{R}{\rho v_m^2} \text{ against the Reynolds number}$$

In the discussion of this paper O. A. Hougen suggests that the analogy between heat transfer and fluid friction has been overemphasised, and that, whilst the analogy holds for flow through and across tubes, the same is not true for flow around bends and through restrictions.

In comparison with the relatively simple case of steady flow in a straight tube, fluid flow in curved pipes is much more complicated due to the occurrence of secondary flow and even details of the mean flow are not known completely. Dean (11), working in the streamline range, has deduced that the motion of a fluid in the cross section of a curved pipe is as shown in Fig. 1. This is in complete agreement with the visual experiments of Eustice (12). Dean (13) has shown furthermore that the frictional resistance

$$\left(\frac{f_c}{\rho v_m^2} \cdot \frac{\rho v_m d}{\mu} \right) \text{ is a function of } \frac{\rho v_m d}{\mu} \left(\frac{d}{D} \right)^{1/2},$$

which has been conclusively confirmed by White (14), who from his results has derived the relationship

$$\frac{f_c}{f_s} = \left[1 - \left\{ 1 - \left(\frac{11.6}{K} \right)^x \right\}^{1/x} \right]^{-1}$$

where $K = \frac{\rho v_m d}{\mu} \cdot \left(\frac{d}{D} \right)^{1/2}$ and $x = 0.45$. A graph may be plotted of

FIG. 1.

SECONDARY MOTION IN A CURVED PIPE

$\frac{f_c}{f_s}$ against $Re \left(\frac{d}{D}\right)^{1/2}$ (15).

However, with respect to the secondary motion for curved ducts with turbulent flow, Herzig and Hansen (16) concluded that the mathematical complexity of such flow makes analytical solutions impossible.

In the turbulent region Piggott (17) and (18) working with bends and fittings, has studied the effects of Reynolds number, radius ratio and pipe roughness. He has put forward the hypothesis that the overall loss in a bend is composed of

- (i) equivalent straight pipe loss, i.e. ordinary pipe friction
- (ii) k_1 – a true bend loss for dead smooth conduit dependent only on R/d .
- (iii) k_2 – a loss due to the relative roughness of the pipe, affected by Reynolds number and roughness.

Using many results from other workers, Piggott has defined the total bend loss k , excluding pipe friction:-

$$k = k_1 + k_2,$$

$$\text{for } \frac{R}{d} < 1, k = 0.157 \left(\frac{d}{R}\right)^{1.75} + 43.8 f_s^{1.5} \text{ and}$$

$$\text{for } \frac{R}{d} > 1, k = 0.157 \left(\frac{d}{R}\right)^2 + 43.8 f_s^{1.5}.$$

Ito (19) has measured friction factors for turbulent flow in curved pipes by passing water through smooth, copper tubing curved to form a complete loop. Results for pipes with a large radius of curvature ($R/r = 648$) coincided with the equation due to Blasius (20) who obtained the following expression for the shear stress in a smooth pipe.

$$\text{viz } \frac{R}{\rho v_m^2} = 0.316 Re^{-0.25}$$

For bends of smaller radius a considerable increase in resistance was observed.

By defining the friction factor of a curved pipe f_c by the equation

$$P_c = f_c \frac{l_c}{d} \frac{v_m^2}{2g},$$

Ito deduced the following empirical formulae from his experimental results for $300 > \text{Re} (r/R)^2 > 0.034$

$$f_c \left(\frac{R}{r}\right)^{1/2} = 0.029 + 0.304 \left[\text{Re} \left(\frac{r}{d}\right)^2\right]^{-0.25}.$$

Below $\text{Re} (r/R)^2 = 0.034$ the friction factor of a curved bend was found to coincide practically with that of a straight pipe. For $\text{Re} (r/R)^2 > 6$

$$f_c \left(\frac{R}{r}\right)^{1/2} = \frac{0.316}{\left[\text{Re} \left(\frac{r}{R}\right)^2\right]^{1/5}}$$

With the introduction of the Blasius formula $f_s = 0.316 \text{Re}^{-1/4}$ into this equation it becomes

$$\frac{f_c}{f_s} = 1.00 \left[\text{Re} \left(\frac{r}{R}\right)^2\right]^{1/20}$$

Ito has extended his previous work (21) in order to include 45° , 90° and 180° bends and two elbows, all of 1.25 in diameter. His measurements show that there is a marked increase in pressure along the outer wall of the bend, accompanied by a corresponding decrease in pressure along the inner wall. A total bend loss coefficient has been defined by

$$k_t = P_t / (v_m^2 / 2g),$$

where P_t is the total loss of head caused by the bend. (This coefficient will be referred to in Chapter 2.3(i)).

The experimental data was correlated by the following empirical formulae, which were subsequently justified by an analytical approach.

For $\text{Re} \left(\frac{r}{R}\right)^2 < 91$,

$$k_t = 0.00873 \propto f_c \theta \frac{R}{r}$$

and for $Re \left(\frac{r}{R}\right)^2 > 91$,

$$k_t = 0.00241 \alpha \theta Re^{-0.17} \left(\frac{R}{r}\right)^{0.84},$$

where α is a numerical coefficient dependent on deflection angle and relative radius.

For $\theta = 90^\circ$

$$\alpha = 0.95 + 17.2 \left(\frac{R}{r}\right)^{-1.96}, \text{ for } \frac{R}{r} < 19.7, \text{ and}$$

$$\alpha = 1 \quad \text{for } \frac{R}{r} > 19.7.$$

For $\theta = 180^\circ$

$$\alpha = 1 + 116 \left(\frac{R}{r}\right)^{-4.52}.$$

With the exception of long radius pipe bends, the total bend loss coefficient was not proportional to the deflection angle for a given value of R/r ; obviously an equilibrium condition was not reached in shorter radius bends. The loss coefficients for the elbows were found to be considerably larger than the loss coefficients in the case of smooth pipe bends.

With reference to heat transfer in curved ducts, McAdams quotes the work of Jeschke (22), who found that for turbulent flow of air in helically coiled tubes the results for long straight tubes should be multiplied by the ratio $1 + 3.5 d/D$. However his results have been found to be suspect by more recent workers. (25)

By means of steam heating on the outside and using water as the cooling fluid, Kirpikov (23) tested four coils in the range of D/d ratios from 10 to 18. He observed marked peripheral variations of wall temperatures and proposed the relationship

$$(Nu)(Pr)^{-0.4} = 0.0456 (Re)^{0.8} \left(\frac{d}{D}\right)^{0.21}$$

for the range $10^4 < Re < 4.5 \times 10^4$.

Results obtained by Seban and McLaughlin (24), who have measured friction and heat transfer coefficients for laminar and turbulent flow, are in excellent agreement with the equations put forward by Ito. Their work was performed on both oil and water flowing through tube coils having ratios of coil to tube diameter of 17 and 104. The fluid was heated by means of electrical dissipation in the wall of the tube and variations in the value of the local heat transfer coefficients were revealed as variations in the temperature of the tube wall. Friction factors for both isothermal and non-isothermal turbulent flow were correlated by the equation

$$\frac{f_c}{f_s} = \left[Re \left(\frac{d}{D} \right)^2 \right]^{1/20},$$

Data on heat transfer was correlated by the equation

$$Nu, Pr^{-0.4} = \frac{f_c}{8} \cdot Re \quad (1)$$

where f_c is given by the previous equation. For laminar flow Seban and McLaughlin obtained friction factor data within 8% of White's formulation. Here heat transfer data was correlated by

$$Nu, Pr^{-1/3} = \text{const.} \left[\frac{f_c}{8} \cdot Re^2 \right]^{1/3}$$

For both flow regimes the heat transfer coefficients on the outside of the coil exceeded those on the inside by factors of 2 and 5 for turbulent and laminar flow respectively.

Equation (1) gives results within 20% of those predicted by Jeschke's equation for Reynolds numbers up to 100,000.

Rogers and Mayhew (25), working with water flowing through coils of radius ratio 10.8, 13.3 and 20.12 (inside diameter of coils 0.3734 inches), have confirmed the isothermal pressure loss equations suggested by Ito. Application of steam heating to these coils has enabled heat transfer

results to be obtained. By accepting Seban and McLaughlin's exponent for d/D of 0.1 these results have been correlated to within $\pm 10\%$ by

$$Nu = 0.023 \cdot Re^{0.85} \cdot Pr^{0.4} \cdot \left(\frac{d}{D}\right)^{0.1},$$

where the physical properties are evaluated at the bulk mean temperature. Estimates of friction factors for non-isothermal flow have been predicted from isothermal results by multiplying the isothermal friction factor by

$$[(Pr)_b / (Pr)_w]^{-1/3}$$

where subscripts b and w refer to the bulk mean and wall temperatures respectively.

Equations have been obtained by Kreith (26) predicting Nusselt numbers for curved surfaces, by considering the flow channel formed by the annulus between two concentric cylinders with the fluid flowing in a direction perpendicular to their common axis. Utilising the results of Wattendorf (27) the ratio $Nu_{concave} / Nu_{convex}$ has been calculated over a range of Reynolds and Prandtl numbers for:-

- (i) Convex and concave surfaces of 0.655 ft and 0.820 ft radius respectively, and
- (ii) Convex and concave surfaces of 0.125 ft and 0.130 ft.

It was found that the heat transfer coefficient from a heating surface with a concave curvature is considerably higher than for a heating surface with a convex curvature. Hence, for a Prandtl number of unity and Reynold's numbers from 10,000 to 50,000 both (i) and (ii) gave values of $Nu_{concave} / Nu_{convex}$ varying from 1.45 to 1.64.

Eckert and Irvine (28) have studied the rearrangement of the temperature field in flow around a bend. However the bends used were rectangular accelerating ducts and the heating of the fluid was such that the temperature distribution upstream of the bend was non-uniform. Their results indicate that the temperature and velocity fields are considerably rearranged due to secondary flow. Kreith and Margolis (29)

have studied this secondary motion, which they imposed on fluid flow by inserting coiled wires and twisted strips into straight pipe sections of 0.53 and 1.12 inches internal diameter. The working fluids were air and water, and heat transfer coefficients, as much as 4 times greater than those obtained in normal straight pipe flow, were obtained. They also found that the degree of increase of the heat transfer coefficients depended on whether the fluid within the tube was being heated or cooled.

The American Gas Association (30) has concluded from its experimental work on 2" diameter gas-fired immersion heaters, containing a return bend of unspecified diameter ratio, that 1.1 ft has to be added to the centre line length in order to allow for the extra heat transfer. The A.G.A. also concluded that the same allowances had to be made for a 90° mitred bend, and that allowances made for pressure loss when applied to heat transfer gave high values of equivalent length. Patrick and Thornton (31) have conducted a survey of 63 immersion tube heated systems, most of which contained bends or elbows, operating under factory conditions. In the interpretation of their results they have used the basic equation for convective heat transfer

$$Q = U.A.\Delta t_m, \text{ where } A = \pi d.l$$

However, it has been found that when changes in the direction of flow of the fluid stream occur, as at bends and elbows, the above equation leads to an underestimation of the rate of heat transfer. The equation may be modified either by altering the heat transfer coefficient or by using an increased heat transfer area. Patrick and Thornton adopted the latter method and have used the correction given by the American Gas Association - i.e. they added 1.1 ft to the length of the system (1) for every bend or elbow. They have also introduced corrections, which are normally used to allow for increased friction at bends and elbows.

Tailby and Clutterbuck (32) compared the results of Patrick and Thornton with their studies on a straight pipe. It was found necessary

to add 4 ft to the centre line length to allow for a bend and obtain similar results. This suggests that the American Gas Association figure is far too low.

The effect of various entry configurations, (including an elbow and 90° and 180° smooth bends of unspecified radius), on local heat transfer coefficients for air flowing turbulently in a 1½ in diameter circular duct was studied by Mills (33). A heating condition of uniform heat flux was imposed downstream of the entry configuration and experiments were conducted over a range of Reynold's numbers from 10,000 to 110,000. Mills' results were reported in the form Nu_x/Nu_∞ - i.e. the ratio of the Nusselt number at distance x downstream of the entry to the value the Nusselt number would have at x if no entry effects were present. This led to the conclusion that the bend effect was independent of Reynolds number. In the case of the elbow the ratio Nu_x/Nu_∞ was 2.5 immediately downstream, decreasing to a value of 1.2 at 15 diameters downstream. Mills suggests that, over a distance of 80 diameters downstream of an elbow, estimates of average heat transfer neglecting entry effects are 10% too low. Local coefficients immediately downstream of 90° and 180° bends were 90% greater than the straight pipe value decreasing to 8% at 15 diameters. Boulter et al (34) stated that average heat transfer coefficients downstream of a 180° bend, could be determined by an equation of the form

$$h_{av} = h_s (1 + k x/d),$$

where k is a constant. However Mills concluded that the use of such a formula would be of doubtful value since the assumption of linearity is an oversimplification.

Lis and Thelwell (35) have expanded the work of Mills, using water in turbulent flow in a 1.92 cm internal diameter pipe. Heat transfer coefficients, downstream of three 180° bends of radius 2, 3 and 4 times that of the pipe, have been measured. They observed that the bends have a considerable effect on the local circumferential heat transfer coefficient.

In the particular case of the 4/1 bend, the value of h_l/h_{pm} (i.e. the ratio of the local coefficient to the peripheral mean coefficient) at $x/d = 2$ is 1.2 for the outside of the bend and 0.8 for the inside, thus showing a considerable distortion around the circumference of the pipe.

Lis and Thelwell have defined a heat transfer parameter as

$$j_x = \left(\frac{hd}{k}\right) \left(\frac{C_p \mu}{k}\right)^{-0.4} \left(\frac{\mu_{am}}{\mu_w}\right)^{-0.14}$$

where μ_{am} is the viscosity at the bulk mean temperature and μ_w is the viscosity at the temperature of the inside wall of the pipe.

Both local heat transfer and average heat transfer parameters j_x and j_{mx} have been correlated in the form

$$j(m)x = a \text{Re}_x^n \left(\frac{x}{d}\right)^s \left(\frac{R}{r}\right)^z$$

Hence for local values

$$j_x = 0.0239 \text{Re}_x^{0.826} \left(\frac{x}{d}\right)^{-0.064} \left(\frac{R}{r}\right)^{-0.12}$$

and for average values

$$j_{mx} = 0.0326 \text{Re}_x^{0.013} \left(\frac{x}{d}\right)^{-0.076} \left(\frac{R}{r}\right)^{-0.12}$$

The data obtained by Lis and Thelwell shows good agreement with that of Mills. However, as pointed out by Lis and Thelwell, Mills used air which has a Prandtl number 10 times smaller than water and should, therefore, indicate a larger entry effect.

With water as the working fluid, Ede (36) has investigated three $1/2$ " internal diameter bends of radius ratio 4/1, 8/1, 21/1 and a mitred elbow. The streamline, transitional and turbulent regions were studied, and heat was transferred to the water by a constant heat flux, which was produced in the pipe wall by means of an alternating current. Results have been reported for the sections upstream and downstream of the

bend, but not for the actual bend since possible irregularities in the pipe wall thickness might lead to non-uniform heat fluxes over this region.

Remarkable results were obtained for laminar flow in that the immediate effect of a 4/1 bend at a Reynolds number of 1780 was to increase the local heat transfer coefficient by about 16 times. Abnormal coefficients were obtained for more than 50 diameters along the pipe and there was a very large difference between the coefficients at the inside and outside positions. When only the section downstream of the bend was heated, local coefficients were not as large as those mentioned previously. Although the elbow produced considerable increases in the peripheral coefficient, the effect was not as large as with smooth bends.

Experiments in the turbulent region showed that the heat transfer coefficient is only slightly affected by the three smooth bends, but with the elbow a greater effect is produced in that the peripheral coefficient immediately following the bend was doubled. Tests with the upstream section unheated and with different heat flux rates demonstrated that the upstream temperature distribution had little or no influence in the case of turbulent flow.

Ede has summarised the effect of the bends in terms of diameters of straight pipe as follows. At $Re = 50,000$ the elbow is equivalent to 8 diameters, the 8/1 and 4/1 bends to 3 diameters and the 21/1 bend to less than one diameter. At $Re = 20,000$ the effects are similar except for the 21/1 bend, where there is a decrease in heat transfer coefficient equivalent to a reduction in length of 2 diameters.

Wood (37) has measured local heat transfer coefficients for hot air flowing through 90° smooth bends and his results indicate that the heat transfer coefficient around and downstream of a bend are greater than the corresponding straight pipe value. However there is a considerable amount of scatter in his results which is of the same order of magnitude as the change in heat transfer coefficient caused by the bend. It is thus impossible to deduce quantitative trends from his work.

Wood also found that average heat transfer coefficients for a system, containing a bend could be predicted using the modification due to Jeschke (22)

$$\text{viz. } h_T = h_S \left(1 + 3.5 \frac{d}{D} \right).$$

Jeschke's equation is applicable to curved ducts whereas Wood's experimental apparatus contained lengths of straight pipe upstream and downstream of the bend. It would appear therefore that the agreement is purely fortuitous.

Ede (38) has also obtained results for three 180° bends of radius ratio 4/1, 8/1 and 22/1, in the range of Reynolds number 700 to 42,000, using the same apparatus as in his previous work (36). Results obtained were generally similar to the results using 90° bends, the bend effect being quite small in the turbulent range and considerably larger for laminar flow.

In the turbulent range, the largest peripheral variation in heat transfer coefficient occurred at slightly more than halfway around the bend, the ratio between maximum and minimum being 2:1 for the 22/1 bend and 4:1 for the 4/1 bend. At $Re = 10,000$ to $20,000$ the value of the mean heat transfer coefficient at a circumference was found to be smaller than the straight pipe value; with a reduction of as much as 25% for the 8/1 bend at a Reynolds number of 10,000. The results from this investigation at $Re = 50,000$ show good agreement with those obtained by Lis and Thelwell in that the local coefficient is proportional to $(x/d)^{-0.064}$. However, the agreement is only approximate at $Re = 10,000$ and $20,000$.

The data has also been presented in the form of a design chart which is a plot of $Nu/Pr^{0.4}$ against the distance downstream from the beginning of the bend at various Reynolds Numbers.

1.2. Conclusion

A summary of the literature shows that there is only limited information available on the flow of fluids through pipe bends. Although Ito has summarised the pressure loss caused by a pipe bend, much less is known about heat transfer in such a system.

The American Gas Association suggested that a pipe bend is equivalent to 1.1 ft of straight pipe. No indication is given of the diameter ratio of the bend investigated and from a consideration of the pressure drop carried out by Ito, it seems likely that this ratio will have a considerable effect on the degree of increase in heat transfer caused.

Wood has investigated 90° bends and local heat transfer coefficients for 90° and 180° bends have been obtained by Ede. However their work is of a qualitative nature and does not allow average heat transfer coefficients for a system to be predicted. The only other studies are due to Mills, and Lis and Thelwell, who measured heat transfer coefficients downstream of 180° bends, but as they did not consider the increase in heat transfer around the bend itself, their equations are of very limited practical use.

Since pipe bends are commonly used in heat transfer equipment in industry and design data for such a system is sparse, further investigation is necessary as was clearly demonstrated by the work of Patrick and Thornton. Information is required concerning the effect of

(i) radius ratio

(ii) Reynolds number and

(iii) deflection angle

on the increase in heat transfer caused by a bend.

In commercial heat exchange equipment 90° and 180° smooth bends and 90° mitred bends are commonly used and the optimum design requires a compromise between the initial and operating costs. As a result the velocities used in the majority of such equipment correspond to Reynolds numbers of no more than 50,000. Since laminar flow is

avoided in heat exchange equipment whenever possible, Reynolds numbers in the range 10,000 to 50,000 should be studied.

The variation of local heat transfer coefficients both around the periphery and along the length of the pipe should be investigated, and design equations should be obtained to enable the prediction of:-

- (i) an average heat transfer coefficient which accounts for the total increase in heat transfer caused by the bend, i.e. around the bend and downstream of the bend
- (ii) an average heat transfer coefficient for the case when the straight pipe downstream of the bend is terminated within the range of disturbance caused by the bend.

CHAPTER 2

THEORETICAL CONSIDERATIONS

It will be shown that the lengths of straight pipe equivalent to the excess pressure drop and to the excess heat transfer caused by a coil are the same. Since these are both due to the secondary motion caused by the coil it is assumed that the same will be true for flow around a pipe bend. Based on this assumption an equation can be derived predicting the heat transfer coefficient for a system containing a bend.

The form of an equation to predict average heat transfer coefficients downstream from the beginning of the bend will be suggested and the theoretical considerations for the analysis of the results will also be discussed.

2.1. Pressure Drop and Heat Transfer in Straight Tubes

2.1.(i) Pressure Drop in Straight Tubes

The loss of head due to friction in a straight pipe is defined by the equation

$$P = f_s \cdot \frac{ls}{d} \cdot \frac{v_m^2}{2g} \quad (1)$$

where f_s , the friction factor for a straight pipe, may be determined from a plot of $R/\rho v_m^2$ versus Re due to Stanton and Pannell (39), or from the Blasius equation (20).

2.1.(ii) Heat Transfer in Straight Tubes

The basic equation for calculating convective heat transfer in a system is

$$Q = UA \Delta t \quad (2)$$

where Q is the amount of heat transferred from a fluid inside a tube to a fluid surrounding the tube,

A is the heat transfer area,
and Δt is the average temperature driving force between the two fluids.

When the temperature of each fluid varies along the length of the tube, the correct temperature difference to use in equation (2) is the logarithmic mean temperature difference Δt_m , of the driving forces at the beginning and end of the tube

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln \frac{\Delta t_1}{\Delta t_2}}$$

In the present research,

$$\Delta t_1 = t_{g1} - t_{w1}$$

$$\text{and } \Delta t_2 = t_{g2} - t_{w2}.$$

In the basic equation (2), U, is a measure of the ease with which heat is transferred through the gas film, the pipe wall material and the liquid film on the outside of the tube. The resistance due to the pipe wall and the liquid film is negligible compared with the resistance offered by the gas film, hence U may be taken as equal to the film coefficient of heat transfer from the gas to the wall, h.

Local heat transfer coefficients are defined by the equation

$$q = h \cdot a \cdot (t_g - t_w).$$

Thus, providing the local heat flux q/a and local gas and water temperatures are known, the local heat transfer coefficient may be determined.

A number of empirical formulae have been derived for the film coefficient of convective heat transfer to and from fluids flowing inside tubes. These are usually by way of dimensional analysis of the form

$$\frac{hd}{k} = \text{const.} \left(\frac{V_m d \rho}{\mu} \right)^m \left(\frac{C_p \mu}{k} \right)^n.$$

Efforts to improve the correlation of data have resulted in slightly differing values for the constant and exponents. Possibly the best known

equation, and the one used to predict straight pipe heat transfer coefficients in this research, is the following form due to Dittus and Boelter (40).

$$\frac{hd}{k} = 0.023 \left(\frac{V_m d \rho}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

where the physical properties are evaluated at the bulk mean temperature of the fluid.

Heat transfer coefficients in straight pipes may also be predicted by using the analogy between heat and momentum transfer. This was first introduced by Osborne Reynolds (41) in 1874 and has been developed to give

$$\frac{h}{C_p \rho v_m} = \frac{R}{\rho v_m^2} \quad (3)$$

Several workers (42), (43), (44), have since proposed modified analogies. However equation (3) agrees well with experimental data for heat transfer in gases whose Prandtl number is nearly unity.

2.2. Pressure Drop and Heat Transfer in Coils

The flow of fluid in a curved duct is extremely complicated, because a secondary flow is superimposed on the main flow pattern, which results in a considerable distortion of the velocity profile across the pipe. The nature of the secondary flow is outward in the central section of the tube and towards the centre of curvature along the tube walls. (See figure 1).

2.2.(i) Pressure Drop in Coils

Ito (19) has found that the friction factor for a curved pipe, f_c , is given by

$$f_c \left(\frac{R}{r} \right)^{1/2} = \frac{0.316}{\left[\text{Re} \left(\frac{r}{R} \right)^2 \right]^{1/5}} \quad (4)$$

for the range of Reynolds numbers and diameter ratios investigated in the present research. Later research (25) has confirmed this equation. Combining equation (4) with the Blasius formula

$$f_s = 0.316 \cdot Re^{-1/4},$$

$$\frac{f_c}{f_s} = \left[Re \left(\frac{r}{R} \right)^2 \right]^{0.05} \quad (5)$$

2.2.(ii) Heat Transfer in Coils

Heat transfer coefficients in coils are given by (24, 25)

$$Nu \cdot Pr^{-0.4} = 0.023 \cdot Re^{0.85} \left(\frac{d}{D} \right)^{0.1} \quad (6)$$

2.2.(iii) Comparison of Pressure Drop and Heat Transfer in Coils

An inspection of the previous equations shows that a coil produces an increase in pressure drop and heat transfer over that obtained in a straight pipe.

The head loss due to friction in a coiled pipe of length l_c is given by

$$P_c = f_c \frac{l_c}{d} \cdot \frac{v_m^2}{2g} \quad (7)$$

Combining equation (7) with (1) the length of straight pipe L_p required to give the same head loss as length l_c of coiled pipe is given by

$$L_p = \frac{f_c}{f_s} l_c \quad (8)$$

$$\text{But } \frac{f_c}{f_s} = \left[Re \left(\frac{r}{R} \right)^2 \right]^{0.05} \quad \text{from (5)}$$

$$\therefore L_p = Re^{0.05} \times \left(\frac{r}{R} \right)^{0.1} \times l_c \quad (9)$$

The amount of heat transferred in length l_c of coiled pipe

$$= h_c \pi d \cdot l_c \cdot \Delta t_m$$

As above, the length of straight pipe L_H required to give the same amount of heat transfer as length l_c of coiled pipe

$$= \frac{h_c}{h_s} \cdot l_c.$$

Now

$$\frac{h_c}{h_s} = \frac{[0.023 \text{ Re}^{0.85} \text{ Pr}^{0.4} (\frac{d}{D})^{0.1}]}{[0.023 \text{ Re}^{0.8} \text{ Pr}^{0.4}]}$$

$$\therefore L_H = \text{Re}^{0.05} \times (\frac{d}{D})^{0.1} \times l_c \quad (10)$$

Equations (9) and (10) are identical, therefore

$$L_P = L_H$$

i.e. the length of straight pipe equivalent to the excess pressure drop caused by a coil ($L_P - l_c$) is equal to the length of straight pipe equivalent to the excess heat transfer in a coil ($L_H - l_c$).

2.3. Pressure Drop and Heat Transfer in Pipe Bends

2.3.(i) Pressure Drop in Pipe Bends

Ito (21) defined a total bend loss coefficient as

$$k_t = \frac{P_t}{\left(\frac{v_m^2}{2g}\right)} \quad (\text{see figure 2}) \quad (11)$$

In the case of a long radius pipe bend

$$k_t = f_c \cdot \frac{l_c}{d}$$

But $l_c = R\theta$

$$\therefore \frac{k_t}{\theta \left(\frac{R}{r}\right)^{1/2}} = \frac{1}{2} f_c \left(\frac{R}{r}\right)^{1/2} \quad (12)$$

FIG. 2.

HYDRAULIC GRADIENT IN A PIPE SYSTEM CONTAINING A BEND.

ABCD = ACTUAL HYDRAULIC GRADIENT.

AB'C'D' = HYDRAULIC GRADIENT IN A CORRESPONDING LENGTH
OF STRAIGHT PIPE.

FIG. 3.

BEND NOTATION.

Substituting equation (4) into equation (12)

$$\frac{kt}{\theta \left(\frac{R}{r}\right)^{1/2}} = \frac{0.158}{\left[\text{Re} \left(\frac{r}{R}\right)^2\right]^{1/5}} \quad (13)$$

Equation (13) is found to apply for pipe bends of large relative radius and for values of $\text{Re} (r/R)^2 < 91$. For $\text{Re} (r/R)^2 > 91$ Ito has deduced

$$\frac{kt}{\theta \left(\frac{R}{r}\right)^{1/2}} = \frac{0.138}{\left[\text{Re} \left(\frac{r}{R}\right)^2\right]^{0.17}} \quad (14)$$

When the relative radius is small such that eddy loss created by the separation of flow may not be ignored, and secondary flow may not be fully developed before the flow reaches the downstream tangent, the total bend loss coefficient is greater than that predicted by equation (14). The loss coefficients in this case are α times as large as predicted by equation (14). Therefore

$$\frac{kt}{\theta \left(\frac{R}{r}\right)^{1/2}} = \frac{0.138 \alpha}{\left[\text{Re} \left(\frac{r}{R}\right)^2\right]^{0.17}} \quad (15)$$

For the bends used in this research Ito has found experimentally:-

$$\theta = 90^\circ, \quad \alpha = 0.95 + 17.2 \left(\frac{R}{r}\right)^{-1.96}$$

$$\theta = 180^\circ, \quad \alpha = 1 + 116 \left(\frac{R}{r}\right)^{-4.52}$$

Combining equation (15) with equation (11) the total head loss due to the bend

$$P_t = \left(\frac{v_m^2}{2g}\right) \cdot 0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84} \text{Re}^{-0.17} \quad (16)$$

The head loss P_b caused by a section of straight pipe of the same length as that of the centre line of the bend is given by

$$P_b = f_s \frac{l_b}{d} \frac{v_m^2}{2g}$$

∴ the loss of head due to the secondary motion at the bend

$$\begin{aligned} &= P_t - P_b \\ &= \frac{v_m^2}{2g} (0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84} Re^{-0.17} - f_s \frac{l_b}{d}) \end{aligned} \quad (17)$$

Combining equation (17) and equation (1) the length of straight pipe L_p equivalent to the head loss due to the secondary motion at the bend is given by

$$L_p = \frac{0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84} d}{Re^{0.17} \cdot f_s} - l_b \quad (18)$$

2.3.(ii) Equation for Heat Transfer in Pipe Bends

It has been shown previously that the length of straight pipe equivalent to the excess pressure drop and the excess heat transfer caused by a coil are the same. Since these are both due to the secondary motion induced by the coil, it is reasonable to assume that the same will be true for a system containing a pipe bend where both the increase in pressure drop and heat transfer over that of a straight pipe are again due to secondary motion caused by the bend.

Considering heat transfer in a system containing a bend (see figure 3); if the average heat transfer coefficient over length l_T is h_T , and the theoretical length of straight pipe equivalent to length l_T is L_S then

$$L_S h_S = l_T h_T \quad (19)$$

The length of straight pipe equivalent to the increased heat transfer

$$L_H = L_S - l_T \quad (20)$$

$$= l_T \left(\frac{h_T}{h_S} - 1 \right) \quad (21)$$

Since $L_H = L_P$ equations (18) and (21) can be combined enabling an equation to predict h_T , the heat transfer coefficient for a system containing a bend, to be produced. Hence

$$\frac{h_T}{h_S} = 1 + \frac{\theta}{l_T} \left(\frac{0.138 \alpha \left(\frac{R}{r} \right)^{0.84} d}{Re^{0.17} \cdot f_S} - R \right) \quad (22)$$

2. 4. Derivation of Equation to Predict Average Heat Transfer

Coefficients Downstream of the Bend

Since the previous equation (22) is based on the total head loss caused by a bend, it enables the overall heat transfer coefficient for a system to be predicted only when the end of the system lies outside the disturbance caused by the bend. In many design problems it is desirable to know the average heat transfer coefficient for an installation, which is terminated within this disturbance.

A review of work on coils shows that, to account for the effects of curvature, an additional dimensionless group (D/d) has been introduced to the groups which are normally used to predict straight pipe heat transfer coefficients. For a system containing a pipe bend, there is a variation in heat transfer coefficient with distance from the beginning of the bend, as well as a change in heat transfer coefficient caused by the curvature of the bend. Hence an additional group X/d , (where X is the distance downstream from the beginning of the bend), is required to predict average heat transfer coefficients completely. Thus the form of the required equation is

$$Nu_{av} = \phi Re^{b_1} Pr^{b_2} \left(\frac{D}{d} \right)^{b_3} \left(\frac{X}{d} \right)^{b_4} \quad (23)$$

2. 5. Air Flow Measurement and Reference Temperature

It is a common practice and one followed in this research to use the bulk mean temperature as the reference fluid temperature. It is

defined as the temperature which the fluid passing a cross sectional area of the conduit during a given time interval would assume if it were collected and mixed in a cup. (45)

The use of the bulk mean fluid temperature together with the weight flow allows heat balances for a system to be made

2.5.(i) Calculation of bulk Mean Temperature and Weight Flow

In order to determine the bulk mean temperature it is necessary to have a knowledge of the velocity profile in the pipe. In the pitot tube a small element of fluid is brought to rest at an orifice situated at right angles to the direction of flow and the flow rate is obtained by measuring the difference between the impact and static pressures. Thus a pitot tube measures the velocity of only a very fine filament of fluid and is, therefore, ideal for exploring the velocity distribution. Since the velocities used in this research are considerably below 200 ft/sec, incompressible flow equations can be used (46). Hence applying Bernoulli's equation

$$\frac{v_1^2}{2} + gz_1 + p_1V = \frac{v_2^2}{2} + gz_2 + p_2V$$

where subscript 1 refers to a section upstream of the pitot tube head and subscript 2 refers to conditions at the pitot tube head. In this particular case $z_1 = z_2$, since the system is horizontal, and $v_2 = 0$.

$$\therefore \frac{v_1^2}{2} + p_1V = p_2V$$

$$\therefore v_1 = \sqrt{2V(p_2 - p_1)}$$

$$\therefore v_1 = (2gh)^{1/2} \quad (24)$$

where h is the difference between the impact pressure head at section 2 and the static pressure head at section 1.

In the present research, this pressure head is recorded directly on the manometer in inches of water (pw),

$$\therefore v_1 = \left(\frac{2g pw \rho_w}{12\rho} \right)^{1/2} \text{ ft/sec}$$

ρ varies with the temperature of the air flowing and may be found from a knowledge of the temperature profile.

Hence the velocity of a small element of air in the pipe is given by

$$v = 18.28 \left(\frac{pw}{\rho} \right)^{1/2} \text{ ft/sec}$$

and assuming that a temperature profile across the pipe can be found then a velocity profile across the pipe may be computed.

The air temperatures in the research did not exceed 400°F, hence, since radiation errors may be ignored, a temperature profile was obtained using a copper-constantan thermocouple. A typical velocity profile across a radius is shown in figure 4.

Mass flow through an annulus (of width dr , at radius r) in the pipe

$$= 2 \cdot \pi \cdot r \cdot v \cdot \rho \cdot dr$$

$\therefore$ Total mass flow through the pipe,

$$W = 2\pi \int_0^{r=1} v \rho \cdot r \cdot dr \quad (25)$$

This integral may be solved by evaluating the area under the curve of $v\rho$ vs. r (see figure 5).

If v_m is the mean velocity of air through the pipe and ρ_{am} is the density of air corresponding to the bulk mean temperature of the air then

$$W = \frac{\pi 2^2}{144} v_m \cdot \rho_{am} \quad (26)$$

$$\therefore v_m = \frac{144}{2 \cdot \rho_{am}} \int_0^{r=1} v \cdot \rho \cdot r \cdot dr \quad (27)$$

VELOCITY PROFILE.

FIG. 5.

$\underline{Vr}$ v. $\underline{r}$.

Thus, if t_{am} and hence ρ_{am} can be calculated, the mean air velocity can be found from equation (27).

Figure 6 shows a typical temperature profile across a radius of the pipe.

Enthalpy transported through an annulus (of width dr , at radius r)

$$= 2\pi \cdot r \cdot \rho \cdot v \cdot t \cdot C_p dr$$

$\therefore$ Total enthalpy transported through the pipe

$$H = 2\pi C_p \int_0^{r=1} v \rho t \cdot r \cdot dr \quad (28)$$

This integral is calculated from the area under the curve of $v \rho t \cdot r$ vs. r (see Figure 7)

Now

$$H = W C_p t_{am} \quad (29)$$

where t_{am} is the bulk mean temperature of the air. W may be calculated from equation (25) and combination of equations (28) and (29) gives

$$t_{am} = \frac{2\pi}{W} \int_0^{r=1} v \rho t \cdot r \cdot dr \quad (30)$$

2.6. Determination of Heat Transfer Coefficients for the System

If temperature and velocity profiles are measured at the two probe stations along the length of the pipe system, one upstream of the bend and the other downstream of the bend and close to the end of the installation, an average heat transfer coefficient for the system can be obtained.

From a knowledge of local heat fluxes, temperatures and hence local heat transfer coefficients at any section in the pipe system may be computed. This allows average heat transfer coefficients to be found at distances downstream from the beginning of the bend.

TEMPERATURE PROFILE.

FIG. 7.

v_{ptr} v. r .

2.6.(i) Average Heat Transfer Coefficients

Enthalpy at upstream probe station = $W.Cp.t_{am1}$

Enthalpy at downstream probe station = $W.Cp.t_{am2}$

Heat lost in test section $Q = W.Cp.(t_{am1}-t_{am2})$

Length of straight pipe in the test section = 13 ft.

Heat transfer area of test section $A = (13+R\Theta) \frac{2\pi r}{12} \text{ ft}^2$

Mean driving force $\Delta t_m = \frac{(t_{am1}-t_w) - (t_{am2}-t_w)}{\ln \frac{t_{am1}-t_w}{t_{am2}-t_w}}$

Average heat transfer coefficient = $Q \frac{1}{A\Delta t_m} \text{ Btu/hr.ft}^2 \text{ } ^\circ\text{F.}$

2.6.(ii) Measurement of Local Heat Flux

A temperature gradient proportional to the heat flow will exist across a metal disc, if it is attached to a surface through which heat is flowing with its plane at right angles to the surface. If the disc is composite, such that at each of its sides there is a junction of dissimilar metals, then an e.m.f. difference proportional to the heat flow will exist between the two junctions. This e.m.f. difference can be calibrated in terms of heat flux (Btu/hr.ft²) (see Chapter 4.1(vii)) and thus an instantaneous value of heat flux at any point in the test section can be found.

2.6.(iii) Calculation of Bulk Mean Fluid Temperature and Local Heat Transfer Coefficient at any Station in the Test Section

The heat lost between two stations in the pipe A and B is given by

$$Q = AR1.ar$$

where AR1 is the area under the curve of local heat flux plotted

against distance along the pipe (see figure 8) and where a_r is the surface area of the pipe per foot run. If the bulk mean temperature at A, t_{Am} is known — e.g. at a probe station — then the bulk mean temperature at B, t_{Bm} is given by

$$t_{Bm} = t_{Am} - \frac{Q}{W.C_p}$$

Thus the air temperature at any station in the test section may be computed.

The local heat transfer coefficient is then equal to the local heat flux divided by the bulk mean temperature at that station:

$$h_l = \frac{\left(\frac{q}{a}\right)}{t_{Bm}}$$

2.6.(iv) Calculation of Average Nusselt Number Downstream of the Bend

A knowledge of local heat transfer coefficients and local temperatures at positions downstream of the bend allows a graph of local Nusselt numbers versus distance downstream of the bend to be drawn (see figure 9).

The average Nusselt number, Nu_{av} , at a distance x from the beginning of the bend is given by:-

$$Nu_{av} = \frac{AR2}{x}$$

Where $AR2$ is the area under figure 9 between 0 and x .

FIG. 8.

HEAT FLUX v DISTANCE ALONG THE PIPE.

FIG. 9.

Nu_{pm} v DISTANCE DOWNSTREAM FROM BEGINNING OF BEND.

CHAPTER 3

EXPERIMENTAL WORK

Experiments were carried out to determine the effect of pipe bends on the heat transfer rate from a fluid flowing through a bend. Hot air was used as the working fluid, and water surrounding the pipe acted as a heat sink. Five 90° bends and four 180° bends were investigated. These are shown in plate 1 and their dimensions in terms of diameter ratio in table 1.

After preliminary calibration experiments had been performed approximately 18 runs were effected for each bend, with Reynolds numbers varying over the range 10,000 to 50,000. The following measurements were made for each run:-

- (i) Electrical input to the blower and heater system
- (ii) Velocity and temperature profiles at two probe stations, one upstream and the other downstream of the bend.
- (iii) e.m.f. outputs from the heat flux meters along the test section.
- (iv) Water temperatures at various positions in the trough.
- (v) Ambient air conditions.

3.1. Experimental Apparatus

A schematic diagram of the apparatus is shown in figure 10 and a typical layout in plate 2. Essentially the apparatus allowed hot air to be blown through a considerable length of straight tubing into the test section, where local heat transfer coefficients were measured. Provision was made in the design for the effect of right angled and return bends of varying diameters of curvature to be tested.

3.1.(i) Straight Pipes and Pipe bends

The pipes studied were constructed from brass tubing of 2" internal diameter and $\frac{1}{16}$ " wall thickness. Brass was chosen, since it is easily

PIPE BENDS

TABLE 1
Bend Dimensions

Bend	D/d	l_b
1	2.5	0.33'
2	4.0	0.52'
3	6.0	0.79'
4	14.0	1.83'
M	Mitred	
A	14.0	3.66'
B	10.0	2.62'
C	6.0	1.57'
D	4.0	1.05'

FIG. 10.

DIAGRAMMATIC LAYOUT OF APPARATUS

LAYOUT OF APPARATUS

PLATE. 2. (cont.)

cleaned and maintained in a smooth condition.

The upstream section of the apparatus consisted of 12 ft of 2 in internal diameter straight brass pipe, with 6 in diameter $\times \frac{1}{8}$ in thick brass flanges at each end to facilitate the coupling to the heater section and bend section. Straightening vanes were inserted in the first 3 ft of this section to assist the calming of the air as it left the blower and heater and the initial 6.5 ft were enclosed by a box containing vermiculite which minimised heat losses. The remaining 5.5 ft formed the preliminary length of the test section.

Downstream of the bend there was a 6 ft section of straight pipe flanged at one end enabling it to be coupled to the bend section.

Four 180° bends and five 90° bends were studied, varying in curvature from a mitred bend to bends with a radius of curvature of 14 in (see table 1 and plate 1). Perfectly smooth bends as distinct from commercial bends are difficult to obtain. However Lee & Wilkes Ltd, Coppersmiths Birmingham were able to produce the required accuracy and manufactured pipe bends with 1 ft of straight pipe at either side onto which were brazed brass flanges. The flanges were made of 6 in diameter by $\frac{1}{8}$ in brass, with six equally spaced $\frac{1}{2}$ in diameter holes on a 4 in P.C.D. Very slight deformation occurred in bending so that for the 2.5 in radius 90° bend the major axis of the resulting elliptical section, which was perpendicular to the bend radius was 7% greater than the minor axis. For the 4 in radius bends this difference was 5% and decreased with increasing diameter ratio.

An investigation of the bends after experimentation had been completed revealed that no buckling had occurred on the inner surface of the bends with the exception of the 2.5 in radius bend, where slight buckling was evident. The inner surfaces of the bends were observed to be in a clean condition.

3.1.(ii) The Hot Air System

Air was supplied to the system by a $\frac{5}{8}$ H.P. hurricane blower, connected to the mains supply through a 1 kw variac and a constant voltage transformer (see figure 11 and plate 3). It was found that fine control of the blower speed and hence of the air flow rate was possible. A voltmeter was connected in parallel with the blower enabling similar blower speeds and air flow rates to be produced for each bend.

The air was heated by means of a 3 kw electrical heater, which was also connected to the constant voltage transformer through a variac. An ammeter and voltmeter were connected into the heating circuit to provide information of the heat input. The electrical system is shown in plate 3 and a circuit diagram in figure 11.

3.1.(iii) The Water System

The test section was immersed in a trough of water, which acted as a heat sink. The trough system was in three sections; the upstream and downstream sections were permanent, whereas the bend section was renewed for each bend. Twenty gauge (0.036 in) mild steel was the material of construction and the dimensions of the cross section were 9 in deep by 6 in wide. Great care was taken to prevent the inside of the trough corroding by treating the metal with dilute phosphoric acid, before coating with polyurethane paint.

Compression joints were incorporated to make a watertight seal between pipe and trough at each end of the trough system. These could be loosened to allow movement of the trough along the pipe thus facilitating removal and installation of the pipe bends and bend sections of the trough.

During preliminary investigations water from a constant head tank was introduced at the beginning of the upstream trough system and flowed along the trough to a take off point at the other end of the system. However to ensure that the water temperature was approximately constant - i.e. change in temperature was not greater than

FIG. II.
CIRCUIT DIAGRAM — HOT AIR SYSTEM

PLATE. 3.

ELECTRICAL SYSTEM FOR HOT AIR

4°F – it was necessary to have a high flow rate. It was found that with the required quantity of water flowing longitudinally through the trough, eddies were caused which disturbed the contact between the heat flux meters and the pipe wall. To overcome this problem it was decided to introduce the water through three perforated copper pipes lying along the bottom of the trough and to have a similar perforated pipe system along the top of the trough connected to two centrifugal pumps acting as the water outlet.

To ensure that an even flow through the trough was maintained checks were made on both the inlet and outlet water flow rates using rotameters. It was found that this system gave an even distribution of water through the trough, with a temperature rise never greater than 4°F.

3.1.(iv) Air Flow Measurement

A micro pilot tube constructed of stainless steel and with a coefficient of unity was used to obtain a velocity profile (see figure 12). The pilot tube consisted of total and static head tubes, forming concentric cylinders with an overall diameter of 2.3 mm and a length of 12 in. The head was manufactured according to N.P.L. design with an ellipsoidal nose.

The pilot tube was inserted into the air stream through a small hole in the pipe wall and a cone was built around the hole to prevent water entering the pipe (see figure 13). Since the cone base was very small, 0.75 in diameter, there was minimal interference with the fluid properties.

Figure 13 also shows the method of locating the pilot tube head in the air stream. This was accomplished by using a circular brass clamp, which was fitted around the pipe wall. Attached to this was an L-shaped stem with a hole at the end through which the pilot tube passed; the latter being held in place by means of a butterfly screw. The exact position of the head of the pilot tube in the air stream was determined

FIG. 13.

METHOD OF LOCATING PITOT TUBE

by placing machined spacers between limb A of the pitot tube and limb B of the clamping device (again see figure 13).

By connecting the pitot tube to an inclined manometer, the velocity head was indicated directly in inches of water. The manometer fluid was Kerosene, which was tinted with red dye and had a specific gravity of 0.787 at 60°F. This fluid was contained in a reservoir at the rear of the instrument and, by adjusting a small piston, the level of fluid in the gauge and hence the zero level of the manometer could be altered. Four ranges were obtainable on the inclined manometer, depending on the angle of inclination (0-0.5 in W.G., 0-1 in W.G., 0-2 in W.G., 0-10 in W.G.) and the manometer could indicate readings accurately to 0.001 in W.G.

The manufacturers stated that the pitot tube had a coefficient of unity and preliminary calibrations of the pitot tube and manometer against a calibrated wet gas meter proved this to be true.

3.1.(v) Air Temperature Measurement

The reference temperature used in this research was the bulk mean fluid temperature. Thus a temperature profile at the same position as the velocity profile was required.

It was considered unnecessary to use a suction pyrometer to obtain a temperature profile for two reasons:-

- a the air temperature did not exceed 400°F.
- b the pipe was only 2 in internal diameter and so the rate at which air had to be drawn through the pyrometer may have interfered considerably with fluid properties in the pipe.

A temperature measuring probe was constructed as shown in figure 14.

The probe consisted of a fibre glass insulated copper constantan thermocouple wire, bent into an L-shape, so that the first inch of

FIG. 14.

TEMPERATURE PROBE.

FIG. 15.

CROSS SECTION OF PIPE LOOKING UPSTREAM
SHOWING HEAT FLUX METER POSITIONS.

the probe was parallel to the air flow and hence lay in an approximately isothermal region. This decreased conduction along the wires, which was further minimized by enclosing that part of the thermocouple wire which was to enter the pipe in ceramic tubing. The probe was held in position in the air stream by a clamping device similar to that used for the pitot tube, and to facilitate this the upper portion of the probe consisted of copper tubing with a limb (D) brazed on to it. This limb indicated the direction in which the head was pointing and also served as a reference for the machined spacers, which were placed between it and the stem of the clamping device.

The leads from the thermocouple were connected to a switch, which in turn was connected to a Cambridge potentiometer. The melting point of ice was used as reference temperature.

This method of obtaining a temperature profile was adjudged to be accurate since (i) it gave a symmetrical temperature profile across the pipe, indicating that there was no conduction along the wires and (ii) when used in conjunction with the pitot tube (which had previously been calibrated) it gave results for the volumetric flow rate through the pipe which were in good agreement with those obtained from a calibrated wet gas meter.

3.1.(vi) Heat Transfer Measurement

The average heat transfer rate over the whole of the test section can be computed from a knowledge of the velocity and temperature profiles at the upstream and downstream probe stations.

However the measurement of local heat transfer is more difficult. Some workers have passed an electric current through an insulated pipe wall; thus generating a uniform heat flux in the wall. Variations in the local heat transfer coefficient were revealed by variations in the temperature of the tube wall. The disadvantage of this method is that the wall thickness at the bend is modified by the bending process

and, hence, the amount of heat generated in such sections will not be uniform.

Other workers have found heat transfer coefficients by condensing steam on the outside of the pipe, but this technique does not lend itself to the calculation of truly local heat transfer coefficients.

Consequently the method used in this research was that due to Hatfield and Wilkins (46), who have devised a heat flow meter which, when placed with its plane at right angles to a flow of heat, registers an e.m.f. which can be calibrated in terms of heat flow.

The heat flow meters (see plate 4) are constructed of silver-tellurium alloy (which has a high thermo e.m.f.) with copper gauze coating on either side. These copper coatings are connected by fine wires to a small terminal block, from which connection can be made to a recorder. When heat passes through the disc a temperature difference is set up between its two sides; thus the disc behaves as a double thermocouple and a small e.m.f. is generated.

The heat flow discs described in the original paper were 0.05 in thick by 0.5 in diameter. It was decided that these were too large to give good contact on a 2 in diameter pipe so smaller Hatfield-Turner heat flux meters (0.004 in thick by 0.20 in diameter) were obtained.

The method of meter attachment had to fulfil two criteria:-

- (i) mobility around the pipe and
- (ii) good contact of the meter with the pipe wall.

These were achieved by means of cotton threads running over the meter area, and attached to two elastic straps, which were snap fastened on the diagonally opposite side of the pipe. This method of attachment was confirmed when preliminary experiments carried out on straight pipe sections, where fully developed flow existed, showed equal e.m.f. outputs as the meter was moved around the pipe. Furthermore, when tested on bend sections results around the

HEAT FLUX METER

circumference of the pipe were reproducible.

Distribution of the meters was at 6 in intervals along straight sections of the pipe and 3 in intervals around the bend sections. The meters were connected to a 12-position two pole switch, which in turn was connected to a kent potentiometer e.m.f. readings were taken at $4 \times 90^\circ$ interval positions around the pipe, referred to as positions A, B, C, D (see figure 15).

3.1.(vii) Miscellaneous Apparatus

- a Water temperature information was obtained using mercury in glass thermometers located in the water trough.
- b A wet gas meter, which had previously been calibrated by the Gas Council, was used to calibrate the pilot tube.
- c During the analysis of results many values had to be read from graphs and put into punched tape form. To achieve this the output from a regulated 12 v power supply was passed through a variable resistance in series with a short length of nichrom wire (see plate 5) (the purpose of the variable resistance was to adjust the voltage drop across the nichrom wire to a suitable value – approx. 2 v). One end of the nichrom wire was permanently attached to the input of a data logging system, the other lead from the data logger being attached to a movable knife edge. By placing the required graph value beneath the nichrom wire and moving the knife edge to the corresponding point on the slide wire, voltages linearly proportional to the graphical value were fed into the data logger. The data logger consisted of a digital voltmeter reading to four significant figures, the output of which appeared as eight channel punched tape in Elliot 503 code from an Addo punch. The command signal was by way of a micro switch, attached to a foot pedal.

PLATE. 5.
POTENTIAL DIVIDING
DEVICE

3.2. Preliminary Experiments

3.2.(i) Location of Probe Stations

It was expected that fully developed flow would exist at the upstream probe station, as this was situated at a distance of 40 diameters downstream of any disturbance. Therefore, after finalising the heater and blower design, this was confirmed by means of pitot tube traverses carried out in horizontal and vertical planes at this probe station. These showed identical profiles which were symmetrical about the pipe axis.

Similar experiments confirmed the location of the downstream probe station.

3.2.(ii) Test of Flanges

As flanged joints were to be used to connect bend sections into the system a test was carried out to ensure that the joints would not interfere with the air flow. A short section of flanged pipe with holes in the horizontal and vertical planes was joined to the upstream straight pipe section. Thus pitot tube tranverses could be effected at a cross section of the pipe in close proximity to the flanged joint. These traverses were again found to be identical and symmetrical about the pipe axis. It was therefore concluded that the flanged joint was not interfering with the fluid flow.

3.2.(iii) Calibration of the Pitot Tube

To verify the manufacturer's statement that the pitot tube had a coefficient of unity, a wet gas meter was installed at the end of the test section. Using cold air flow through the system, pitot tube traverses were made at both the upstream and downstream probe stations; these were in good agreement with one another, and using a coefficient of unity, showed good agreement with the previously calibrated wet gas meter.

3.2.(iv) Calibration of the Temperature Probe

Before construction of the temperature probe the copper-constantan thermocouple was calibrated against a calibrated thermometer using a chemical melting point apparatus with the thermocouple placed in the compartment where the melting point sample is normally placed. The thermocouple was calibrated over the range 100°F to 350°F. A calibration curve of e.m.f. versus temperature was then plotted, and the resultant equation of temperature in terms of e.m.f. found, using the method of least squares.

The resultant equation was

$$t = 33.848 + 44.672 (e.m.f.) - 0.623 (e.m.f.)^2 \quad (1)$$

which was used in ensuing computer programs.

The accuracy of the temperature profiles obtained using the probe was verified by applying a small amount of heating to the air stream and obtaining temperature and velocity profiles at the upstream probe station. The mass flow rate from these profiles showed excellent agreement with the results given by the wet gas meter installed at the end of the system. By using a small amount of heating, it can be assumed that the air temperature is uniform before it enters the gas meter.

3.2.(v) Calibration of Heat Flux Meters

The heat flux meters were attached to the pipe at the required intervals. Velocity and temperature profiles were determined at the upstream and downstream probe stations; after which readings from the heat flow meters were taken at their four positions around the bend. A relationship between individual meters was found by consecutively placing meters on the same area of the pipe and noting their readings; this was done for various outputs from the meters, varying the heat flow over the range likely to be encountered in the research. For each two meters, e.m.f. outputs were plotted against each other. The resultant graphs were straight lines and by a series of such

plots it was possible to interpret the output from each meter in terms of a single meter. Thus the test section was effectively traversed by one meter.

The area under the graph of e.m.f. (in terms of a single meter) versus distance downstream from the upstream probe station was equated to the heat lost between the two probe stations, which made it possible for all the meters to be calibrated.

Results of the comparison of e.m.f. from meters 1, 2, and 3 for various values of heat flux are shown in table 2. This enables figures 16 and 17 to be drawn, from the slope of which the multiplier necessary to reduce the readings to a single meter (i.e. the corrected e.m.f.) is obtained

Hence if meter 1 is taken as the reference meter:-

Multiplier for meter 1 = 1

Multiplier for meter 2 = 0.99

Multiplier for meter 3 = 0.99

The multipliers found in this way showed good agreement with the manufacturer's calibration.

Values of the corrected e.m.f. versus distance along the pipe for experiment A.10 are shown in table 3. Figures 18 a, b, c and d show values of the local heat flux plotted against distance from the upstream probe station for the four positions around the pipe. These values were translated into punch tape form using the potential dividing device described in chapter 3.1.(vii). Thus average values of e.m.f. around the circumference at a station were obtained and plotted against distance downstream from the upstream probe station (see figure 19 and program 3)

Area under figure 19 = 8.150 mv.ft

Area /ft run of pipe = 0.524 ft²/ft

∴ 8.150 . 0.524 mv ft² = 7862.3 Btu/hr

∴ 1 mv = 1840 Btu/hr ft².

TABLE 2**Data for Comparison of Heat Flux Meters 1, 2, and 3**

e.m.f. Meter 1	e.m.f. Meter 2	e.m.f. Meter 2	e.m.f. Meter 3
118	110	111	103
151	140	140	148
225	206	187	180
225	218	191	190
238	234	209	193
250	243	250	270
373	380	373	380
420	415	420	415

FIG. 17.

TABLE 3

Recorded and Corrected e.m.f.'s versus Distance along the Pipe

Experiment No. A. 10

l ft	Recorded e.m.f.'s (mV)				Meter factor	Corrected e.m.f.'s (mV)				t (°F)
	A	B	C	D		A	B	C	D	
0.25	0.787	0.825	0.842	0.788	1.03	0.812	0.850	0.869	0.813	272
0.75	0.854	0.805	0.821	0.775	1.00	0.854	0.805	0.821	0.775	265
1.25	0.805	0.820	0.844	0.813	0.96	0.770	0.786	0.809	0.780	258
1.75	0.791	0.759	0.782	0.745	0.99	0.784	0.752	0.775	0.737	251
2.25	0.702	0.702	0.715	0.711	1.04	0.730	0.730	0.745	0.740	244
2.75	0.653	0.688	0.678	0.648	1.07	0.698	0.735	0.725	0.694	238
3.25	0.728	0.772	0.757	0.740	0.93	0.677	0.718	0.705	0.689	231
3.75	0.624	0.719	0.720	0.698	0.99	0.617	0.711	0.712	0.691	225
4.08	0.628	0.686	0.628	0.623	1.02	0.640	0.700	0.640	0.635	221
4.41	0.690	0.658	0.648	0.675	0.97	0.670	0.638	0.630	0.655	217
4.75	0.687	0.781	0.722	0.614	0.99	0.681	0.774	0.715	0.608	213
5.08	0.578	0.640	0.544	0.502	1.21	0.700	0.775	0.658	0.607	209
5.41	0.465	0.571	0.507	0.382	1.42	0.660	0.810	0.720	0.543	205
5.75	0.593	0.723	0.602	0.537	1.08	0.640	0.780	0.650	0.580	202
6.08	0.651	0.805	0.670	0.598	0.97	0.630	0.780	0.640	0.560	198
6.41	0.575	0.710	0.615	0.510	1.06	0.610	0.753	0.652	0.652	194
6.75	0.605	0.705	0.590	0.510	1.05	0.635	0.740	0.630	0.535	191
7.08	0.653	0.687	0.520	0.408	1.10	0.718	0.756	0.572	0.572	187
7.41	0.630	0.738	0.648	0.540	0.93	0.586	0.686	0.603	0.503	184
7.75	0.490	0.641	0.498	0.415	1.14	0.558	0.731	0.568	0.474	180
8.08	0.590	0.738	0.578	0.489	0.95	0.560	0.701	0.555	0.464	177
8.41	0.577	0.572	0.552	0.490	0.98	0.565	0.560	0.540	0.480	174
8.75	0.380	0.464	0.382	0.324	1.31	0.497	0.608	0.500	0.424	171
9.25	0.505	0.488	0.505	0.478	0.95	0.480	0.464	0.480	0.454	166
9.75	0.490	0.491	0.462	0.418	0.91	0.445	0.447	0.421	0.380	162

TABLE 3 continued

1 ft	Recorded e.m.f.'s(mV)				Meter factor	Corrected e.m.f.'s (mV)				t (°F)
	A	B	C	D		A	B	C	D	
10.25	0.510	0.508	0.488	0.546	0.83	0.423	0.422	0.405	0.454	158
10.75	0.308	0.407	0.364	0.386	1.04	0.321	0.423	0.378	0.402	154
11.25	0.367	0.393	0.380	0.366	0.95	0.348	0.373	0.361	0.348	151
11.75	0.374	0.390	0.358	0.368	0.92	0.344	0.359	0.329	0.338	148
12.25	0.328	0.356	0.345	0.333	0.96	0.315	0.342	0.331	0.320	144
12.75	0.322	0.328	0.302	0.316	0.98	0.316	0.321	0.296	0.309	141
13.25	0.364	0.347	0.352	0.388	0.85	0.309	0.295	0.299	0.330	138
13.75	0.365	0.356	0.334	0.358	0.84	0.307	0.299	0.280	0.301	136
14.25	0.268	0.278	0.288	0.309	0.97	0.260	0.269	0.280	0.300	133
14.75	0.234	0.241	0.211	0.240	1.13	0.265	0.272	0.250	0.271	130
15.25	0.284	0.273	0.218	0.305	0.99	0.282	0.270	0.216	0.302	127
15.75	0.273	0.266	0.221	0.328	0.99	0.270	0.224	0.219	0.325	125
16.50	0.234	0.240	0.260	0.254	1.00	0.234	0.240	0.260	0.254	121

FIG. 18.

$\frac{e.m.f.}{I/d.} \text{ v } \frac{I/d.}{I/d.}$ EXPERIMENT NO. A-10.

FIG. 18(cont.)

FIG. 19.

AVERAGE e.m.f. v l/d . EXPERIMENT NO. A-10.

3.2.(vi) Calibration of Blower and Heating System

Preliminary experiments were carried out to determine the voltage across the blower and the power input to the heaters corresponding to certain Reynolds numbers in the pipe under equilibrium conditions, at the same time ensuring that there was a measurable heat flux throughout the whole test section. This enabled similar Reynolds numbers to be investigated for each bend.

3.3. Experimental Procedure

The experimental programme consisted of approximately 160 runs; an average of 18 runs for each of the nine bends at Reynolds numbers varying from 10,000 to 50,000, which was considered to be the range used in most industrial applications (see chapter 1.2.)

Initially the inlet water valve was opened and the water take-off pumps switched on. Adjustment of the inlet and outlet control valves in conjunction with observation of the inlet and outlet rotameters allowed an even distribution of water through the trough to be obtained.

The air flow through the pipe was adjusted by means of the variacs connected to the heaters and blower and the apparatus was allowed to run until equilibrium conditions had been attained in the test section. This was shown in two ways:- (i) the output from the pyrometer, inserted in the middle of the pipe at the two probe stations, was constant and (ii) the output from the heat flux meters had reached a steady value. Velocity and temperature profiles were then taken at the upstream probe station, and the upstream probe hole was sealed with a plug, the inside surface of which had contours corresponding to those of the pipe. The same procedure was then carried out at the downstream probe station.

All the heat flux meters were placed at the A position on the pipe and recordings of their output were made on the three potentiometric recorders. The meters were then, in turn, moved to positions

B, C and D on the pipe, output recordings being taken at each position. After the whole test section had thus been surveyed, further velocity and temperature profiles were obtained at the two probe stations to ensure that no change in the air flow rate had occurred during the run. In addition close watch was kept on the blower and heater input and on the flow rate through the trough, throughout the experimental run.

CHAPTER 4

ANALYSIS OF RESULTS

The method of calculation will be illustrated by the results of experiment number A. 10.

Calculated results for the experimental runs are tabulated in the appendix (p. 177) and the variations of local and peripheral mean heat transfer coefficients with Reynolds number and diameter ratio shown in figures 33-50.

Experimental values of average heat transfer coefficients over the test section (probe station to probe station) are given in tables 7-15 and figures 24-32. Superimposed on the results are the values predicted by equation 2.3(ii) 22.

Average heat transfer coefficients at distances downstream from the beginning of the bend are illustrated in figures 59-61.

4.1. General Data for Experiment No. A. 10.

Air Blower	130 volts
Heater	260 volts 13.8 amps
Average Water Temperature	66.7°F
Ambient Temperature	69°F

4.2. Calculation of Weight Flow of Air

The equation used for finding the local air velocity at a probe station is given by

$$v = 18.28 \left(\frac{pw}{\rho} \right)^{1/2} \text{ ft/sec} \quad (2)$$

Observations of velocity head, and e.m.f. from the temperature probe, for values of r across the pipe at the upstream and downstream probe stations are shown in table 4. These readings together with equations (1) and (2) enable velocity and temperature profiles to be established for

TABLE 4

Velocity Head and e.m.f. Readings at the Probe Stations

Experiment No. A. 10

r	Upstream Probe Station		Downstream Probe Station	
	p_w (in H_2O)	e.m.f. (mV)	p_w (in H_2O)	e.m.f. (mV)
0	0.500	6.159	0.401	2.312
0.25	0.492	6.130	0.385	2.280
0.50	0.446	6.041	0.364	2.184
0.75	0.352	5.633	0.288	2.039
0.85	0.306	5.250	0.244	1.863
0.90	0.287	5.000	0.240	1.695

TABLE 5

Data for Temperature and Velocity Profiles at the Probe Stations

Experiment No. A. 10

r	Upstream Probe Station		Downstream Probe Station	
	Velocity (ft/s)	Temp. (°F)	Velocity (ft/s)	Temp. (°F)
0	57.92	285.35	46.29	133.80
0.25	57.10	284.00	45.31	133.00
0.50	54.54	280.98	43.91	128.44
0.75	48.17	265.21	38.85	122.34
0.85	45.00	250.00	35.63	115.11
0.90	43.21	240.18	35.38	108.04

each probe station (see table 5, figures 20 and 21, and program 1). Values of $v \cdot \rho \cdot r$ and $v \cdot \rho \cdot t \cdot r$ were then computed for values of r (see program 2). The results are tabulated in table 6 and plotted in figures 22 and 23. From graphs of $v \rho r$ versus r .

$$\int_0^1 v \cdot \rho \cdot r \cdot dr = 8.94 \cdot 10^{-3} \text{ lb/sec.}$$

$$\begin{aligned} \therefore \text{Mean weight flow} &= 2\pi \cdot 8.94 \cdot 10^{-3} \text{ lb/sec.} \\ &= 0.0563 \text{ lb/sec.} \end{aligned}$$

4.3. Calculation of Bulk Mean Fluid Temperature

From figure 23:-

$$\int_0^1 v \cdot \rho \cdot t \cdot r \cdot dr = 2.475 \text{ lbs}^\circ\text{F/sec. for the upstream probe station}$$

$$\begin{aligned} \therefore \text{tam}_1 &= \frac{2\pi}{0.0563} \cdot 2.475^\circ\text{F} \\ &= 276.1^\circ\text{F} \end{aligned}$$

At the downstream probe station

$$\int_0^1 v \cdot \rho \cdot t \cdot r \cdot dr = 1.085 \text{ lb}^\circ\text{F/sec}$$

$$\begin{aligned} \therefore \text{tam}_2 &= \frac{2\pi}{0.0563} \cdot 1.085^\circ\text{F} \\ &= 121.2^\circ\text{F.} \end{aligned}$$

4.4. Calculation of Average Heat Transfer Coefficient Between the Two Probe Stations

Mean specific heat of air = $0.25 \text{ Btu/lb}^\circ\text{F}$

$$\begin{aligned} \therefore \text{Heat lost between the two stations} &= 0.0563 \cdot 0.25 \cdot (276.1 - 121.2) \cdot 3600 \text{ Btu/hr} \\ &= 7862.3 \text{ Btu/hr} \end{aligned}$$

FIG. 20.

VELOCITY PROFILES.

EXPERIMENT NO. A-10.

FIG. 21

TEMPERATURE PROFILES

EXPERIMENT NO. A-10.

TABLE 6

Values of v_{pr} and v_{ptr} at the Probe Stations
Experiment No. A. 10

r	Upstream Probe Station		Downstream Probe Station	
	v_{pr}	v_{ptr}	v_{pr}	v_{ptr}
0	0.0	0.0	0.0	0.0
0.2	0.6098	173.8	0.6171	81.5
0.4	1.1982	336.7	1.2021	153.9
0.6	1.6995	469.1	1.7135	212.5
0.7	1.9013	515.2	1.9137	231.6
0.75	1.9841	525.8	1.9820	237.8
0.80	2.0662	533.1	2.0830	245.8
0.85	2.1298	532.4	2.1426	246.4
0.90	2.1776	517.2	2.1983	239.6
0.95	2.1700	473.1	2.0992	203.8
1.00	0.0	0.0	0.0	0.0

FIG. 23.

v_{ptr} v. r

EXPERIMENT NO. A-10.

$$\begin{aligned}\text{Mean driving force} &= \frac{(276.1 - 66.7) - (121.2 - 66.7)}{\ln. \left(\frac{276.1 - 66.7}{121.2 - 66.7} \right)} \\ &= 115.2.\end{aligned}$$

Area for heat transfer = 8.71 ft²

$$\begin{aligned}\therefore U &= \frac{7862.3}{8.71 \times 115.2} \\ &= 7.84 \text{ Btu/hr ft}^2\text{°F}\end{aligned}$$

4. 5. Calculation of Reynolds Number

Mean weight flow = 0.0563 lb/sec

Mean air temperature = 188.1°F

$$\text{Re} = \frac{Gd}{\mu}$$

where G is the mass flow/hr ft²

$$\begin{aligned}\therefore \text{Re} &= \frac{0.0563 \times 144.3600.2}{\pi \times 12.0 \times 0.0526} \\ &= 29,400.\end{aligned}$$

Results of equivalent calculations for each bend are shown in tables 7-15 (p 94). These were obtained using program 2. Figures 24-32 (p 103) show experimental values of the overall heat transfer coefficient plotted against Reynolds numbers. Superimposed on these results are the values of the overall heat transfer coefficient predicted from equation (2.3(ii) 22) and tabulated in table 16, which were obtained from a consideration of pressure drop in pipe bends.

4. 6. Calculation of Peripheral Mean and Local Heat Transfer Coefficients

Coefficients at a distance 4.75 ft downstream from the upstream probe station will be evaluated in order to illustrate the method of calculation.

From fig. 19 area under the graph between the upstream probe station and 4.75 ft downstream = 3.299 mv ft.

Now 1 mv = 1840 Btu/hr ft² (see Chapter 3.2(v)) and Area of pipe/ft run = 0.524 ft²/ft

$$\begin{aligned}\therefore \text{Heat lost} &= 3.299 \cdot 1840 \cdot 0.524 \text{ Btu/hr.} \\ &= 3180.2 \text{ Btu/hr.}\end{aligned}$$

$$\begin{aligned}\therefore \text{Mean air temperature at 4.75 ft downstream} \\ &= 276.1 - \frac{3180.2}{0.0563 \cdot 3600 \cdot 0.25} \\ &= 213.3^\circ\text{F}\end{aligned}$$

$\therefore$ the peripheral mean heat transfer coefficient h_{pm} at 4.75 ft downstream may be found.

From figure 19, mean value of heat flux at 4.75 ft downstream

$$= 0.694 \text{ mv}$$

But 1 mv = 1840 Btu/hr ft²

and temperature difference between air and water

$$\begin{aligned}&= (213.3 - 66.7)^\circ\text{F} \\ &= 146.6^\circ\text{F}\end{aligned}$$

$$\begin{aligned}\therefore h_{pm} &= \frac{0.694 \cdot 1840}{146.6} \text{ Btu/hr ft}^2\text{F} \\ &= 8.71 \text{ Btu/hr ft}^2\text{F}\end{aligned}$$

Peripheral mean heat transfer coefficients are shown in the appendix (p 177) and in figures 33-41.. (pp 113-121)

From the values of local heat flux in figures 18a, b, c, d, truly local coefficients can now be computed in a similar manner:-

$$h_A = \frac{0.675 \cdot 1840}{146.6} = 8.47 \text{ Btu/hr ft}^2$$

$$h_B = \frac{0.767 \cdot 1840}{146.6} = 9.62 \text{ Btu/hr ft}^2$$

$$h_c = \frac{0.687.1840}{146.6} = 8.61 \text{ Btu/hr ft}^2$$

$$h_D = \frac{0.648.1840}{146.6} = 8.12 \text{ Btu/hr ft}^2.$$

The calibration of heat flux meters and determination of mean air temperature and local heat transfer coefficients at a point in the pipe were computed using program 3. Tables of local heat transfer coefficients are shown in the appendix and figures 42-50 (p 122) provide a graphical representation of the variation of local heat transfer coefficient along the test section with Reynolds number and diameter ratio D/d .

4.7. Calculation of Average Nusselt Number Downstream of the Bend

Figure 51 shows peripheral mean values of $Nu/Pr^{0.4}$ plotted against the dimensionless group x/d for experiment number A. 10.

Area below the curve between 0 and $x/d = 14$ is 1414

$\therefore$ Average value of $Nu/Pr^{0.4}$ between x/d and 0 and $x/d = 14$
 $= 101.0$

The average value of $Nu/Pr^{0.4}$ for various x/d values was found for each run using program 4.

4.8. Correlation of Average Heat Transfer Coefficients Downstream of the Bend

The average heat transfer coefficients downstream of the bend were correlated in the form

$$\frac{Nu}{Pr^{0.4}} = \text{const.} Re^{b_1} \left(\frac{D}{d}\right)^{b_2} \left(\frac{x}{d}\right)^{b_3} \quad (3)$$

Using the experimental values of $Nu/Pr^{0.4}$, D/d and x/d a multiple regression analysis was conducted using a standard computer procedure to determine the constants const , b_1 , b_2 , and b_3 in equation 3.

The following equations resulted which are valid in the range

FIG. 51.
 $\left(\frac{\text{Nu}}{\text{Pr}^{0.4}}\right)_{\text{pm.}} \text{ v } \frac{x}{d.}$

$$6 \leq \frac{x}{d} \leq 30 \quad (\text{see Chapter 6.4})$$

For 90° bends, excluding the mitred bend

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot \left(\frac{D}{d}\right)^{-0.06} \cdot \left(\frac{x}{d}\right)^{-0.06}$$

with a standard error in $\ln (Nu/Pr^{0.4})$ of 0.071.

For 180° bends,

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot \left(\frac{D}{d}\right)^{-0.11} \cdot \left(\frac{x}{d}\right)^{-0.04}$$

with a standard error in $\ln (Nu/Pr^{0.4})$ of 0.068.

For the mitred bend in the range $2 \leq x/d \leq 30$

$$\frac{Nu}{Pr^{0.4}} = 0.0428 \cdot Re^{0.81} \cdot \left(\frac{x}{d}\right)^{-0.15},$$

standard error in $\ln (Nu/Pr^{0.4}) = 0.049$.

A correlation of average heat transfer coefficient downstream of the bend was also carried out for each bend individually (see Chapter 6.4)

The resultant equations which are of the following form,

$$\frac{Nu}{Pr^{0.4}} = \text{const.} \cdot Re^{b_1} \cdot \left(\frac{D}{d}\right)^{b_2} \cdot f\left(\frac{x}{d}\right)$$

are applicable over the range $0 \leq \frac{x}{d} \leq 30$.

$f(x/d)$ was found for each bend using corresponding values of

$$\frac{Nu}{\text{const.} \cdot Pr^{0.4} \cdot Re^{b_1} \cdot (D/d)^{b_2}}$$

and x/d and a least squares polynomial program (see program 5).

Hence for 90° bends

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot \left(\frac{D}{d}\right)^{-0.06} \cdot f\left(\frac{x}{d}\right)$$

Bend	$f(x/d)$	Standard error
	$0.66584692 + 0.08018155 (x/d)$	
1	$-0.00790986 (x/d)^2 + 0.00029124 (x/d)^3$	0.03922313
$D/d = 2.5$	$-0.00000371 (x/d)^4$	
	$0.67067066 + 0.06628566 (x/d)$	
2	$-0.00628568 (x/d)^2 + 0.00022516 (x/d)^3$	0.04136984
$D/d = 4$	$-0.00000280 (x/d)^4$	
	$0.68818876 + 0.05323686 (x/d)$	
3	$-0.00487036 (x/d)^2 + 0.00016967 (x/d)^3$	0.04530948
$D/d = 6$	$-0.00000207 (x/d)^4$	
	$0.72231569 + 0.02817373 (x/d)$	
4	$-0.00233446 (x/d)^2 + 0.00008065 (x/d)^3$	0.03000955
$D/d = 14$	$-0.00000102 (x/d)^4$	

and for 180° bends

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot \left(\frac{D}{d}\right)^{-0.11} \cdot f_1(x/d)$$

Bend	$f_1(x/d)$	Standard error
	$0.75722910 + 0.03106490 (x/d)$	
A	$-0.00248863 (x/d)^2 + 0.00008550 (x/d)^3$	0.04602590
$D/d = 14$	$-0.00000107 (x/d)^4$	
	$0.72624403 + 0.04371877 (x/d)$	
B	$-0.00362241 (x/d)^2 + 0.00012217 (x/d)^3$	0.02663540
$D/d = 10$	$-0.00000149 (x/d)^4$	
	$0.70706713 + 0.05262630 (x/d)$	
C	$-0.00438619 (x/d)^2 + 0.00014261 (x/d)^3$	0.04236990
$D/d = 6$	$-0.00000166 (x/d)^4$	

table continued

Bend	$f_1 (x/d)$	Standard error
	$0.69265262 + 0.07714593 (x/d)$	
D	$-0.00717857 (x/d)^2 + 0.00024946 (x/d)^3$	0.04236990
$D/d = 4$	$-0.00000304 (x/d)^4$	

For the mitred bend

$$\frac{Nu}{Pr^{0.4}} = 0.0428 \cdot Re^{0.81} \cdot f_2 (x/d)$$

where $f_2 (x/d) = 0.76885154 + 0.06540172 (x/d)$

$$- 0.00946555 (x/d)^2 + 0.00041230 (x/d)^3 - 0.00000580 (x/d)^4$$

$$\text{standard error} = 0.03871852.$$

TABLE 7

Average Heat Transfer Coefficients: Bend 1

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ²) °F
1·1	10,500	0·0211	364·8	138·8	67·1	4280·2	3·92
1·2	13,100	0·0257	334·9	129·5	66·8	4760·4	4·90
1·3	15,200	0·0295	296·0	126·7	66·5	4491·0	5·16
1·4	16,400	0·0317	284·5	128·0	66·7	4460·3	5·23
1·5	17,400	0·0333	265·4	122·5	66·2	4284·9	5·51
1·6	19,300	0·0367	254·0	122·3	66·5	4358·7	5·82
1·7	20,700	0·0396	261·6	122·8	65·8	4947·9	6·41
1·8	20,200	0·0400	327·9	142·7	67·6	6676·6	6·49
1·9	23,000	0·0452	310·5	136·5	67·1	7076·1	7·40
1·10	26,300	0·0522	281·3	136·2	69·0	6819·9	7·86
1·11	28,300	0·0563	274·7	138·6	68·8	6889·7	7·99
1·12	32,700	0·0644	259·5	131·7	68·0	7406·9	9·33
1·13	34,600	0·0679	249·0	132·0	68·4	7153·7	9·26
1·14	36,500	0·0714	243·5	129·3	67·6	7345·8	9·81
1·15	38,800	0·0760	238·5	128·1	67·7	7552·7	10·34
1·16	41,200	0·0805	232·6	126·3	67·3	7703·0	10·88
1·17	43,200	0·0845	232·6	128·7	67·3	7900·1	11·00

TABLE 8

Average Heat Transfer Coefficients: Bend 2

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
2·1	10,100	0·0179	341·0	118·9	66·3	3577·7	3·65
2·2	10,100	0·0183	350·83	135·7	64·1	3543·5	3·17
2·3	12,300	0·0219	248·0	124·2	65·8	4423·1	4·27
2·4	13,800	0·0254	370·0	135·7	63·7	5343·6	4·57
2·5	15,700	0·0282	346·0	134·7	64·5	5370·5	4·90
2·6	17,400	0·0312	337·9	130·9	64·2	5814·2	5·50
2·7	19,700	0·0334	339·6	135·6	64·0	6135·2	5·97
2·8	22,000	0·0387	315·27	132·3	65·3	6378·4	6·35
2·9	24,700	0·0428	294·5	129·3	66·3	6360·7	6·86
2·10	31,200	0·0581	264·5	126·7	65·2	7205·1	8·74
2·11	33,900	0·0627	251·8	124·6	65·4	7177·5	9·20
2·12	36,100	0·0664	246·6	123·8	65·5	7340·1	9·64
2·13	38,900	0·0710	236·2	121·7	65·5	7315·5	10·08
2·14	41,200	0·0749	229·7	119·2	65·8	7438·7	10·70
2·15	44,100	0·0798	220·6	118·1	65·9	7368·5	11·07
2·16	45,300	0·0817	222·1	112·5	65·5	8052·0	12·55

TABLE 9

Average Heat Transfer Coefficients: Bend 3

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
3·1	10,800	0·0205	412·9	146·1	64·2	4915·5	3·74
3·2	13,400	0·0249	377·1	146·3	64·7	5163·5	4·38
3·3	13,000	0·0243	390·0	146·3	65·2	5333·2	4·30
3·4	15,000	0·0324	383·4	146·3	65·6	6164·9	5·08
3·5	18,400	0·0380	325·1	141·0	66·5	6289·7	5·99
3·6	19,800	0·0410	325·2	141·2	66·3	6794·4	6·46
3·7	20,500	0·0434	376·4	156·7	67·6	8590·4	6·86
3·8	22,600	0·0460	296·8	139·0	66·8	6540·8	6·76
3·9	23,400	0·0493	342·7	157·0	67·1	8250·3	6·99
3·10	25,900	0·0522	276·7	136·4	66·9	6584·5	7·30
3·11	28,800	0·0573	265·7	133·8	66·9	6808·5	7·93
3·12	32,500	0·0649	263·6	129·0	66·3	7864·5	9·43
3·13	34,200	0·0682	248·1	128·2	66·1	7364·9	9·29
3·14	36,900	0·0716	237·2	126·9	66·2	7107·5	9·58
3·15	39,200	0·0766	229·8	128·2	67·4	7008·1	9·50
3·16	42,600	0·0829	224·8	122·2	66·6	7652·1	10·97
3·17	45,200	0·0869	216·4	120·7	66·9	7487·2	11·25

TABLE 10

Average Heat Transfer Coefficients: Bend 4

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
4·1	9,100	0·0175	332·8	131·8	64·9	3164·0	2·83
4·2	12,400	0·0236	333·0	120·1	65·7	4517·1	4·35
4·3	14,200	0·0268	309·4	122·2	65·4	4518·3	4·54
4·4	14,800	0·0273	277·1	112·4	65·7	4047·2	4·79
4·5	16,400	0·0303	267·9	117·7	65·1	4099·8	4·78
4·6	18,300	0·0338	259·8	116·7	65·2	4348·1	5·24
4·7	20,300	0·0371	247·3	114·3	65·5	4439·3	5·67
4·8	20,400	0·0392	323·0	136·0	65·8	6603·4	5·90
4·9	23,500	0·0445	300·9	128·2	65·5	6912·1	6·84
4·10	26,600	0·0515	290·0	131·8	66·6	7339·6	7·45
4·11	29,300	0·0566	279·3	126·2	66·7	7792·8	8·44
4·12	32,300	0·0619	263·3	124·6	66·2	7731·2	8·85
4·13	35,200	0·0669	250·5	122·6	65·9	7704·8	9·29
4·14	37,000	0·0703	241·4	123·8	65·8	7439·1	9·16
4·15	40,000	0·0756	230·0	116·4	65·6	7726·4	10·40
4·16	42,600	0·0792	222·2	115·7	66·4	7594·6	10·71
4·17	44,600	0·0829	216·4	116·9	66·2	7421·7	10·58
4·18	47,000	0·0872	213·6	116·0	66·7	7652·8	11·12

TABLE 11

Average Heat Transfer Coefficients: Mitred Bend

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
M·1	9,200	0·0174	333·2	119·1	65·7	3362·0	3·72
M·2	10,000	0·0190	331·4	122·8	64·7	3566·1	3·85
M·3	12,400	0·0235	305·4	122·6	65·4	3862·6	4·47
M·4	13,400	0·0251	291·0	124·2	65·7	3738·5	4·48
M·5	15,400	0·0286	280·0	117·0	66·1	4200·8	5·43
M·6	18,100	0·0333	257·1	115·8	65·4	4236·3	5·92
M·7	19,300	0·0352	247·0	114·7	65·6	4196·8	6·12
M·8	19,100	0·0369	329·8	139·1	65·8	6331·3	6·26
M·9	22,500	0·0429	304·1	133·5	65·8	6579·3	7·15
M·10	24,900	0·0470	290·9	130·4	65·4	6787·0	7·76
M·11	27,900	0·0519	266·4	128·5	65·3	6444·5	7·98
M·12	31,400	0·0579	249·8	125·9	65·1	6453·6	8·57
M·13	34,300	0·0630	242·7	124·5	65·4	6704·6	9·20
M·14	36,000	0·0660	235·9	124·5	65·4	6616·0	9·30
M·15	38,400	0·0703	236·9	123·7	65·3	7158·3	10·09
M·16	41,000	0·0745	222·2	122·0	66·0	6718·4	10·11
M·17	44,000	0·0742	216·1	118·4	65·8	6985·0	11·07
M·18	46,500	0·0831	200·0	115·9	65·1	6291·4	10·81

TABLE 12

Average Heat Transfer Coefficients: Bend A

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
A·1	9,220	0·0176	340·5	117·7	65·5	3527·3	3·04
A·2	12,500	0·0241	299·9	111·9	65·7	4070·3	4·14
A·3	15,500	0·0298	292·7	111·5	65·7	4844·5	5·02
A·4	17,000	0·0324	276·8	109·2	65·9	4898·9	5·42
A·5	19,000	0·0360	255·7	108·9	64·8	4755·2	5·59
A·6	20,600	0·0386	231·6	106·3	65·3	4353·1	5·70
A·7	19,900	0·0392	337·3	131·6	67·3	7264·2	5·90
A·8	22,700	0·0446	328·5	126·2	67·2	8128·9	6·96
A·9	26,200	0·0509	301·0	123·9	66·4	8111·7	7·52
A·10	29,400	0·0563	276·1	121·2	66·7	7862·3	7·84
A·11	31,400	0·0601	274·1	119·9	66·0	8344·4	8·55
A·12	34,200	0·0653	268·7	118·7	65·9	8811·2	9·25
A·13	39,700	0·0770	226·2	113·2	66·0	7831·9	9·96
A·14	42,000	0·0806	226·8	113·8	66·6	8200·6	10·47
A·15	44,500	0·0853	217·5	112·7	66·5	8044·0	10·71
A·16	46,600	0·0881	215·8	111·3	67·2	8289·2	11·30

TABLE 13

Average Heat Transfer Coefficients: Bend B

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
B·1	10,700	0·0198	293·0	109·7	65·5	3264·2	3·58
B·2	12,200	0·0224	274·4	110·2	65·8	3313·3	3·82
B·3	13,500	0·0247	261·5	110·1	65·8	3360·8	4·03
B·4	14,500	0·0265	255·0	106·7	65·3	3532·9	4·45
B·5	20,400	0·0393	342·3	130·1	65·9	7502·8	6·30
B·6	20,800	0·0397	355·0	112·8	65·5	8652·0	7·94
B·7	25,500	0·0484	308·5	127·3	65·5	7894·5	7·30
B·8	28,300	0·0531	291·3	124·0	65·8	7992·3	7·90
B·9	32,000	0·0593	270·1	120·9	65·4	7960·7	8·55
B·10	33,600	0·0617	260·2	114·4	65·7	8100·7	9·42
B·11	35,600	0·0652	249·7	116·1	65·8	7839·4	9·30
B·12	38,500	0·0703	239·7	117·1	65·7	7755·1	9·44
B·13	40,600	0·0736	232·5	112·3	65·8	7968·3	10·37
B·14	43,500	0·0784	224·0	113·2	65·9	7818·5	10·40
B·15	46,200	0·0830	221·9	108·9	65·2	8445·6	11·77

TABLE 14

Average Heat Transfer Coefficients: Bend C

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
C·1	12,600	0·0238	324·5	115·7	65·1	4471·8	4·63
C·2	14,200	0·0266	309·3	115·0	66·0	4657·8	5·05
C·3	16,200	0·0301	289·7	112·7	65·1	4791·3	5·56
C·4	17,900	0·0331	279·9	110·9	65·0	5033·7	6·10
C·5	19,800	0·0363	264·6	111·9	65·0	4991·3	6·28
C·6	21,100	0·0384	245·7	109·5	65·3	4702·2	6·42
C·7	21,000	0·0403	323·1	130·1	65·7	6992·4	6·60
C·8	23,800	0·0451	309·9	128·8	64·9	7357·9	7·23
C·9	27,200	0·0510	288·0	125·7	65·2	7450·3	7·90
C·10	30,000	0·0552	272·9	122·0	65·5	7496·7	8·51
C·11	31,600	0·0592	291·0	121·4	65·6	9043·6	9·81
C·12	34,400	0·0635	258·0	121·8	65·3	7787·4	9·27
C·13	37,000	0·0682	256·3	121·1	65·7	8297·4	9·98
C·14	39,800	0·0727	242·9	118·4	65·4	8148·7	10·46
C·15	42,400	0·0773	238·8	115·7	65·2	8560·5	11·38
C·16	45,200	0·0821	232·3	117·9	65·1	8455·0	11·29
C·17	46,800	0·0850	231·7	117·4	65·7	8738·2	11·72

TABLE 15

Average Heat Transfer Coefficients: Bend D

Experi- ment No.	Re	w (lb/s)	t _{am1} (°F)	t _{am2} (°F)	t _w (°F)	Q (Btu/hr)	U (Btu/ hr ft ² °F)
D·1	11,900	0·0228	336·4	125·3	65·7	4325·7	4·23
D·2	14,000	0·0266	320·6	121·4	65·7	4766·1	4·97
D·3	16,400	0·0308	302·4	119·3	65·7	5074·2	5·62
D·4	18,400	0·0342	286·5	118·2	65·7	5186·9	6·04
D·5	20,200	0·0374	275·7	118·3	65·7	5300·8	6·37
D·6	22,200	0·0406	252·2	113·7	65·5	5055·8	6·77
D·7	21,600	0·0416	331·4	138·8	65·2	7220·1	6·59
D·8	24,600	0·0485	306·1	137·9	66·5	7354·2	7·31
D·9	26,600	0·0526	313·0	137·8	66·4	8307·9	8·11
D·10	29,600	0·0583	300·8	136·1	66·5	8638·8	8·77
D·11	32,500	0·0630	279·6	133·2	67·2	8301·8	9·11
D·12	35,300	0·0681	274·7	129·4	66·6	8913·0	10·13
D·13	38,300	0·0730	248·3	124·2	66·4	8157·0	10·36
D·14	39,700	0·0751	249·9	123·9	66·9	8509·7	10·90
D·15	42,000	0·0800	245·8	125·0	66·6	8706·4	11·11
D·16	44,100	0·0829	239·3	120·6	66·8	8857·9	11·98
D·17	47,500	0·0887	225·4	121·1	67·1	8323·4	11·82

FIG. 24.

$h_T \propto Re.$ — BEND I.

FIG. 25.

$\bar{h}_T \propto Re.$ — BEND 2.

FIG. 26.

$\bar{h}_T \propto Re.$ — BEND 3.

FIG. 27.

$\bar{h}_T \propto Re.$ — BEND 4.

FIG. 28.

$\bar{h}_T \propto Re.$ — BEND M.

FIG. 29.

$\bar{h}_T \propto Re.$ —BEND A.

FIG. 30.

$\bar{h}_T \propto Re$ —BEND B.

FIG. 31.

$\bar{h}_T \propto Re^{-1/4}$ BEND C.

FIG. 32.

$h_T \propto Re^{-1/2}$ BEND D.

TABLE 16

Predicted Average Heat Transfer Coefficients

$$\frac{h_T}{h_S} = 1 + \frac{\theta}{l_T} = \left(\frac{0.138 \cdot \alpha \cdot (R/r)^{0.84} \cdot d}{Re^{0.17} \cdot f_S} - R \right)$$

D/d	Re. 10^{-3}	(Btu/hr ft ² °F)	h_T (Btu/hr ft ² °F)	
			90° Bend	180° Bend
2.5	10	3.20	3.57	
	20	5.57	6.27	
	30	7.71	8.69	
	40	9.70	10.97	
	50	11.60	13.14	
4.0	10	3.20	3.45	3.42
	20	5.57	6.05	6.02
	30	7.71	8.39	8.36
	40	9.70	10.59	10.55
	50	11.60	12.67	12.63
6.0	10	3.20	3.38	3.39
	20	5.57	5.94	5.97
	30	7.71	8.24	8.28
	40	9.70	10.39	10.46
	50	11.60	12.44	12.52
10.0	10	3.20		3.40
	20	5.57		6.02
	30	7.71		8.37
	40	9.70		10.58
	50	11.60		12.67
14.0	10	3.20	3.33	3.41
	20	5.57	5.88	6.06
	30	7.71	8.16	8.43
	40	9.70	10.30	10.67
	50	11.60	12.33	12.79

FIG. 33.

$h_{pm} \propto l/d - \text{BEND I. } (D/d = 2.5)$

FIG. 34.
 $h_{pm} \propto 1/d - \text{BEND 2. (D/d=4)}$

FIG. 35.

$\bar{h}_{pm} \propto l/d$ BEND 3 ($D/d=6$)

FIG. 36.

$\underline{h_{pm}} \propto \underline{l/d} - \text{BEND 4 (D/d=14)}$

FIG. 37

$\bar{h}_{pm} \text{ v } \bar{l}/\bar{d}$ -BEND M (MITRED)

FIG. 38.

$\underline{h_{pm}} \text{ v } \underline{l/d} - \text{BEND A (D/d=14)}$

FIG. 39.
 $\bar{h}_{pm} \propto \frac{l}{d} - \text{BEND } B(D/d=10)$

FIG. 40.

$\frac{h_{pm}}{l/d} \propto \frac{1}{d} - \text{BEND } C(D/d=6)$

FIG. 41

$h_{pm} \propto l/d - \text{BEND } D(d:4)$

Key for Figs. 42-50

- A Position
- B Position
- C Position
- D Position

Fig. 42 (cont.)

h_1 v $1/d$ - Bend 2

h_1 v l/d - Bend 3

h_1 v $1/d$ - Bend 4

h_1 v l/d - Bend M

Fig. 44 (cont.)

Fig. 49 (cont.)

Fig. 50 (cont.)

CHAPTER 5

FLOW VISUALISATION

The nature of the secondary flow caused by a bend was examined qualitatively using the flow visualisation apparatus developed at Watson House, The Gas Council. (48).

Many methods of flow visualisation are available; some are dependent on physical changes that occur in the flow field, others on the addition of a tracer to the flow. The relative merits of various techniques are discussed by Dance (48). He enumerates the chief disadvantages of air experiments as:

- (1) High particle velocities which make photography difficult and necessitate intense light sources.
- (2) Particle opacity or light scattering properties are poor, and
- (3) large density differences between the particles and air superimpose buoyancy effects on the flow pattern,

and concludes that simulation of air flow patterns in a water model is preferable. For the same size model and the same Reynolds number dynamic similarity is achieved at a water to air velocity of 1:12.8.

5.1. Description of Apparatus

5.1.(i) Water Circuit

A diagram of the water circuit is shown in figure 52. The 6 in internal diameter pipe bends and T pieces were constructed of P.V.C., to prevent corrosion and subsequent discolouration of the water.

Water was pumped around the system by a 15 H.P. centrifugal pump and flow through the test section was governed by means of the diaphragm valve on the main bypass and measured by orifice plates (area ratio 0.13) coupled to manometers filled with alkazene (chloro-ethyl benzene S.G. = 2.47).

FIG. 52.

DIAGRAM OF WATER CIRCUIT

Although only one water inlet and outlet were used in the present research, the apparatus is very flexible and can accommodate up to six inlet and five outlet connections to the test section. Air relief valves were fitted to the highest points in the system to facilitate filling and the elimination of air bubbles.

5.1.(ii) Tracer Technique

The tracers used were spherical polystyrene beads (S.G. 1.05, diameter 0.03 in) coated with fluorescent paint in order to increase the light intensity in a direction perpendicular to the plane of illumination.

5.1.(iii) Lighting System

Sections of the model were illuminated with ultraviolet light obtained from a 1 kw high pressure (20 atm) mercury vapour lamp with strong ultra-violet output.

A ray diagram of the light source is shown in figure 53.

Light from the mercury vapour lamp was formed into a parallel beam by a plano-spherical condenser lens A, then focussed in a horizontal plane by a plano-cylindrical lens B and finally focussed into a parallel beam by another plano-convex lens C.

Using this system a vertical parallel beam of light up to 5 in in width and $\frac{1}{4}$ in thickness was produced. A horizontal beam was obtained by removing the aluminised mirror from the system.

5.1.(iv) Test Model

Flow patterns were found for a 90° glass bend of 2 in internal diameter and diameter ratio 6/1. The bend was flanged at each end and was connected to 5 ft lengths of 2 in internal diameter straight glass tubing. Great care was taken to machine the flanges accurately in order to avoid disturbances in the flow pattern.

FIG. 53.

RAY DIAGRAM OF LIGHT SOURCE

100

A square perspex cell was built surrounding the areas to be photographed and filled with distilled water. This prevented light distortion caused by the curved surfaces of the bend and tubing (see plate 6).

5.2. Photographic Techniques

The water flow rate was adjusted to give the required Reynolds number and a selected flow plane was illuminated from beneath the model. Initial exploratory photographs were taken at various apertures and speeds in order to determine the required exposure to give suitable particle track lengths and image densities. Optimum exposures were found to be $\frac{1}{8}$ s and $\frac{1}{15}$ s, at f8 and f11 using Kodak tri-X film.

5.3. Experimental Programme

The apparatus was filled with water, the flow rate adjusted to give a Reynolds number of 25,000 and with the illumination beneath the model, flow patterns for four planes within the bend were studied:-

- (i) a plane parallel to the direction of flow at inlet to the bend and in the central portion of the bend,
- (ii) a plane parallel to the direction of flow at inlet to the bend close to the side wall of the bend.
- (iii) a plane midway between (i) and (ii),
- (iv) a plane perpendicular to the direction of flow at inlet and in the central portion of the vertical exit limb of the bend.

Using a horizontal beam of light a further two planes ((v) and (vi)), downstream of the bend at right angles to one another through the central portion of the pipe, were investigated.

A diagrammatic description of these planes is shown in figure 54.

FLOW VISUALISATION MODEL

FLOW VISUALISATION PLANES

PLANES (i)(ii)(iii)

PLAN VIEW

SIDE VIEW

PLANE (iv)

PLAN VIEW

SIDE VIEW

PLANES (v)(vi)

PLAN VIEW

SIDE VIEW

5.4. Discussion

Flow patterns for the planes described previously are shown in plate 7.

Patterns obtained in a small section of the pipe adjacent to the pipe wall (plate 7(ii)) show that there is a fluid flow from the outside of the bend towards the inside. Combination of these photos with those taken from the end position (plate 7(iv)) indicate that the cross flow is due to elements of fluid on the outside of the bend breaking up into two parts; each of which leaves the outer wall in opposite directions and follows the wall of the tube to the central plane of the inside wall.

The movement of an element of fluid close to the outer wall of the bend is shown in figure 55 by the line aa.

On reaching the central plane of the inside of the bend these elements of fluid create a spiral vortex as illustrated by plate 7(i) and line aa, figure 55. Some elements of fluid on the outside of the bend do not cross over to the inside wall, but form a spiral vortex on the outside wall (see plate 7(i) and line bb, figure 55).

Both these vortices grow in amplitude as they pass through the bend.

Streams of fluid not in the central plane of the tube exhibit the same behaviour, but to a lesser degree, in that they strike the outer wall of the bend and cross over to the inner wall of the outlet limb (see plate 7 (iii) and line cc figure 55).

Filaments of fluid in the central plane of the bend, close to the inside wall at inlet pass through the bend without touching the walls, but are displaced to the outer wall of the downstream limb (see plate 7(i) and line dd, figure 55).

Downstream of the bend the two vortices described previously have developed to give a complex swirling flow. (see plates 7(v) and (vi).)

In addition to enabling the flow path of various particles in the cross

PLATE. 7.

FLOW VISUALISATION PATTERNS

7(i)

7(ii)

7(iii)

7(iv)

7(v)

7(vi)

FIG. 55.

FLOW VISUALISATION PARTICLE TRACKS

PLAN VIEW

SIDE VIEW

END VIEW

section of the pipe to be drawn, the flow visualisation photographs indicate both the increase in turbulence caused by the bend which would be expected to result in higher heat transfer coefficients and also the complexity of the flow which has rendered mathematical analysis impossible.

CHAPTER 6

DISCUSSION OF RESULTS

Peripheral mean heat transfer coefficients are shown in the tables in the appendix (pp. 177) and in figures 33-41.

Local coefficients are also shown in the tables in the appendix (p. 177) and in figures 42-50. Average heat transfer coefficients downstream of the bend are shown in figures 59-61, and average coefficients (probe station to probe station) in tables 7-15 and in figures 24-32.

6.1. Accuracy of the Results

A comparison of the weight flow obtained from the readings of the pitot tube (using a coefficient of unity) with that indicated by a calibrated wet gas meter showed a deviation within $\pm 6\%$. Furthermore, inspection of the mean weight flows obtained from the temperature and velocity profiles at the upstream and downstream probe stations during the course of the experimental runs showed very fair agreement with one another, in that the discrepancy was always less than 10%.

The temperature of the water surrounding the pipe and acting as a heat sink was measured using mercury-in-glass thermometers graduated to 0.2°F . The mean of several readings of water temperature throughout the trough was used as the temperature of the heat sink. Although this will lead to error in the determination of the driving force for the calculation of local coefficients it should be remembered that the minimum value of the driving force through the system is 50°F and since the change in water temperature is never greater than 4°F , the maximum error introduced by this approximation is 4%.

In the calculation of overall coefficients (probe station to probe station) the temperature difference used was the logarithmic mean temperature difference. The derivation of the logarithmic mean temperature assumes a constant film coefficient from one end of the pipe to the other. In the

present system there is a change in the film coefficient for some sections of the pipe, but since these are not large it is felt that the true mean temperature difference is very close to the logarithmic mean.

It was assumed in chapter 2.1(ii) that the resistance of the pipe wall and the liquid film were negligible compared with the resistance offered by the gas film. This has been ascertained using a technique put forward by Wilson (49). The overall and film transfer coefficients can be related by the equation

$$\frac{1}{U} = \frac{1}{h} + \frac{x}{k} + \frac{1}{h_w} \quad (1)$$

For conditions of turbulent flow the inside coefficient is proportional to the velocity of the working fluid raised to the power 0.8. The water side (outside) film coefficient is independent of the air velocity. Thus equation (1) reduces to

$$\frac{1}{U} = \text{const.} + \frac{1}{v^{0.8}} \quad (2)$$

The intercept of a plot of $1/U$ against $1/v^{0.8}$ allows the constant in equation (2) which is the resistance of the water film and pipe wall to be found.

In figure 56, where $1/U$ is plotted against $1/v^{0.8}$ for Bend A, the intercept is very small, thus confirming the original assumption.

It is difficult to estimate the error in the determination of the film coefficient, however for straight sections of the pipe where fully developed flow existed the film coefficients were within 10% of the film coefficient predicted by the Dittus Boulter equation.

The accuracy of the equations correlating heat transfer coefficients has previously been shown in Chapter 4.

FIG. 56.

WILSON PLOT BEND A.

$\frac{1/U \propto 1/v^{0.8}}$

6.2. Peripheral Mean Heat Transfer Coefficients

These were evaluated from the average of the four local heat transfer coefficients around the periphery at a section in the pipe.

The flow visualisation study indicated that the effect of a bend is to distort the initial fully developed velocity profile and create a much higher degree of turbulence both during and after the bend. The expected result would be an increase in the value of the heat transfer coefficients around the bend. This was verified in practice, as seen in figures 33-41 where values of peripheral mean heat transfer coefficients are plotted against l/d for each bend and various Reynolds numbers.

These graphs suggest that within the turbulent range Reynolds number has little effect on the distribution of the heat transfer coefficient during and after the bend. This was substantiated by plotting values of the peripheral mean heat transfer coefficient around the pipe, h_{pm} , divided by the value for fully developed flow in a straight pipe h_s , against x/d for various Reynolds numbers (see figure 57). This finding supports the work of Mills (33). The diameter ratio of the bend has, however, a considerable effect on the heat transfer coefficient distribution. With decreasing diameter ratio, the magnitude of the perturbation caused by the bend increases.

In table 17, for the D/d values used in the present research the peak values of peripheral mean coefficient caused by the bends divided by the corresponding straight pipe value, h_p/h_s are compared with similar values obtained in a coil of the same D/d ratio, h_c/h_s ; h_c the equilibrium value of the peripheral mean heat transfer coefficient for a coil being calculated from the equation suggested by Rogers and Mayhew (25) and Seban and McLaughlin (24)

$$\text{viz } Nu = 0.023 \cdot Re^{0.85} \cdot Pr^{0.4} \cdot (D/d)^{0.1}.$$

It can be seen that for 180° bends the ratio h_p/h_s is always greater than that obtained for a 90° bend, and in some cases exceeds the equilibrium

$\frac{h_{pm}}{h_s} \text{ v } x/d.$

TABLE 17

Comparison of h_p/h_s and h_c/h_s

$\frac{D}{d}$	$\frac{h_p}{h_s}$ 90° bend	$\frac{h_p}{h_s}$ 180° bend	$\frac{h_c}{h_s}$ coil
Mitred	-	-	-
2.5	1.42	-	1.51
4.0	1.36	1.51	1.44
6.0	1.29	1.41	1.38
10.0	-	1.30	1.31
14.0	1.22	1.25	1.27

TABLE 18

Distance to Peak Peripheral Mean Coefficient from
Beginning of Bend

Distance to peak (pipe dias.)			
D/d	90° bends	180° bends	Ede (180°)
2.5	2.5	-	-
4	4	5	3+
6	5	6	4.5+
10	-	7-9	7.5+
14	7	10-18	10+

value for a coil. This is, presumably, because the secondary flow has a longer length in which to develop in the 180° bends before the effect of the curvature is lost. (i.e. before the downstream straight section is reached). Further evidence of this is the fact that the position of the maximum peripheral mean coefficient in a 90° bend is nearer the beginning of the bend than in the case of the 180° bend; the position at which the peak heat transfer coefficient occurs (in terms of diameters of pipe from the beginning of the bend) is shown in table 18. Ede (38) concluded that for 180° bends the maximum heat transfer coefficient occurs rather more than half way around each bend and his results have been included in table 18. Ede (38), whose work offers the only other available information on maximum values of peripheral mean coefficients around a bend, found that at $Re = 20,000$ and for 180° bends $h_p/h_s = 1.15$ for an $8/1$ diameter ratio bend. His observations are at considerable variance with the present ones (see table 17). However values of h_p/h_s between 1.15 and 2.0 at the exit of 180° bends of diameter ratio from $2/1$ to $4/1$ have been reported by Mills (33) and Lis and Thelwell (35). Since the peak values of heat transfer coefficient are considerably greater within the bend than at the exit, it would appear that Ede's ratios are low.

The present research shows that whilst there is a considerable effect on the peripheral mean heat transfer coefficients immediately downstream of the bend, the effect of the pipe bend is barely noticeable upstream of the bend. In all cases the peripheral mean coefficients return to straight pipe heat transfer values within 30 diameters downstream from the beginning of the bend.

Peripheral mean heat transfer coefficients downstream of 180° bends have been correlated in terms of Re , (x/d) and (D/d) by Lis and Thelwell (35). They deduced that the peripheral mean coefficient is proportional to $Re^{0.83} \cdot (x/d)^{-0.06} \cdot (D/d)^{-0.06}$. In their experiments, heating and measurements were commenced at the exit of the bend. Since Ede's results (38) demonstrated that values of the peripheral mean coefficient

downstream of the bend were independent of whether the upstream section and the bend itself were heated or not, it is feasible to analyse the results of the present research in a manner analogous to that of Lis and Thelwell and to make comparisons with their work.

Accepting the Re and D/d exponents of Lis and Thelwell, the results for all the experimental values from bends ABCD taken together indicate that the peripheral mean coefficient is proportional to $(x/d)^{-0.09}$ whilst for bends A, B, C and D analysed individually the exponent of x/d was found to be -0.05 , -0.06 , -0.11 and -0.13 respectively. This shows that the x/d exponent is dependent on D/d , and that a correlation of the type suggested by Lis and Thelwell can lead to considerable errors in the prediction of peripheral mean coefficients downstream of the bend. Ede has analysed his data for a $4/1$ diameter ratio bend in the same way. Whilst obtaining a value of the x/d exponent in agreement with that of Lis and Thelwell at $Re = 50,000$, the agreement was only approximate at $Re = 10,000$ and $20,000$. Thus Ede's results which indicate a variation with Reynolds number are in conflict with the work of Mills, Lis and Thelwell and the present author.

6.3. Local Heat Transfer Coefficients

Graphs of local coefficients for the four positions around the pipe are shown in figures 42-50.

Generally three facts emerge: firstly, that in the range investigated Reynolds number has no effect on the distribution of the local heat transfer coefficient around the bend; secondly, a maximum value of the local transfer coefficient occurs on the outside of the bend with a minimum on the inside; and thirdly that intermediate values occur at the top and bottom positions.

The local heat transfer coefficients at all positions around a cross section of the pipe show an increase over the straight pipe value, with the exception of the long radius bends (diameter ratio $14/1$). In the case of the latter, there is a very slight decrease in the inside

coefficient for both the 90° and 180° bends. Ede (36)(38), who investigated bends varying from an elbow to bends of diameter ratio 21/1 observed a 'dip' effect in the coefficient at the inside position for all the bends he investigated, and, in addition found that for the particular case of an 8/1 bend at a Reynolds number of 10,000, the value of the peripheral mean coefficient fell below the straight pipe value.

The values of all the local heat transfer coefficients increase whereas the ratio between the maximum and minimum (for a given value of x/d along the bend) decreases with diminishing diameter ratio. The apparent reason for this is that in the longer radius bends the faster flowing fluid breaks up the laminar film as it moves towards the outside wall, whereas a relatively slow moving layer of fluid develops adjacent to the inner wall, barely affecting the boundary conditions. This results in considerable differences in the thickness of the laminar layer and hence in heat transfer coefficients at the outside and inside positions. As the diameter ratio of the bend decreases, the degree of turbulence increases considerably, affecting the laminar layer at all positions around the circumference of the pipe. Hence, with decreasing radius ratio, the values of all the local coefficients around the bend increase and the distribution of h_1 around a circumference of the pipe becomes less distorted. On this basis one would expect a mitred bend to give an almost symmetrical distribution of the local heat transfer coefficient around a cross section of the pipe, and figure 46 shows that this is indeed the case.

For a bend of diameter ratio 4/1, Ede, who measured local heat transfer coefficients by transferring heat from a heated pipe wall to the fluid, flowing inside the pipe obtained a maximum ratio of 4:1 between the local coefficients at the outside and inside positions at a circumference. The corresponding value in the present research of 1.5:1 is considerably lower. A possible explanation of the difference between the two ratios is that in flow around a bend the heavier (cooler) fluid particles are forced to the outside of the bend, whilst the lighter (warmer) ones

move inward. Consequently when a fluid is being heated the heat transfer coefficient on the outside of the bend should be greater than when the fluid is being cooled, with a corresponding decrease in the coefficient on the inside of the bend.

As would be expected in the shorter radius bends (D/d less than 6.0) where there is a high degree of turbulence a peak value of local heat transfer coefficient is reached simultaneously at all four positions around the pipe, whereas in the longer radius bends the peak at the outside of the bend occurs after the peaks for the other positions have been achieved.

When peripheral mean coefficients were considered, there was a return to straight pipe values within 30 pipe diameters of the beginning of the bend, which suggests that there was a return to fully developed flow conditions within this distance. However, for bends A and 4, a consideration of local coefficients (see figures 45 and 47) shows that a distance of nearly 40 diameters is required before straight pipe conditions are re-established.

6.4. Average Heat Transfer Coefficients Downstream of the Bend

Average values of heat transfer coefficients downstream of the bend (i.e. the average value between the beginning of the bend and a cross section distance x/d downstream from the beginning of the bend) were determined from a plot of $Nu/Pr^{0.4}$ (using peripheral mean values of heat transfer coefficient) against x/d (see figure 51).

In figure 58 average values of $Nu/Pr^{0.4}$ at distance x/d downstream from the beginning of the bend are plotted against x/d for the four 90° bends at various Reynolds numbers. These are typical of all the results in that a peak in the average heat transfer coefficient occurs shortly downstream from the beginning of the bend and the variation of $Nu/Pr^{0.4}$ with dimensionless group x/d is unaffected by Reynolds number but dependent on D/d . Hence in a correlation of $Nu/Pr^{0.4}$ in terms of Re , D/d and x/d , the function of the latter term should be expressed as a function of D/d . The resultant equation will be complex and of little practical use, so the following general equation has been obtained:-

BEND 3

BEND 4

$$\frac{Nu}{Pr^{0.4}} = \text{const.} Re^{b_1} \cdot (D/d)^{b_2} \cdot (x/d)^{b_3} \quad (1)$$

(see Chapter 4.8)

(It should be noted that the results obtained in this research make no contribution to the determination of the exponent of the Prandtl number for pipe bends.)

This general equation (1) will not account for the peak in the average heat transfer coefficient and is only applicable in the range $6 \leq x/d \leq 30$.

The correlations obtained were:-

$$\frac{Nu}{Pr^{0.4}} = 0.0336 Re^{0.81} \cdot (D/d)^{-0.06} \cdot (x/d)^{-0.06}$$

for 90° bends and

$$\frac{Nu}{Pr^{0.4}} = 0.0341 Re^{0.82} \cdot (D/d)^{-0.11} \cdot (x/d)^{-0.04}$$

for 180° bends. (see Chapter 4.8).

In a similar manner, for the mitred bend in the range $2 \leq x/d \leq 30$

$$\frac{Nu}{Pr^{0.4}} = 0.0428 Re^{0.81} \cdot (x/d)^{-0.15}$$

Lis and Thelwell (35) correlated average heat transfer coefficients in the straight section immediately following 180° bend. They found an exponent of D/d equal to -0.12 , which shows good agreement with the present work, but agreement is only approximate with respect to x/d where they suggest an exponent of -0.076 . This latter value, however, is incompatible with the value of -0.064 for the exponent of x/d which they obtained when correlating peripheral mean heat transfer coefficients, since the variation of heat transfer coefficient with respect to x/d should be greater for peripheral mean than for average values. This raises some doubt as to the validity of the exponents of x/d found by Lis and Thelwell.

Since the function of x/d in the general equation (1) does not fully describe the variation of $Nu/Pr^{0.4}$ downstream of the bend, equations of greater accuracy than the general equation, accounting for the peak in the average heat transfer coefficient and applicable over the range $0 \leq x/d \leq 30$ (covering the whole range of increased coefficients) have been found in the form

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot (D/d)^{-0.06} \cdot f(x/d)$$

for 90° bends

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot (D/d)^{-0.04} \cdot f_1(x/d)$$

for 180° bends

where, since the function of x/d is dependent on D/d , $f(x/d)$ and $f_1(x/d)$ have been determined for each bend by relating the values of $(Nu/0.0336 \cdot Pr^{0.4} \cdot Re^{0.81} \cdot (D/d)^{-0.06})$ and x/d , and $(Nu/0.0341 \cdot Pr^{0.4} \cdot Re^{0.82} \cdot (D/d)^{-0.04})$ and x/d using a computer program for polynomial fits up to the sixth order.

The equations giving the best fits and hence $f(x/d)$ and $f_1(x/d)$ have been tabulated in Chapter 4.8.

The experimental results for average heat transfer coefficients downstream of 90° and 180° bends are shown in figures 59 and 60 where $\ln[Nu/Pr^{0.4} \cdot (D/d)^{-0.06} \cdot f(x/d)]$ and $\ln[Nu/Pr^{0.4} \cdot (D/d)^{-0.11} \cdot f_1(x/d)]$ are plotted against $\ln Re$.

Similarly for the mitred bend

$$\frac{Nu}{Pr^{0.4}} = 0.0428 \cdot Re^{0.81} \cdot f_2(x/d) - (\text{see Chapter 4.8 for } f_2(x/d));$$

and in figure 61 $\ln[Nu/Pr^{0.4} \cdot f_2(x/d)]$ is plotted against $\ln Re$.

The x/d functions are complex polynomials and in order to aid practical computations, average heat transfer coefficients are reported in

FIG. 59.

$\ln[Nu/Pr^{0.4}(D/d)^{0.06} f(x/d)] \propto \ln Re. - 90^\circ \text{ BENDS.}$

FIG. 60.

$$\frac{\ln[Nu/Pr^{0.4}(D/d)^{0.11}]}{\ln[Re-180^\circ \text{BENDS}]} \quad v \quad \frac{f(x/d)}{f(x/d)}$$

FIG. 61.

$\ln[Nu/Pr^{0.4} f_2(x/d)] \quad v \quad \ln Re. - \text{MITRED BEND}$

the form

$$\frac{Nu}{Pr^{0.4}} = \text{const.} \cdot Re^{b_1} \cdot F.$$

$$\text{Where } F = \left(\frac{D}{d}\right)^{b_2} \cdot f\left(\frac{x}{d}\right).$$

Thus for 90° bends

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot F_1,$$

where F_1 may be obtained from figure 62 which shows F_1 plotted against (x/d) for values of (D/d)

and for 180° bends

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot F_2$$

where F_2 is obtained from figure 63.

For the mitred bend

$$\frac{Nu}{Pr^{0.4}} = 0.0428 \cdot Re^{0.81} \cdot F_3.$$

where F_3 is obtained from figure 64.

6.5. Average Heat Transfer Coefficient for the System

Experimental values of average heat transfer coefficients (probe station to probe station) are shown in tables 7 to 15 and are plotted against Reynolds number in figures 24 to 32. There are similar values reported in the literature with which a comparison of these results can be made.

Superimposed on the experimental results in figures 24 to 32 are values of overall heat transfer coefficients predicted by equation (2.3(ii)22), which was derived assuming an analogy between heat transfer and fluid friction for flow around a pipe bend.

FIG. 63.

CHART FOR THE DETERMINATION OF F_2 180° BENDS.

FIG. 64.

CHART FOR THE DETERMINATION OF F_3 MITRED BEND

$$\text{i.e. } \frac{h_T}{h_S} = 1 + \frac{\theta}{l_T} \left[\frac{0.138 \cdot \alpha \cdot \left(\frac{R}{r}\right)^{0.84} d}{Re^{0.17} \cdot f_S} - R \right] \quad (2)$$

values of h_S in equation 2 were found from the Dittus Boelter equation

$$\text{viz. } Nu = 0.023 Re^{0.8} Pr^{0.4}.$$

As there is excellent agreement between the two plots, the amount of heat transferred in length l_T of pipe containing a bend can be obtained from the equation

$$Q = h_T \cdot \pi \cdot d \cdot l_T \cdot \Delta \cdot t_m.$$

where h_T is obtained from equation 2.

Note: Since the theoretical equation was derived from a consideration of the total head loss caused by a bend, it only applies for systems in which the length of straight pipe after the bend is greater than the distance downstream of the bend for which the disturbance persists. i.e. >30 diameters.

From equation 2

$$\frac{h_T}{h_S} = 1 + \frac{\theta}{l_T} \left[\frac{0.138 \alpha \left(\frac{R}{r}\right)^{0.84} d}{Re^{0.17} \cdot f_S} - R \right]$$

This equation may be written in the form

$$\frac{l_T}{d} \left(\frac{h_T}{h_S} - 1 \right) = \frac{0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84}}{Re^{0.17} \cdot f_S} - \frac{D}{d} \frac{\theta}{2} \quad (3)$$

For a given value of Reynolds number, diameter ratio and deflection angle, the right hand side of equation 3 is constant

$$\therefore \frac{h_T}{h_S} = 1 + Z \cdot \frac{d}{l_T} \quad (4)$$

where

$$Z = \frac{0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84}}{Re^{0.17} \cdot f_s} - \frac{D}{d} \cdot \frac{\theta}{2}.$$

Values of α were calculated from the present experimental data and tables 18 and 19 were drawn up, which shows values of Z corresponding to values of D/d and Reynolds number. A graphical representation of Z values is shown in figs. 65 and 66. This enables heat transfer coefficients for a system containing a bend to be predicted from equation 4.

For design purposes it is often more convenient to base calculations on the straight pipe heat transfer coefficient and an equivalent length of straight pipe. From equation (2.3.(ii).20), expressing the length of straight pipe equivalent to the increased heat transfer due to the bend in terms of L_S ,

$$L_H = L_S - L_S \frac{h_S}{h_T} \quad (5)$$

Substituting L_H from equation 5 into equation 3 gives

$$\begin{aligned} \frac{L_S}{d} \left(1 - \frac{h_S}{h_T}\right) &= \frac{0.138 \alpha \theta \left(\frac{R}{r}\right)^{0.84} d}{Re^{0.17} \cdot f_s} - \frac{D}{d} \cdot \frac{\theta}{2} \\ &= Z \end{aligned}$$

$$\therefore h_T = \frac{h_S}{1 - \frac{Zd}{L_S}}$$

$$\text{But } \frac{h_T}{h_S} = \frac{L_S}{L_T}.$$

TABLE 19

Z Values: 90° Bends

Re. 10^{-3}	Diameter Ratio of Bends				
	2.5	4.0	6.0	10.0	14.0
10	6.75	5.41	4.50	3.46	2.69
15	7.03	5.69	4.80	3.83	3.14
20	7.25	5.89	5.02	4.10	3.47
25	7.41	6.06	5.20	4.32	3.73
30	7.55	6.19	5.34	4.50	3.95
35	7.66	6.31	5.47	4.65	4.13
40	7.77	6.41	5.58	4.79	4.29
45	7.86	6.50	5.67	4.91	4.44
50	7.95	6.58	5.76	5.01	4.57

TABLE 20

Z Values: 180° Bends

Re. 10^{-3}	Diameter Ratio of Bend			
	4	6	10	14
10	6.96	6.61	5.41	3.82
15	7.42	7.14	6.10	4.67
20	7.81	7.52	6.61	5.29
25	8.06	7.83	7.01	5.77
30	8.27	8.08	7.34	6.19
35	8.46	8.30	7.63	6.54
40	8.65	8.49	7.88	6.84
45	8.82	8.66	8.11	7.12
50	8.98	8.81	8.31	7.36

FIG. 65.

Z VALUES 90° BENDS

FIG. 66.

Z VALUES 180° BENDS

$$\therefore L_S = \frac{L_T}{1 - \frac{Zd}{L_S}}$$

$$\text{i.e. } L_S = L_T + Zd$$

Thus Z is also the number of diameters of pipe, which must be added to the centre line length of the pipe system to obtain the equivalent length of straight pipe.

Ede has found that at $Re = 30,000$ and for 90° bends of diameter ratio $8/1$ and $4/1$ the bend effect is equivalent to increasing the length of the pipe by 3 diameters. At lower Reynolds Numbers the effect is slightly smaller. This is of a similar order of magnitude as found in the present research (see table 1). The American Gas Association from its work with 2 in diameter gas fired immersion heaters concluded that a 180° smooth bend was equivalent to 1.1 ft of straight pipe. This shows excellent agreement with the present research for a 180° bend of diameter ratio of 14. However they do not suggest a variation of equivalent length with diameter ratio and Reynolds number, which is evident from both the work of Ede and the present author.

CHAPTER 7

SUMMARY AND CONCLUSIONS

A literature survey has revealed the need for further investigation into the factors influencing heat transfer from a fluid flowing through a pipe bend. Although it was known that the effect of the pipe bend was to increase the heat transfer rate, no detailed information was available concerning the degree of increase caused.

An apparatus was constructed to study the effect of Reynolds number and 180° and 90° bends of varying diameter ratio on the value of the heat transfer coefficient. Basically, hot air was blown through a system consisting of two lengths of 2 in internal diameter straight pipe into which bends of varying diameter ratio could be fitted. The pipe system was immersed in a trough of water, which acted as a heat sink.

Measurements were made of both bulk mean temperature and weight flow of the air at two probe stations at either end of the system, and local heat flux at four positions around the periphery of the pipe at intervals along the whole of the test section. This allowed air temperatures at any position in the pipe system to be calculated and also enabled four local heat transfer coefficients and a peripheral mean heat transfer coefficient for any cross section of the pipe to be computed. The following conclusions were drawn.

- (i) The peripheral mean heat transfer coefficients produced by a bend are considerably higher than the corresponding straight pipe value, and increase as the diameter ratio of the bend decreases.
- (ii) The peak value of peripheral mean coefficient produced is greater for 180° bends than for 90° bends.
- (iii) Peripheral mean coefficients greater than the corresponding straight pipe value are obtained for distances up to 30 diameters downstream from the beginning of the bend.

- (iv) A bend has very little effect on the value of the peripheral mean coefficient upstream of the bend.
- (v) The maximum value of the local heat transfer coefficient occurs on the outside of the bend with a corresponding minimum on the inside – the ratio between the maximum and the minimum values increasing with increasing bend diameter ratio.
- (vi) With the exception of the long radius bends (diameter ratio 14/1) there is an increase in the value of the local coefficient over the straight pipe values at all points around the circumference of the pipe.
- (vii) Within the turbulent range, Reynolds number has no effect on the distribution of the local heat transfer coefficient around and downstream of the bend.
- (viii) A non-uniform distribution of local heat transfer coefficient is obtained for distances up to 40 diameters downstream from the beginning of the bend.

Average heat transfer coefficients downstream from the beginning of the bend have been calculated from the peripheral mean coefficients and correlated by:-

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot \left(\frac{D}{d}\right)^{-0.06} \cdot \left(\frac{x}{d}\right)^{-0.06} \text{ for } 90^\circ \text{ bends.}$$

and

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot \left(\frac{D}{d}\right)^{-0.11} \cdot \left(\frac{x}{d}\right)^{-0.04} \text{ for } 180^\circ \text{ bends.}$$

However, these equations do not account for the peak which occurs in the average heat transfer coefficient at a short distance downstream of the bend and are only applicable in the range $6 \leq x/d \leq 30$.

Design equations applicable over the complete range of increased coefficients, $0 \leq x/d \leq 30$, are given by

$$\frac{Nu}{Pr^{0.4}} = 0.0336 \cdot Re^{0.81} \cdot F_1 \text{ for } 90^\circ \text{ bends}$$

and

$$\frac{Nu}{Pr^{0.4}} = 0.0341 \cdot Re^{0.82} \cdot F_2 \text{ for } 180^\circ \text{ bends}$$

where values of F_1 and F_2 may be obtained from a plot of F against x/d and various D/d values (see figures 62 and 63).

Utilizing published work on the pressure loss caused by a bend, an equation has been developed to predict heat transfer coefficients for a system containing a bend. Comparison of experimental values of heat transfer coefficients over the complete length of the test section with values predicted by this theoretical equation indicated that it may be used to predict average heat transfer coefficients for a system containing a bend, provided that the length of straight pipe after the bend is greater than the length for which the disturbance caused by the bend persists. For design purposes this equation has been written in the form

$$\frac{h_T}{h_S} = 1 + Z \cdot \frac{d}{l_T}$$

and it has also been shown that Z is the number of diameters of straight pipe equivalent to the increase in heat transfer caused by the bend.

2.1.(i) Scope for Further Work

The work reported in this thesis should find considerable application in the design of some industrial heat exchanger equipment. However larger internal diameter pipes than 2 in are often encountered and a study investigating a series of larger internal diameter pipes should be included in any new experimental programme. In this way a series of design equations covering varying pipe internal diameters and diameters of curvature could be established.

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The complexity of fluid flow through pipe bends has been illustrated by the present flow visualisation work. This part of the work should be continued and the flow visualisation technique developed in order to enable the velocities of elements of fluid within the bend to be found. This could be done by incorporating a cine camera and a light beam chopper into the present system or by using a different technique such as introducing hydrogen bubbles into the fluid flow.

APPENDIX A

Tables of Local and Peripheral Mean Coefficients

EXPERIMENT NUMBER 1.1Re = 10,500

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	356	3.92	3.96	4.06	3.92	3.72
3.0	348	3.77	3.78	3.87	3.85	3.57
4.5	341	3.64	3.65	3.75	3.70	3.47
7.5	327	3.60	3.56	3.66	3.74	3.44
10.5	314	3.55	3.45	3.65	3.72	3.37
13.5	302	3.49	3.38	3.53	3.67	3.37
16.5	290	3.50	3.39	3.54	3.71	3.36
19.5	278	3.47	3.39	3.45	3.73	3.33
22.5	268	3.53	3.41	3.56	3.73	3.43
24.0	263	3.57	3.42	3.59	3.79	3.45
25.5	258	3.64	3.63	3.70	3.73	3.51
27.0	253	3.91	4.04	4.03	3.83	3.72
27.4	251	4.15	4.63	4.26	3.95	3.75
27.7	250	4.53	5.12	4.98	4.18	3.85
28.5	247	5.24	5.54	5.95	5.08	4.41
29.2	243	5.38	5.54	5.79	5.51	4.67
30.0	240	5.44	5.56	5.61	5.69	4.90
30.7	237	5.26	5.29	5.26	5.55	4.95
31.5	234	5.21	5.23	5.20	5.50	4.93
33.0	229	5.12	5.01	5.18	5.34	4.94
36.0	219	4.91	4.82	5.09	4.99	4.75
39.0	209	4.68	4.50	4.91	4.74	4.56
42.0	202	4.45	4.20	4.77	4.50	4.35
45.0	194	4.18	3.95	4.47	4.23	4.07
46.5	191	3.97	3.70	4.24	4.02	3.93
48.0	188	3.76	3.48	4.09	3.80	3.69
51.0	182	3.66	3.35	4.01	3.67	3.62
54.0	176	3.52	3.17	3.79	3.54	3.62
57.0	171	3.46	3.10	3.82	3.41	3.52
60.0	166	3.47	3.12	3.68	3.49	3.61
63.0	162	3.51	3.20	3.73	3.36	3.76
66.0	157	3.51	3.11	3.71	3.55	3.67
69.0	153	3.54	3.06	3.85	3.46	3.79
72.0	149	3.56	3.07	3.87	3.47	3.86
75.0	145	3.66	3.10	3.95	3.43	3.91
80.0	139	3.65	3.23	4.05	3.57	4.05

EXPERIMENT NUMBER 1.3Re = 15,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	290	4.91	4.99	4.91	4.89	4.85
3.0	284	4.72	4.78	4.62	4.77	4.69
4.5	279	4.56	4.56	4.48	4.62	4.57
7.5	268	4.49	4.51	5.37	4.55	4.51
10.5	259	4.43	4.44	4.27	4.48	4.54
13.5	250	4.33	4.34	4.14	4.41	4.41
16.5	241	4.31	4.27	4.07	4.44	4.44
19.5	233	4.32	4.23	4.07	4.47	4.50
22.5	225	4.39	4.33	4.20	4.51	4.53
24.0	222	4.43	4.43	4.38	4.42	4.48
25.5	218	4.57	4.61	4.66	4.42	4.58
27.0	214	4.81	4.88	5.23	4.42	4.72
27.4	213	5.26	5.37	5.94	4.71	5.02
27.7	212	5.65	5.65	6.75	4.96	5.25
28.5	210	6.17	6.43	7.71	6.11	6.01
29.2	207	6.58	6.68	7.61	7.17	6.45
30.0	205	6.47	6.49	7.15	7.09	6.76
30.7	202	6.25	6.33	6.73	6.79	6.75
31.5	200	6.04	6.09	6.38	6.69	6.58
33.0	196	5.87	6.10	6.23	6.38	6.37
36.0	189	5.53	5.78	6.06	5.94	5.96
39.0	182	5.30	5.49	5.79	5.87	5.64
42.0	176	5.25	5.32	5.87	5.82	5.60
45.0	171	5.18	5.27	5.78	5.78	5.49
46.5	168	4.95	4.99	5.46	5.56	5.41
48.0	166	4.86	4.89	5.43	5.49	5.32
51.0	161	4.69	4.75	5.14	5.27	5.20
54.0	157	4.50	4.51	5.00	5.15	4.94
57.0	153	4.52	4.32	4.59	4.70	4.46
60.0	149	4.41	4.15	4.60	4.63	4.27
63.0	145	4.37	4.37	4.55	4.57	3.99
66.0	142	4.39	4.38	4.42	4.64	4.11
69.0	138	4.47	4.31	4.44	4.73	4.40
72.0	135	4.52	4.36	4.55	4.75	4.41
75.0	132	4.47	4.34	4.45	4.69	4.42
80.0	127	4.62	4.61	4.53	4.83	4.59

EXPERIMENT NUMBER 1.8Re = 20,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	322	6.21	6.21	6.44	6.03	6.15
3.0	316	6.04	5.98	6.26	5.89	6.01
4.5	310	5.93	5.91	6.14	5.74	5.91
7.5	300	5.93	5.88	6.18	5.74	5.91
10.5	290	5.95	5.89	6.21	5.77	5.92
13.5	280	5.91	5.84	6.22	5.74	5.84
16.5	271	5.93	5.80	6.27	5.73	5.90
19.5	262	5.95	5.81	6.27	5.79	5.92
22.5	253	5.99	5.81	6.34	5.84	5.99
24.0	249	5.94	5.68	6.42	5.72	5.92
25.5	245	5.93	5.54	6.61	5.71	5.88
27.0	241	6.02	5.33	7.06	5.73	5.96
27.4	240	6.17	5.41	7.77	5.68	5.80
27.7	239	6.82	7.64	8.37	5.68	5.57
28.5	236	8.07	9.07	9.56	6.86	6.74
29.2	233	8.57	9.20	9.70	7.73	7.63
30.0	231	8.58	8.89	9.19	8.16	8.06
30.7	228	8.49	8.49	8.75	8.33	8.40
31.5	226	8.33	8.31	8.54	8.12	8.35
33.0	221	8.02	8.20	8.37	7.85	7.65
36.0	213	7.80	7.96	8.06	7.70	7.50
39.0	205	7.61	7.67	7.89	7.45	7.36
42.0	199	7.34	7.51	7.56	7.01	7.27
45.0	193	7.04	7.06	7.36	6.67	7.04
46.5	190	6.79	6.51	7.15	6.52	6.88
48.0	187	6.49	6.49	6.51	6.41	6.55
51.0	182	6.19	6.05	6.14	6.11	6.47
54.0	177	5.83	5.63	5.77	5.86	6.06
57.0	173	5.92	5.81	6.00	6.00	5.88
60.0	168	5.85	5.67	5.89	5.83	6.02
63.0	164	5.89	5.64	5.97	5.86	6.08
66.0	160	5.96	5.63	5.98	5.95	6.28
69.0	156	5.88	5.54	5.94	5.93	6.11
72.0	152	5.93	5.66	5.94	5.88	6.25
75.0	149	5.97	5.64	5.91	5.98	6.34
80.0	143	6.01	5.86	6.19	6.20	6.59

EXPERIMENT NUMBER 1.10Re = 26,300

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	277	7.43	7.72	7.61	7.23	7.18
3.0	272	7.19	7.34	7.41	7.01	7.00
4.5	268	7.03	7.10	7.24	6.84	6.93
7.5	260	6.98	6.93	7.27	6.88	6.85
10.5	252	6.93	6.74	7.20	6.90	6.88
13.5	245	6.86	6.64	7.17	6.83	6.78
16.5	238	6.90	6.56	7.18	6.92	6.95
19.5	231	6.90	6.51	7.16	6.92	6.99
22.5	224	6.96	6.56	7.21	6.92	7.17
24.0	221	6.94	6.53	7.17	6.86	7.20
25.5	218	7.09	6.69	7.28	7.10	7.31
27.0	214	7.29	7.03	7.65	7.05	7.45
27.4	214	7.26	7.07	7.77	6.86	7.35
27.7	213	7.79	7.99	8.49	7.04	7.59
28.5	211	9.10	9.45	10.16	8.15	8.63
29.2	209	9.69	9.99	10.56	8.94	9.29
30.0	207	9.68	9.71	10.00	9.64	9.37
30.7	205	9.54	9.50	9.58	9.80	9.28
31.5	203	9.45	9.52	9.66	9.46	9.15
33.0	199	9.10	9.42	9.32	8.76	8.90
36.0	193	8.83	9.07	9.10	8.41	8.74
39.0	187	8.36	8.48	8.68	7.94	8.32
42.0	182	8.14	8.17	8.47	7.77	8.17
45.0	177	7.88	7.68	8.20	7.62	8.00
46.5	175	7.62	7.23	7.98	7.36	7.91
48.0	173	7.37	7.11	7.45	7.19	7.71
51.0	169	7.16	6.98	7.03	7.00	7.65
54.0	165	6.86	6.67	6.83	6.60	7.34
57.0	161	6.93	6.77	6.95	6.61	7.41
60.0	157	6.90	6.78	6.84	6.91	7.07
63.0	154	6.94	6.89	6.91	6.83	7.11
66.0	151	6.99	7.01	6.96	6.80	7.18
69.0	147	7.01	7.16	6.87	6.89	7.12
72.0	144	7.07	7.31	7.01	6.96	7.00
75.0	141	7.13	7.40	7.19	6.82	7.12
80.0	136	7.50	7.71	7.61	7.21	7.46

EXPERIMENT NUMBER 1.12Re = 32,700

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	255	8.97	9.04	9.21	8.82	8.79
3.0	252	8.73	8.80	8.97	8.58	8.56
4.5	248	8.56	8.52	8.76	8.43	8.55
7.5	241	8.48	8.38	8.67	8.38	8.50
10.5	234	8.40	8.21	8.62	8.33	8.42
13.5	228	8.33	8.11	8.49	8.28	8.46
16.5	222	8.35	7.94	8.57	8.26	8.61
19.5	216	8.28	7.99	8.45	8.27	8.42
22.5	210	8.36	8.00	8.51	8.30	8.61
24.0	207	8.30	7.87	8.54	8.26	8.51
25.5	204	8.38	8.03	8.64	8.26	8.59
27.0	202	8.63	8.41	9.02	8.31	8.78
27.4	201	8.73	8.54	9.67	8.14	8.54
27.7	200	9.47	10.25	10.94	8.21	8.49
28.5	199	11.15	12.22	12.86	9.50	10.00
29.2	197	11.96	12.76	13.19	10.95	10.94
30.0	195	12.27	12.72	12.70	12.46	11.21
30.7	193	12.21	12.64	12.39	11.45	11.35
31.5	191	12.22	12.83	12.37	10.75	11.60
33.0	188	11.87	12.52	12.08	10.67	11.45
36.0	182	11.40	12.07	11.68	10.27	11.16
39.0	177	11.00	11.34	11.32	9.96	11.02
42.0	172	10.66	10.96	10.74	9.94	10.87
45.0	168	10.09	10.16	10.16	9.36	10.30
46.5	166	9.64	9.74	9.58	9.08	9.95
48.0	164	9.22	9.25	9.12	8.85	9.48
51.0	160	8.71	8.78	8.67	8.43	8.96
54.0	157	8.27	8.16	8.22	8.16	8.59
57.0	153	8.22	8.04	8.25	8.13	8.46
60.0	150	8.13	8.03	8.13	7.98	8.40
63.0	147	8.16	7.95	8.18	8.04	8.45
66.0	144	8.22	8.18	8.07	8.12	8.49
69.0	141	8.17	8.09	8.07	8.05	8.47
72.0	139	8.24	8.15	8.22	8.15	8.46
75.0	136	8.28	8.20	8.24	8.26	8.42
80.0	132	8.51	8.46	8.53	8.55	8.53

EXPERIMENT NUMBER 1.15Re = 38,800

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	235	10.08	9.84	10.14	10.24	10.11
3.0	232	9.80	9.52	9.82	9.99	9.85
4.5	229	9.55	9.22	9.50	9.89	9.61
7.5	223	9.52	9.05	9.45	9.95	9.61
10.5	218	9.42	8.92	9.42	9.97	9.48
13.5	212	9.33	8.78	9.29	9.81	9.45
16.5	207	9.32	8.65	9.33	9.78	9.52
19.5	202	9.30	8.61	9.24	9.77	9.60
22.5	197	9.35	8.61	9.39	9.84	9.56
24.0	195	9.34	8.70	9.38	9.59	9.69
25.5	193	9.43	8.97	9.58	9.43	9.74
27.0	190	9.62	9.21	9.92	9.46	9.90
27.4	190	9.53	9.23	9.96	9.08	9.85
27.7	189	10.17	10.04	10.89	9.22	10.53
28.5	188	12.00	12.16	13.09	10.73	12.02
29.2	186	13.10	13.29	13.66	13.01	12.42
30.0	185	13.47	14.35	13.59	13.61	12.33
30.7	183	13.42	14.75	13.26	13.50	12.18
31.5	182	13.12	14.91	13.02	12.30	12.24
33.0	179	12.73	13.42	12.99	12.06	12.45
36.0	174	12.20	12.25	12.77	11.69	12.11
39.0	169	11.72	11.50	12.26	11.38	11.73
42.0	165	11.35	10.92	11.99	11.05	11.41
45.0	161	11.00	10.45	11.45	10.88	11.23
46.5	159	10.65	10.13	11.00	10.51	10.95
48.0	158	10.41	9.82	10.77	10.32	10.74
51.0	154	10.04	9.44	10.28	10.11	10.33
54.0	151	9.75	9.64	10.04	9.77	10.06
57.0	148	9.41	9.44	9.43	9.35	9.43
60.0	145	9.09	9.06	9.06	9.08	9.16
63.0	143	9.07	9.00	8.99	9.09	9.21
66.0	140	9.15	9.29	8.97	9.06	9.27
69.0	137	9.11	9.31	8.92	9.00	9.22
72.0	135	9.18	9.17	9.04	9.04	9.48
75.0	132	9.26	9.23	9.12	9.12	9.59
80.0	128	9.26	9.24	9.14	9.12	9.54

EXPERIMENT NUMBER 1.17Re = 43,200

$1/d$	t_g	h_{pm}	h_A	h_b	h_C	h_D
1.5	230	10.91	11.05	11.01	10.79	10.79
3.0	227	10.59	10.70	10.77	10.47	10.41
4.5	224	10.33	10.46	10.50	10.25	10.13
7.5	218	10.25	10.22	10.46	10.23	10.09
10.5	213	10.21	10.14	10.54	10.19	9.96
13.5	208	10.16	10.03	10.42	10.24	9.93
16.5	203	10.18	9.98	10.49	10.20	10.03
19.5	198	10.15	9.86	10.50	10.22	10.00
22.5	194	10.22	9.93	10.53	10.37	10.04
24.0	191	10.16	9.95	10.47	10.23	10.00
25.5	189	10.29	10.22	10.51	10.13	10.32
27.0	187	10.62	10.70	10.65	10.22	10.92
27.4	186	11.91	12.44	12.80	11.48	10.92
27.7	186	12.75	12.70	13.25	11.32	13.73
28.5	184	13.38	13.73	14.12	11.30	14.37
29.2	183	14.00	14.55	14.65	12.44	14.35
30.0	182	14.47	15.01	14.60	14.16	14.10
30.7	180	14.59	15.36	14.74	14.58	13.67
31.5	179	14.32	15.63	14.56	13.70	13.39
33.0	176	14.03	15.02	14.39	13.41	13.30
36.0	171	13.36	13.86	13.67	12.99	12.92
39.0	167	13.00	13.01	13.50	12.70	12.77
42.0	163	12.48	12.14	13.11	12.11	12.57
45.0	160	12.11	11.79	12.56	12.06	12.03
46.5	158	11.56	11.05	12.10	11.48	11.63
48.0	156	11.03	10.44	11.69	10.77	11.22
51.0	153	10.56	9.84	11.38	10.29	10.75
54.0	150	10.24	9.50	11.14	9.91	10.42
57.0	148	10.06	9.84	10.48	9.75	10.26
60.0	145	9.95	9.80	10.45	9.74	10.23
63.0	142	9.98	9.52	10.33	9.69	10.25
66.0	140	10.03	9.60	10.44	9.69	10.18
69.0	137	10.11	9.78	10.40	9.71	10.23
72.0	135	10.26	9.84	10.51	9.76	10.32
75.0	133	10.36	9.82	10.74	9.85	10.65
80.0	129	10.63	9.99	10.86	9.98	10.60

EXPERIMENT NUMBER 2.1

Re = 10,100

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	333	3.24	3.29	3.17	3.21	3.30
4.5	319	3.30	3.34	3.20	3.22	3.43
7.5	306	3.29	3.26	3.11	3.27	3.54
10.5	292	3.38	3.37	3.16	3.30	3.69
13.5	280	3.45	3.38	3.22	3.40	3.80
16.5	268	3.58	3.56	3.35	3.49	3.92
19.5	255	3.58	3.77	3.31	3.39	3.86
21.0	249	3.37	3.71	3.08	3.13	3.57
22.5	244	3.35	3.74	3.20	3.04	3.41
24.0	238	3.50	3.82	3.63	3.12	3.43
25.5	231	3.65	3.79	4.16	3.26	3.41
27.0	225	3.84	3.81	4.47	3.56	3.51
28.5	220	4.40	4.31	5.11	4.22	3.97
30.0	214	5.11	4.98	5.77	5.01	4.67
31.5	208	5.41	5.16	6.06	5.36	5.05
33.0	203	5.26	4.99	5.79	5.26	4.99
34.5	198	5.07	4.91	5.40	5.03	4.95
36.0	193	4.69	4.58	4.87	4.67	4.64
37.0	191	4.48	4.37	4.61	4.51	4.44
40.0	183	4.14	4.06	4.22	4.06	4.22
43.0	176	3.99	4.02	3.97	3.87	4.08
46.0	169	3.84	3.89	3.78	3.79	3.89
49.0	163	3.74	4.00	3.65	3.55	3.76
52.0	157	3.69	3.87	3.60	3.50	3.80
55.0	152	3.64	3.84	3.51	3.45	3.76
58.0	148	3.53	3.64	3.50	3.30	3.70
61.0	143	3.45	3.48	3.42	3.22	3.66
64.0	139	3.21	3.31	3.23	3.07	3.31
67.0	135	3.27	3.16	3.27	3.25	3.41
70.0	132	3.23	3.00	3.17	3.36	3.40
73.0	128	3.34	3.09	3.23	3.36	3.48
76.0	125	3.43	3.09	3.35	3.46	3.62
81.0	119	3.62	3.22	3.45	3.72	3.87

EXPERIMENT NUMBER 2.5Re = 15,700

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	340	4.65	4.87	4.65	4.68	4.39
4.5	327	4.66	4.74	4.66	4.70	4.54
7.5	315	4.97	4.78	4.73	4.65	4.74
10.5	303	4.77	4.81	4.79	4.70	4.80
13.5	291	4.84	4.81	4.88	4.77	4.90
16.5	280	4.95	4.90	4.93	4.84	5.12
19.5	269	5.15	5.26	5.09	4.93	5.32
21.0	263	4.93	5.09	4.61	5.01	5.01
22.5	257	5.05	5.52	4.79	5.12	4.78
24.0	252	5.23	5.70	5.17	5.24	4.81
25.5	246	5.41	5.68	5.65	5.32	4.88
27.0	240	5.50	5.58	6.07	5.44	4.90
28.5	235	5.83	5.16	5.65	5.02	4.45
30.0	230	6.50	6.48	7.24	6.39	5.89
31.5	225	6.82	6.75	7.54	6.78	6.22
33.0	219	6.94	6.65	7.33	6.67	6.29
34.5	215	6.80	6.77	7.12	6.73	6.49
36.0	211	6.39	6.42	6.63	6.40	6.10
37.0	208	6.01	4.90	-	-	-
40.0	201	5.68	5.75	5.73	5.63	5.63
43.0	193	5.48	5.61	5.52	5.42	5.36
46.0	186	5.26	5.35	5.35	5.07	5.23
49.0	181	5.23	5.32	5.32	5.07	5.19
52.0	176	5.18	5.31	5.31	5.07	5.25
55.0	171	4.84	4.82	5.01	4.68	4.85
58.0	167	4.76	4.75	5.07	4.61	4.62
61.0	161	4.59	4.44	4.90	4.60	4.43
64.0	155	4.63	4.37	4.93	4.60	4.62
67.0	152	4.58	4.21	4.94	4.60	4.58
70.0	148	4.61	4.35	4.93	4.57	4.63
73.0	144	4.68	4.41	4.86	4.64	4.80
76.0	141	4.67	4.44	4.77	4.72	4.74
81.0	135	4.65	4.52	4.81	4.82	4.84

EXPERIMENT NUMBER 2.7Re = 19,700

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	334	5.66	5.85	5.67	5.75	5.37
4.5	323	5.68	5.92	5.64	5.73	5.42
7.5	312	5.72	5.94	5.68	5.77	5.48
10.5	302	5.81	5.98	5.78	5.78	5.71
13.5	292	5.87	6.04	5.81	5.80	5.83
16.5	282	5.64	5.77	5.53	5.48	5.80
19.5	272	5.55	5.69	5.48	5.30	5.72
21.0	267	5.74	5.97	5.92	5.45	5.61
22.5	262	5.73	6.05	5.93	5.50	5.45
24.0	257	5.76	5.95	6.03	5.55	5.53
25.5	251	5.78	5.90	6.03	5.60	5.60
27.0	246	5.98	5.86	6.78	5.76	5.53
28.5	241	6.65	6.80	7.63	6.61	5.56
30.0	236	7.29	7.20	8.16	7.74	6.05
31.5	232	7.82	7.61	8.52	8.56	6.58
33.0	227	7.85	7.61	8.45	8.64	6.70
34.5	223	7.80	7.02	7.81	7.51	6.22
36.0	218	7.24	6.82	7.35	7.23	6.13
37.0	215	6.88	6.84	7.38	7.37	6.30
40.0	207	6.64	6.75	6.93	6.95	5.95
43.0	199	6.51	6.67	6.89	6.54	5.92
46.0	192	6.38	6.46	6.57	6.43	6.04
49.0	186	6.21	6.34	6.41	6.22	5.88
52.0	181	6.22	6.22	6.40	6.28	5.97
55.0	176	6.10	6.08	6.26	6.18	6.89
58.0	169	6.15	5.98	6.05	6.03	5.71
61.0	162	6.20	5.76	6.03	6.03	5.58
64.0	158	5.86	5.75	6.12	5.93	5.63
67.0	153	5.87	5.62	6.13	6.11	5.61
70.0	149	5.87	5.65	6.18	5.99	5.66
73.0	145	5.87	5.55	6.23	6.09	5.60
76.0	142	5.88	5.48	6.00	6.16	5.48
81.0	136	6.22	5.70	6.06	6.13	5.81

EXPERIMENT NUMBER 2.9Re = 24,700

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	290	6.64	6.66	6.71	6.80	6.40
4.5	281	6.68	6.64	6.70	6.83	6.56
7.5	272	6.71	6.46	6.75	6.83	6.78
10.5	263	6.75	6.43	6.74	6.85	6.78
13.5	255	6.69	6.41	6.77	6.80	6.78
16.5	247	6.73	6.60	6.50	6.98	6.85
19.5	239	6.79	6.70	6.65	7.00	6.82
21.0	236	6.79	6.87	6.76	6.04	6.49
22.5	232	6.83	7.06	6.81	7.04	6.39
24.0	228	6.75	7.09	7.10	6.44	6.37
25.5	224	6.91	7.07	7.35	6.86	6.35
27.0	220	7.25	7.41	7.89	7.28	6.80
28.5	215	7.91	7.66	8.91	8.25	6.81
30.0	211	8.90	8.80	9.96	9.22	7.63
31.5	207	9.53	9.45	10.50	9.85	8.32
33.0	204	9.37	9.36	10.16	9.70	8.26
34.5	200	9.10	9.14	9.73	9.39	8.12
36.0	196	8.48	8.46	9.04	8.68	7.72
37.0	194	8.16	8.04	8.64	8.37	7.61
40.0	188	7.84	7.91	8.24	8.00	7.50
43.0	181	7.63	7.71	8.01	7.53	7.26
46.0	176	7.43	7.64	7.65	7.25	7.18
49.0	171	7.37	7.54	7.47	7.30	7.16
52.0	166	7.27	7.48	7.43	6.96	7.22
55.0	161	7.11	7.18	7.17	6.94	7.17
58.0	157	7.00	7.12	7.04	6.82	7.02
61.0	153	6.94	6.91	7.02	6.66	7.17
64.0	149	6.94	6.89	7.12	6.71	7.05
67.0	145	6.92	6.81	7.09	6.84	6.95
70.0	142	6.97	6.78	7.25	6.90	6.95
73.0	138	6.94	6.74	7.00	7.15	6.88
76.0	135	6.88	6.78	6.93	7.06	6.77
81.0	129	6.94	6.88	7.19	6.80	6.89

EXPERIMENT NUMBER 2.10Re = 31,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	261	7.98	7.90	8.04	8.01	7.97
4.5	253	7.98	7.89	8.14	8.02	7.87
7.5	246	8.00	7.91	8.16	7.88	8.04
10.5	239	8.03	7.88	8.05	7.92	8.28
13.5	232	7.99	7.80	8.13	7.91	8.13
16.5	225	8.07	7.83	8.15	8.05	8.24
19.5	219	7.95	7.66	8.16	7.86	8.11
21.0	216	8.04	7.75	8.21	7.95	8.27
22.5	212	8.15	7.76	8.46	8.10	8.27
24.0	209	7.95	7.72	8.27	7.67	8.12
25.5	206	8.41	8.48	8.98	8.09	8.11
27.0	203	8.60	8.54	9.57	8.24	8.04
28.5	199	8.72	8.44	9.95	8.68	7.81
30.0	196	10.33	10.21	11.46	10.44	9.19
31.5	193	11.18	10.91	12.01	11.59	10.21
33.0	189	11.09	10.88	11.96	11.48	10.15
34.5	186	10.81	10.78	11.52	10.93	10.01
36.0	183	10.12	10.18	10.65	10.21	9.44
37.0	181	9.75	9.68	10.21	9.84	9.27
40.0	176	9.07	8.83	9.57	9.14	8.72
43.0	171	8.75	8.47	9.24	8.73	8.58
46.0	166	8.68	8.45	9.08	8.51	8.67
49.0	162	8.47	8.26	8.74	8.32	8.57
52.0	158	8.37	8.23	8.56	8.25	8.46
55.0	154	8.21	7.98	8.31	8.14	8.42
58.0	150	8.19	8.13	8.18	7.88	8.59
61.0	147	8.00	7.92	8.08	7.76	8.24
64.0	143	8.15	7.98	8.10	8.04	8.50
67.0	140	7.84	7.88	8.10	8.00	8.18
70.0	137	8.01	7.85	8.21	7.93	8.06
73.0	134	8.06	7.86	8.24	8.02	8.14
76.0	131	8.08	7.84	8.22	8.15	8.13
81.0	127	8.08	7.82	8.15	8.18	8.17

EXPERIMENT NUMBER 2.11Re = 33,900

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	248	8.47	8.44	8.59	8.56	8.30
4.5	242	8.58	8.42	8.64	8.73	8.53
7.5	235	8.51	8.22	8.65	8.58	8.60
10.5	228	8.57	8.26	8.69	8.59	8.73
13.5	222	8.57	8.07	8.63	8.53	9.02
16.5	216	8.26	7.82	8.29	8.16	8.76
19.5	210	8.39	7.89	8.33	8.32	9.04
21.0	207	8.49	8.19	8.42	8.18	9.15
22.5	205	8.67	8.45	8.56	8.52	9.13
24.0	202	8.48	8.51	8.44	8.43	8.66
25.5	199	9.00	9.15	9.27	8.96	8.72
27.0	195	9.09	9.21	9.98	8.92	8.24
28.5	192	9.29	9.37	10.28	9.36	8.13
30.0	189	10.87	11.09	12.05	10.88	9.46
31.5	186	11.55	11.79	12.49	11.60	10.32
33.0	183	11.30	11.38	12.16	11.42	10.22
34.5	180	10.99	11.32	11.45	11.08	10.09
36.0	178	10.30	10.38	10.65	10.55	9.61
37.0	176	9.96	10.16	10.20	10.06	9.35
40.0	171	9.34	9.50	9.58	9.33	8.95
43.0	167	9.02	9.12	9.26	8.92	8.79
46.0	162	8.99	9.28	9.23	8.74	8.71
49.0	158	8.85	9.03	8.91	8.58	8.86
52.0	154	8.70	8.96	8.53	8.34	8.96
55.0	151	8.64	8.73	8.50	8.45	8.89
58.0	147	8.68	8.74	8.42	8.42	8.70
61.0	144	8.36	8.37	8.32	8.32	8.33
64.0	141	8.35	8.28	8.41	8.41	8.32
67.0	138	8.35	8.27	8.38	8.38	8.32
70.0	135	8.29	8.28	8.42	8.42	8.33
73.0	132	8.41	8.20	8.63	8.63	8.35
76.0	129	8.36	8.19	8.56	8.56	8.25
81.0	125	8.72	8.66	8.96	8.96	8.50

EXPERIMENT NUMBER 2.13Re = 38,900

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	233	9.54	9.85	9.62	9.48	9.20
4.5	227	9.49	9.64	9.62	9.37	9.34
7.5	221	9.50	9.62	9.62	9.42	9.36
10.5	215	9.47	9.56	9.65	9.43	9.25
13.5	209	9.35	9.31	9.60	9.28	9.24
16.5	204	9.45	9.34	9.59	9.32	9.56
19.5	199	9.57	9.33	9.68	9.59	9.67
21.0	196	9.43	9.11	9.37	9.55	9.67
22.5	193	9.62	9.60	9.54	9.62	9.70
24.0	191	9.48	9.85	9.30	9.49	9.30
25.5	188	9.71	10.25	9.74	9.76	9.08
27.0	185	10.19	10.31	11.03	10.56	8.88
28.5	182	11.06	11.03	12.33	11.48	9.40
30.0	180	11.91	11.69	13.14	12.73	10.06
31.5	177	12.84	12.94	13.78	13.70	10.92
33.0	174	12.60	12.87	13.43	13.44	10.64
34.5	172	12.15	12.41	12.81	13.00	10.37
36.0	169	11.33	11.82	11.96	11.54	9.98
37.0	168	10.92	11.64	11.46	10.84	9.79
40.0	164	10.06	10.65	10.52	9.88	9.41
43.0	160	9.60	10.02	9.94	9.32	9.12
46.0	156	9.57	10.19	9.80	9.20	9.18
49.0	152	9.41	9.99	9.49	9.04	9.11
52.0	149	9.30	9.44	9.52	9.06	9.18
55.0	146	9.13	9.25	9.15	8.94	9.18
58.0	142	9.07	9.30	8.92	8.77	9.27
61.0	139	9.13	9.20	9.20	8.74	9.39
64.0	136	9.11	9.08	9.22	8.91	9.24
67.0	134	9.23	9.23	9.22	8.95	9.53
70.0	131	9.27	9.24	9.22	9.09	9.53
73.0	128	9.20	9.01	9.23	9.14	9.41
76.0	126	9.21	8.93	9.32	9.29	9.31
81.0	122	9.22	8.94	9.42	9.25	9.26

EXPERIMENT NUMBER 3.4Re = 15,000

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	382	4.50	4.45	4.49	4.45	4.61
4.5	367	4.49	4.49	4.46	4.44	4.56
7.5	352	4.47	4.47	4.44	4.42	4.53
10.5	339	4.45	4.50	4.40	4.45	4.44
13.5	326	4.45	4.52	4.38	4.49	4.41
16.5	313	4.48	4.60	4.38	4.52	4.43
19.5	302	4.50	4.63	4.47	4.58	4.30
21.5	294	4.51	4.63	4.49	4.67	4.25
23.0	288	4.63	4.66	4.63	4.70	4.43
24.5	283	4.61	4.69	4.64	4.69	4.43
26.0	277	4.71	4.76	4.95	4.75	4.37
27.5	272	4.85	4.89	5.18	4.82	4.31
29.0	267	5.08	5.10	5.59	5.06	4.57
30.5	261	5.46	5.68	5.88	5.58	4.71
32.0	256	5.60	5.79	5.92	5.73	4.96
33.5	251	5.60	5.84	5.81	5.65	5.10
35.0	246	5.45	5.71	5.61	5.42	5.07
36.5	241	5.26	5.57	5.42	5.25	4.78
39.5	232	5.00	5.32	5.24	4.97	4.46
42.5	223	4.74	5.01	4.91	4.62	4.43
45.5	215	4.62	4.85	4.76	4.47	4.29
48.5	208	4.70	4.91	4.80	4.60	4.58
51.5	200	4.58	4.81	4.61	4.41	4.61
54.5	194	4.54	4.77	4.53	4.42	4.41
57.5	188	4.51	4.75	4.43	4.45	4.43
60.5	182	4.47	4.75	4.43	4.40	4.32
63.5	176	4.42	4.74	4.30	4.34	4.30
66.5	171	4.46	4.82	4.34	4.37	4.31
69.5	166	4.56	4.85	4.56	4.37	4.47
72.5	161	4.58	4.84	4.53	4.39	4.55
75.5	157	4.67	4.85	4.66	4.49	4.69
78.5	153	4.75	4.88	4.79	4.58	4.74
83.0	146	4.85	4.89	4.76	4.75	4.99

EXPERIMENT NUMBER 3.7Re = 20,500

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	370	5.92	5.73	5.97	6.09	5.90
4.5	357	5.92	5.76	5.90	6.10	5.90
7.5	345	5.87	5.76	5.80	6.01	5.91
10.5	333	5.85	5.77	5.75	6.00	5.89
13.5	322	5.85	5.80	5.77	5.99	5.83
16.5	311	5.84	5.83	5.73	5.95	5.83
19.5	301	5.87	5.86	5.80	5.98	5.85
21.5	294	5.84	5.80	5.88	5.90	5.78
23.0	290	5.81	5.77	5.95	5.84	5.67
24.5	285	5.84	5.86	5.96	5.84	5.71
26.0	280	6.02	5.96	6.39	5.95	5.76
27.5	275	6.15	5.88	6.82	6.06	5.82
29.0	271	6.75	6.57	7.86	6.72	5.84
30.5	266	7.46	7.30	8.44	7.61	6.51
32.0	261	7.64	7.56	8.26	7.88	6.86
33.5	256	7.59	7.67	8.04	7.79	6.87
35.0	252	7.36	7.63	7.68	7.41	6.74
36.5	247	7.10	7.56	7.32	7.05	6.50
39.5	239	6.81	7.43	7.02	6.70	6.07
42.5	231	6.39	6.33	6.61	6.27	6.35
45.5	224	6.25	6.36	6.39	6.09	6.15
48.5	217	6.19	6.45	6.34	5.97	6.02
51.5	210	6.17	6.40	6.40	6.05	5.85
54.5	204	6.04	6.24	6.17	5.95	5.82
57.5	198	5.93	6.07	6.09	5.78	5.77
60.5	192	5.86	6.07	6.02	5.77	5.60
63.5	187	5.80	5.90	6.06	5.71	5.54
66.5	182	5.76	5.88	5.98	5.69	5.47
69.5	177	5.78	5.85	6.02	5.79	5.48
72.5	172	5.83	5.83	6.10	5.81	5.58
75.5	167	5.80	5.67	6.07	5.81	5.66
78.5	163	5.86	5.62	6.25	5.86	5.73
83.0	157	5.86	5.57	6.24	5.87	5.76

EXPERIMENT NUMBER 3.10Re = 25,900

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	272	7.76	7.36	7.94	7.78	7.97
4.5	264	7.63	7.27	7.77	7.66	7.80
7.5	256	7.38	7.03	7.50	7.51	7.49
10.5	249	7.30	6.87	7.50	7.42	7.41
13.5	242	7.14	6.68	7.36	7.32	7.18
16.5	236	7.10	6.63	7.32	7.35	7.08
19.5	229	7.04	6.66	7.30	7.35	6.85
21.5	225	6.98	6.72	7.24	7.24	6.73
23.0	222	6.99	6.83	7.03	7.25	6.83
24.5	219	7.07	7.00	7.05	7.30	6.94
26.0	217	7.21	7.15	7.43	7.39	6.87
27.5	214	7.40	7.33	7.73	7.62	6.94
29.0	211	7.88	7.81	8.93	8.12	6.67
30.5	208	8.78	8.68	9.79	9.20	7.44
32.0	205	9.16	8.79	9.97	9.68	8.21
33.5	201	9.20	8.99	9.78	9.57	8.46
35.0	198	8.94	8.92	9.28	9.04	8.50
36.5	196	8.59	8.81	8.99	8.48	8.09
39.5	190	8.15	8.69	8.54	7.85	7.52
42.5	185	7.77	7.64	8.29	7.75	7.38
45.5	180	7.46	7.41	8.03	7.35	7.07
48.5	175	7.35	7.30	7.88	7.20	7.02
51.5	171	7.15	7.13	7.61	7.01	6.83
54.5	167	7.00	6.95	7.53	6.83	6.70
57.5	163	6.94	6.86	7.43	6.83	6.64
60.5	159	6.88	6.87	7.35	6.71	6.59
63.5	155	6.80	6.84	7.27	6.64	6.55
66.5	152	6.78	6.94	7.16	6.55	6.47
69.5	149	6.73	6.91	7.08	6.53	6.38
72.5	146	6.71	6.88	7.08	6.52	6.36
75.5	143	6.62	6.76	6.92	6.44	6.36
78.5	140	6.59	6.51	6.98	6.56	6.33
83.0	136	6.69	6.55	7.05	6.66	6.51

EXPERIMENT NUMBER 3.12Re = 32,500

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	260	8.83	9.00	8.80	8.60	8.91
4.5	252	8.73	8.82	8.74	8.60	8.75
7.5	245	8.58	8.70	8.66	8.43	8.53
10.5	238	8.50	8.60	8.48	8.55	8.39
13.5	231	8.38	8.47	8.32	8.50	8.22
16.5	225	8.34	8.47	8.29	8.43	8.15
19.5	219	8.42	8.42	8.33	8.56	8.27
21.5	215	8.43	8.54	8.34	8.58	8.26
23.0	213	8.45	8.58	8.52	8.34	8.36
24.5	210	8.50	8.67	8.55	8.41	8.35
26.0	207	8.68	8.76	9.14	8.42	8.40
27.5	204	8.89	8.88	9.65	8.64	8.37
29.0	202	9.42	9.47	10.53	9.14	8.55
30.5	198	10.22	10.56	11.70	10.39	8.93
32.0	195	10.83	10.73	11.63	11.14	9.80
33.5	192	11.08	11.00	11.66	11.51	10.16
35.0	189	10.81	11.01	11.34	10.75	10.13
36.5	186	10.41	10.46	10.84	10.15	10.09
39.5	180	9.92	9.96	10.42	9.56	9.76
42.5	175	9.23	9.48	9.74	8.71	8.99
45.5	171	9.24	9.57	9.67	8.72	9.01
48.5	166	9.14	9.43	9.60	8.66	8.97
51.5	162	8.97	9.35	9.28	8.37	8.87
54.5	158	8.92	9.25	9.25	8.45	8.75
57.5	154	8.67	8.80	8.89	8.39	8.59
60.5	151	8.66	8.65	8.95	8.44	8.60
63.5	148	8.69	8.57	9.01	8.51	8.69
66.5	144	8.55	8.49	8.81	8.36	8.55
69.5	141	8.49	8.43	8.70	8.36	8.48
72.5	138	8.48	8.45	8.79	8.35	8.34
75.5	136	8.43	8.15	8.84	8.44	8.30
78.5	133	8.42	8.19	8.80	8.42	8.29
83.0	129	8.36	8.24	8.75	8.34	8.10

EXPERIMENT NUMBER 3.15Re = 39,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	227	9.82	9.75	9.80	9.95	9.80
4.5	221	9.79	9.75	9.75	9.85	9.83
7.5	216	9.75	9.82	9.77	9.65	9.78
10.5	211	9.69	9.71	9.81	9.58	9.66
13.5	206	9.59	9.57	9.80	9.49	9.50
16.5	202	9.55	9.55	9.72	9.60	9.35
19.5	197	9.50	9.23	9.61	9.72	9.44
21.5	194	9.48	9.32	9.63	9.63	9.35
23.0	191	9.36	9.32	9.82	9.00	9.30
24.5	189	9.49	9.58	9.96	9.18	9.26
26.0	187	9.72	9.69	10.30	9.69	9.19
27.5	185	10.10	10.30	10.83	10.10	9.17
29.0	183	10.47	10.67	11.46	11.01	9.44
30.5	181	11.89	12.15	12.96	12.40	10.03
32.0	179	12.18	12.34	12.98	12.32	11.07
33.5	176	12.01	12.29	12.77	11.90	11.08
35.0	174	11.78	12.36	12.67	11.42	10.79
36.5	172	11.62	12.47	12.17	11.29	10.57
39.5	167	10.51	11.81	11.13	10.22	9.70
42.5	163	10.20	10.42	10.50	9.64	10.24
45.5	160	10.06	10.36	10.34	9.60	9.94
48.5	157	9.88	10.29	10.12	9.23	9.87
51.5	153	9.91	10.40	10.16	9.37	9.95
54.5	150	9.76	10.22	9.92	9.24	9.66
57.5	147	9.66	10.10	9.83	9.03	9.70
60.5	144	9.55	10.04	9.66	8.99	9.51
63.5	142	9.45	9.91	9.67	8.87	9.37
66.5	140	9.41	9.70	9.62	9.00	9.30
69.5	137	9.32	9.33	9.67	9.02	9.28
72.5	135	9.27	9.25	9.60	8.98	9.26
75.5	133	9.33	9.35	9.52	9.14	9.33
78.5	131	9.37	9.43	9.53	9.23	9.29
83.0	128	9.43	9.52	9.61	9.35	9.24

EXPERIMENT NUMBER 3.17Re = 45,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	214	10.79	10.69	11.07	10.48	10.90
4.5	208	10.57	10.32	10.85	10.44	10.68
7.5	203	10.50	10.37	10.62	10.45	10.55
10.5	199	10.30	10.25	10.20	10.33	10.42
13.5	194	10.22	10.24	10.19	10.19	10.25
16.5	190	10.22	10.22	10.10	10.42	10.14
19.5	185	10.22	10.31	10.03	10.37	10.16
21.5	183	10.24	10.31	10.12	10.52	10.00
23.0	181	10.37	10.44	10.31	10.60	10.13
24.5	179	10.52	10.59	10.58	10.51	10.42
26.0	177	10.78	10.95	11.06	10.66	10.45
27.5	175	11.22	11.47	11.71	11.01	10.68
29.0	173	11.94	12.46	12.59	11.67	11.02
30.5	170	13.22	13.61	14.27	13.27	11.73
32.0	168	13.84	13.98	14.65	14.29	12.46
33.5	166	13.89	13.92	14.53	14.35	12.77
35.0	164	13.32	13.66	13.80	13.44	12.36
36.5	162	12.61	13.04	13.09	12.57	11.74
39.5	158	11.81	11.72	12.16	11.56	11.79
41.5	155	11.27	11.40	11.53	10.91	11.26
45.5	151	10.98	11.15	11.08	10.59	11.10
48.5	148	10.83	11.15	10.81	10.57	10.79
51.5	145	10.70	11.04	10.56	10.41	10.79
54.5	142	10.56	11.01	10.19	10.36	10.66
57.5	140	10.55	10.84	10.19	10.47	10.69
60.5	137	10.57	10.87	10.38	10.42	10.63
63.5	135	10.51	10.74	10.22	10.54	10.55
66.5	132	10.48	10.65	10.19	10.52	10.57
69.5	130	10.42	10.39	10.27	10.56	10.47
72.5	128	10.52	10.26	10.53	10.72	10.56
75.5	126	10.54	10.30	10.82	10.58	10.47
78.5	124	10.57	10.39	10.82	10.75	10.32
83.0	121	10.58	10.44	10.73	10.94	10.20

EXPERIMENT NUMBER 4.1Re = 15,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	326	3.28	2.99	3.50	3.33	3.30
4.5	313	3.28	3.09	3.42	3.28	3.31
7.5	301	3.23	3.08	3.36	3.18	3.29
10.5	290	3.22	3.12	3.30	3.17	3.29
13.5	279	3.18	3.11	3.19	3.14	3.26
16.5	269	3.15	3.09	3.15	3.12	3.25
19.5	259	3.14	3.05	3.16	3.14	3.20
22.5	250	3.16	3.10	3.15	3.18	3.21
24.0	245	3.16	3.05	3.11	3.16	3.09
25.5	241	3.09	3.02	3.16	3.19	3.00
27.0	237	3.12	3.07	3.27	3.26	2.88
28.5	233	3.24	3.21	3.47	3.39	2.88
30.0	229	3.31	3.32	3.62	3.46	2.84
31.5	225	3.34	3.37	3.77	3.48	2.73
33.0	221	3.34	3.42	3.86	3.44	2.66
34.5	217	3.31	3.38	3.82	3.41	2.62
36.0	213	3.28	3.36	3.80	3.37	2.59
37.5	210	3.24	3.37	3.76	3.32	2.50
39.0	206	3.19	3.32	3.66	3.28	2.51
40.5	203	3.14	3.25	3.54	3.22	2.54
42.0	199	3.12	3.22	3.47	3.26	2.54
45.0	193	3.15	3.27	3.41	3.31	2.62
48.0	187	3.18	3.27	3.46	3.26	2.73
51.0	182	3.13	3.21	3.38	3.18	2.75
54.0	176	2.99	3.00	3.18	3.13	2.65
57.0	171	3.10	2.82	3.02	3.17	2.56
60.0	166	2.90	2.75	2.95	3.20	2.69
63.0	162	2.85	2.66	2.80	3.26	2.68
66.0	157	2.87	2.76	2.80	3.22	2.74
69.0	153	2.76	2.60	2.67	3.09	2.69
72.0	149	2.73	2.57	2.69	2.93	2.72
75.0	145	2.67	2.57	2.64	2.71	2.75
78.0	142	2.65	2.51	2.67	2.77	2.67
81.0	139	2.65	2.54	2.61	2.80	2.63
84.0	136	2.61	2.52	2.56	2.61	2.75
88.5	132	2.64	2.52	2.61	2.59	2.85

EXPERIMENT NUMBER 4.3Re = 14,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	303	4.46	4.36	4.51	4.47	4.49
4.5	292	4.39	4.22	4.42	4.50	4.42
7.5	281	4.41	4.28	4.38	4.49	4.48
10.5	271	4.40	4.21	4.40	4.51	4.50
13.5	261	4.42	4.24	4.34	4.54	4.56
16.5	252	4.40	4.16	4.36	4.56	4.53
19.5	243	4.41	4.20	4.38	4.59	4.50
22.5	234	4.44	4.31	4.40	4.52	4.55
24.0	230	4.42	4.33	4.41	4.50	4.42
25.5	226	4.42	4.46	4.43	4.51	4.28
27.0	222	4.46	4.56	4.55	4.52	4.22
28.5	218	4.70	4.85	4.98	4.63	4.32
30.0	214	4.84	5.07	5.23	4.79	4.25
31.5	210	4.97	5.26	5.49	4.91	4.23
33.0	207	5.04	5.34	5.68	4.99	4.13
34.5	203	5.08	5.44	5.74	5.05	4.10
36.0	199	5.10	5.34	5.89	5.11	4.07
37.5	195	5.07	5.28	5.90	5.08	4.05
39.0	192	4.97	5.20	5.64	5.00	4.03
40.5	189	4.85	5.01	5.55	4.86	3.99
42.0	185	4.76	4.85	5.44	4.73	4.03
45.0	179	4.76	4.83	5.32	4.79	4.10
48.0	174	4.80	4.76	5.36	4.81	4.24
51.0	168	4.75	4.70	5.16	4.74	4.39
54.0	163	4.50	4.34	5.04	4.45	4.17
57.0	159	4.24	4.04	4.76	4.18	3.98
60.0	154	4.34	4.05	4.85	4.23	4.23
63.0	150	4.27	4.04	4.75	4.04	4.26
66.0	146	4.21	3.88	4.64	4.18	4.15
69.0	143	4.20	3.91	4.56	4.10	4.22
72.0	139	4.16	3.93	4.36	4.09	4.25
75.0	136	4.15	4.04	4.22	4.09	4.26
78.0	133	4.26	4.03	4.30	4.26	4.44
81.0	130	4.26	4.12	4.28	4.24	4.39
84.0	127	4.27	4.15	4.21	4.36	4.34
88.5	122	4.40	4.33	4.38	4.49	4.40

EXPERIMENT NUMBER 4.7Re = 20,300

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	243	5.80	5.51	6.08	5.84	5.78
4.5	235	5.73	5.35	5.96	5.89	5.71
7.5	227	5.66	5.26	5.87	5.87	5.63
10.5	220	5.65	5.30	5.75	5.88	5.67
13.5	213	5.59	5.18	5.70	5.86	5.60
16.5	207	5.62	5.25	5.65	5.94	5.66
19.5	200	5.64	5.28	5.64	6.01	5.61
22.5	194	5.63	5.38	5.60	6.03	5.51
24.0	191	5.58	5.32	5.67	6.01	5.34
25.5	188	5.60	5.40	5.76	6.06	5.17
27.0	186	5.70	5.58	6.04	6.03	5.15
28.5	183	5.98	5.94	6.42	6.36	5.19
30.0	180	6.20	6.26	6.85	6.56	5.13
31.5	177	6.39	6.64	7.12	6.70	5.10
33.0	174	6.52	7.01	7.20	6.80	5.06
34.5	172	6.58	7.01	7.47	6.77	5.06
36.0	169	6.54	6.92	7.34	6.83	5.06
37.5	166	6.42	6.74	7.16	6.62	5.15
39.0	164	6.26	6.36	7.00	6.57	5.09
40.5	161	6.08	6.09	6.72	6.37	5.14
42.0	159	5.94	5.91	6.52	6.22	5.11
45.0	155	5.88	5.72	6.38	6.13	5.30
48.0	151	5.90	5.77	6.42	6.02	5.41
51.0	147	5.74	5.49	6.12	5.90	5.44
54.0	143	5.61	5.32	5.90	5.78	5.43
57.0	140	5.71	5.38	6.07	5.82	5.56
60.0	137	5.68	5.28	6.14	5.68	5.61
63.0	134	5.54	5.13	6.00	5.41	5.62
66.0	131	5.48	5.13	5.84	5.37	5.57
69.0	129	5.40	4.96	5.89	5.19	5.56
72.0	126	5.42	5.14	5.84	5.10	5.61
75.0	124	5.39	5.10	5.74	5.12	5.59
78.0	122	5.42	4.96	5.74	5.19	5.78
81.0	120	5.43	5.07	5.73	5.04	5.87
84.0	117	5.54	5.23	5.87	5.15	5.92
88.5	114	5.62	5.25	5.95	5.30	5.98

EXPERIMENT NUMBER 4.10Re = 26,600

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	285	6.99	6.51	7.17	7.34	6.93
4.5	277	6.98	6.57	7.11	7.40	6.86
7.5	268	6.97	6.52	7.12	7.35	6.91
10.5	260	6.99	6.58	7.10	7.35	6.92
13.5	253	6.98	6.43	7.19	7.35	6.95
16.5	245	7.02	6.60	7.19	7.37	6.95
19.5	238	7.08	6.67	7.29	7.39	7.00
22.5	231	7.16	6.83	7.40	7.37	7.05
24.0	228	7.18	6.87	7.40	7.38	6.97
25.5	224	7.24	7.09	7.46	7.50	6.90
27.0	221	7.45	7.38	7.66	7.86	6.91
28.5	217	7.97	7.96	8.26	8.55	7.12
30.0	214	8.39	8.52	8.73	9.02	7.28
31.5	210	8.72	9.03	9.40	9.28	7.15
33.0	207	8.87	9.38	9.62	9.21	7.28
34.5	203	8.87	9.48	9.76	9.15	7.10
36.0	200	8.78	9.35	9.75	8.99	7.03
37.5	196	8.59	9.06	9.51	8.72	7.07
39.0	193	8.27	8.82	9.01	8.38	6.87
40.5	190	7.93	8.34	8.56	8.12	6.69
42.0	188	7.72	8.10	8.23	7.90	6.65
45.0	182	7.60	8.03	8.04	7.71	6.61
48.0	178	7.59	7.92	7.95	7.75	6.74
51.0	173	7.44	7.74	7.92	7.51	6.56
54.0	169	7.27	7.53	7.71	7.41	6.43
57.0	165	7.21	7.48	7.57	7.31	6.48
60.0	161	7.27	7.43	7.65	7.31	6.69
63.0	157	7.20	7.34	7.50	7.30	6.64
66.0	154	7.14	7.13	7.38	7.30	6.73
69.0	150	7.05	6.93	7.30	7.18	6.79
72.0	147	7.09	6.96	7.16	7.29	6.95
75.0	144	7.09	6.93	7.18	7.35	6.89
78.0	141	7.15	7.06	7.16	7.37	7.00
81.0	138	7.19	7.16	7.03	7.41	7.16
84.0	136	7.24	7.22	7.06	7.43	7.24
88.5	132	7.31	7.27	7.10	7.52	7.34

EXPERIMENT NUMBER 4.12Re = 32,300

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	259	7.97	7.83	7.99	8.26	7.81
4.5	252	7.94	7.67	8.02	8.26	7.79
7.5	245	7.95	7.65	8.00	8.28	7.89
10.5	238	7.96	7.63	8.07	8.25	7.91
13.5	231	8.02	7.73	8.09	8.27	7.99
16.5	225	8.02	7.74	8.09	8.19	8.05
19.5	219	8.14	7.89	8.27	8.22	8.18
22.5	212	8.26	8.11	8.36	8.31	8.27
24.0	209	8.28	8.32	8.38	8.29	8.17
25.5	207	8.40	8.43	8.52	8.44	8.19
27.0	204	8.58	8.60	8.65	8.76	8.29
28.5	201	8.93	8.79	9.04	9.42	8.48
30.0	198	9.38	9.60	9.42	9.86	8.63
31.5	195	9.80	10.43	9.92	10.27	8.56
33.0	191	10.05	10.94	10.43	10.29	8.56
34.5	188	10.09	11.59	11.17	10.44	8.58
36.0	185	10.06	11.31	11.62	10.26	8.51
37.5	182	9.93	10.96	11.84	9.99	8.39
39.0	179	9.58	10.16	11.60	9.66	8.35
40.5	176	9.18	9.69	11.19	9.18	8.09
42.0	174	8.90	9.22	10.58	9.05	8.21
45.0	169	8.70	8.94	10.29	8.92	8.09
48.0	165	8.67	8.96	9.92	9.09	8.14
51.0	160	8.41	8.73	9.48	8.85	8.03
54.0	157	8.36	8.53	9.33	8.98	8.05
57.0	153	8.30	8.02	8.88	8.56	7.76
60.0	150	8.38	8.20	8.80	8.55	8.00
63.0	147	8.11	7.88	8.46	8.20	7.88
66.0	144	8.05	7.89	8.28	8.16	7.87
69.0	141	8.07	7.96	8.19	8.36	7.75
72.0	138	8.06	7.97	8.20	8.26	7.84
75.0	135	8.06	7.84	8.22	8.41	7.86
78.0	133	8.04	7.81	7.96	8.43	7.96
81.0	130	8.01	7.71	7.93	8.44	7.95
84.0	128	8.07	7.74	7.91	8.48	8.15
88.5	125	8.19	7.87	8.05	8.70	8.14

EXPERIMENT NUMBER 4.14Re = 37,000

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	238	8.32	8.21	8.56	8.45	8.04
4.5	232	8.32	8.17	8.55	8.47	8.08
7.5	226	8.29	8.14	8.47	8.44	8.10
10.5	221	8.29	8.08	8.47	8.41	8.15
13.5	215	8.31	8.09	8.57	8.34	8.25
16.5	210	8.39	8.28	8.58	8.32	8.35
19.5	205	8.42	8.27	8.51	8.38	8.43
22.5	200	8.56	8.53	8.80	8.44	8.47
24.0	198	8.65	8.56	8.89	8.68	8.45
25.5	195	8.81	8.61	9.20	8.91	8.52
27.0	192	9.43	9.37	10.18	9.30	8.86
28.5	189	10.16	10.13	11.28	10.02	9.23
30.0	187	10.19	10.12	11.66	10.03	8.97
31.5	184	10.54	10.60	11.95	10.53	9.05
33.0	181	11.12	11.39	12.28	11.37	9.45
34.5	179	11.24	11.66	11.98	11.92	9.37
36.0	176	11.31	11.62	12.48	11.76	9.35
37.5	173	10.89	11.26	12.25	11.04	9.01
39.0	171	10.76	10.80	11.87	11.28	9.08
40.5	169	10.36	10.64	11.72	10.17	8.90
42.0	166	10.04	10.29	11.20	9.74	8.91
45.0	162	9.86	10.03	10.86	9.55	9.00
48.0	158	9.78	10.04	10.53	9.44	9.10
51.0	155	9.53	9.77	10.06	9.29	8.98
54.0	152	9.37	9.55	9.93	9.19	8.81
57.0	149	9.24	9.33	9.66	9.11	8.86
60.0	146	9.28	9.35	9.61	9.30	8.85
63.0	143	9.16	9.13	9.30	9.18	8.84
66.0	140	9.08	9.01	9.17	9.13	9.00
69.0	138	8.95	8.65	9.09	8.98	9.10
72.0	135	8.89	8.75	8.91	8.86	9.03
75.0	133	8.76	8.44	8.66	8.95	9.01
78.0	131	8.86	8.60	8.66	9.00	9.16
81.0	129	8.81	8.59	8.45	9.05	9.15
84.0	127	8.84	8.53	8.45	9.20	9.17
88.5	124	8.95	8.69	8.49	9.29	9.34

EXPERIMENT NUMBER 4.18Re = 47,000

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	211	10.31	10.44	10.41	10.48	9.91
4.5	206	10.24	10.19	10.26	10.55	9.95
7.5	201	10.22	10.08	10.14	10.63	10.02
10.5	197	10.14	9.98	10.14	10.47	9.97
13.5	192	10.14	9.82	10.15	10.66	10.05
16.5	188	10.13	9.71	10.24	10.59	9.98
19.5	184	10.18	9.68	10.26	10.67	10.12
22.5	180	10.28	9.78	10.41	10.81	10.01
24.0	178	10.32	9.86	11.09	10.47	9.85
25.5	176	10.67	10.16	12.01	10.76	9.76
27.0	173	11.01	10.63	12.64	11.11	9.64
28.5	171	11.70	11.41	13.57	11.94	9.89
30.0	169	12.28	12.40	14.23	12.51	9.97
31.5	167	12.76	12.91	14.75	13.42	9.94
33.0	165	13.07	13.30	14.79	14.09	10.11
34.5	163	13.24	13.57	14.82	14.58	10.01
36.0	161	13.32	13.80	15.10	14.22	10.15
37.5	159	13.21	13.84	14.96	13.89	10.14
39.0	157	12.84	13.34	14.59	13.20	10.22
40.5	155	12.38	12.91	13.61	12.85	10.16
42.0	153	12.08	12.44	12.84	12.36	10.67
45.0	149	11.90	12.12	12.68	12.06	10.73
48.0	146	11.88	12.07	12.48	11.89	11.08
51.0	143	11.64	11.72	11.98	11.83	11.02
54.0	140	11.23	11.08	11.71	11.27	10.75
57.0	138	11.18	10.91	11.56	11.28	10.97
60.0	135	11.12	10.89	11.40	11.37	10.82
63.0	133	10.91	10.57	11.17	11.24	10.64
66.0	130	10.84	10.46	10.97	11.19	10.72
69.0	128	10.67	10.48	10.72	10.96	10.52
72.0	126	10.54	10.42	10.53	10.93	10.28
75.0	124	10.43	10.24	10.37	10.82	10.27
78.0	122	10.43	10.17	10.56	10.68	10.32
81.0	120	10.30	10.04	10.53	10.50	10.14
84.0	118	10.26	9.96	10.38	10.60	10.10
88.5	116	10.28	10.10	10.29	10.71	10.02

EXPERIMENT NUMBER M.2Re = 10,000

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	324	3.59	3.84	3.45	3.39	3.70
4.5	310	3.63	3.81	3.54	3.46	3.71
7.5	296	3.63	3.76	3.57	3.47	3.70
10.5	283	3.65	3.79	3.63	3.51	3.68
13.5	271	3.67	3.85	3.70	3.51	3.64
16.5	260	3.71	3.85	3.76	3.58	3.67
19.5	249	3.74	3.96	3.82	3.60	3.59
20.5	246	3.61	3.83	3.71	3.50	3.42
21.2	243	3.56	3.80	3.69	3.43	3.30
22.0	240	3.50	3.78	3.62	3.36	3.23
23.5	235	3.56	3.82	3.69	3.38	3.34
25.0	231	3.70	3.92	3.73	3.47	3.69
26.5	225	4.16	4.04	3.89	3.99	4.73
27.5	221	7.02	7.68	7.71	6.94	5.72
28.5	215	7.93	7.82	8.27	8.12	7.68
29.5	209	7.48	7.11	7.99	7.16	7.49
31.0	202	6.13	6.66	6.32	5.56	5.99
32.5	196	4.95	5.68	5.08	4.55	4.52
34.0	192	4.31	4.86	4.25	4.02	4.11
37.0	184	3.88	4.29	3.75	3.60	3.90
40.0	178	3.75	4.04	3.72	3.48	3.77
43.0	172	3.67	3.91	3.80	3.39	3.70
46.0	166	3.62	3.84	3.68	3.27	3.67
49.0	161	3.56	3.67	3.73	3.15	3.65
50.5	156	3.51	3.60	3.80	3.24	3.49
52.0	151	3.46	3.47	3.66	3.24	3.44
55.0	146	3.43	3.31	3.73	3.14	3.46
58.0	142	3.36	3.27	3.52	3.18	3.48
61.0	138	3.26	3.16	3.44	3.11	3.31
64.0	135	3.24	3.15	3.53	3.06	3.24
67.0	131	3.19	2.94	3.62	3.01	3.20
70.0	128	3.13	2.82	3.66	2.94	3.09
75.0	123	3.23	2.91	3.82	2.89	3.19

EXPERIMENT NUMBER M.5Re = 15,400

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	275	4.76	4.67	4.48	4.88	4.99
4.5	265	4.79	4.71	4.54	4.92	4.97
7.5	255	4.83	4.61	4.75	4.97	4.98
10.5	245	4.85	4.61	4.81	4.98	4.98
13.5	237	4.87	4.70	4.89	4.98	4.93
16.5	228	4.90	4.70	4.94	5.06	4.91
19.5	220	4.96	4.80	5.06	5.06	4.90
20.5	218	4.90	4.80	5.03	5.00	4.77
21.2	215	4.83	4.76	5.01	4.95	4.61
22.0	213	4.78	4.59	5.01	4.91	4.64
23.5	210	4.86	4.66	5.01	5.04	4.73
25.0	206	5.06	4.73	5.09	5.36	5.05
26.5	202	5.55	4.85	5.59	6.09	5.66
27.5	198	9.28	10.34	9.95	9.85	6.99
28.5	194	10.69	11.04	11.20	10.86	9.67
29.5	189	10.30	10.64	10.80	11.10	8.65
31.0	184	8.50	8.97	8.84	8.30	7.86
32.5	179	6.90	7.12	6.94	6.76	6.77
34.0	176	6.06	6.14	5.92	6.10	6.07
37.0	170	5.51	5.55	5.28	5.46	5.76
40.0	164	5.35	5.24	5.27	5.38	5.50
43.0	159	5.26	5.03	5.23	5.37	5.41
46.0	154	5.18	4.98	5.11	5.32	5.31
49.0	150	5.06	4.90	5.05	5.08	5.22
50.5	145	5.01	4.88	5.02	5.07	5.07
52.0	141	4.98	4.67	5.18	5.10	4.95
55.0	138	4.93	4.68	5.13	5.10	4.79
58.0	134	4.89	4.68	5.06	5.26	4.35
61.0	131	4.89	4.66	5.12	5.19	4.60
64.0	127	4.80	4.63	4.99	4.97	4.63
67.0	124	4.81	4.52	5.21	4.92	4.60
70.0	122	4.81	4.52	5.20	5.02	4.50
75.0	117	4.84	4.62	5.07	5.07	4.58

EXPERIMENT NUMBER M.9Re = 22,500

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	299	6.28	6.30	6.01	6.50	6.31
4.5	289	6.34	6.33	6.12	6.55	6.36
7.5	279	6.40	6.35	6.24	6.52	6.47
10.5	270	6.47	6.43	6.35	6.57	6.53
13.5	261	6.53	6.58	6.52	6.56	6.45
16.5	252	6.54	6.62	6.66	6.51	5.38
19.5	244	6.63	6.63	6.83	6.66	6.41
20.5	242	6.56	6.48	6.77	6.63	6.36
21.2	239	6.46	6.47	6.74	6.46	6.27
22.0	237	6.44	6.38	6.75	6.54	6.21
23.5	233	6.53	6.38	6.75	6.72	6.27
25.0	229	6.78	6.46	6.85	6.97	6.88
26.5	225	7.29	6.59	7.14	7.62	7.80
27.5	222	11.24	10.51	11.97	12.63	9.83
28.5	218	12.67	11.00	14.39	13.41	11.85
29.5	213	12.38	10.78	13.22	13.26	12.33
31.0	208	10.38	10.30	10.70	10.64	9.90
32.5	204	8.72	9.26	8.52	8.42	8.66
34.0	200	7.87	8.35	7.71	7.69	7.73
37.0	193	7.29	7.63	7.23	6.93	7.37
40.0	187	7.08	7.33	7.02	6.67	7.31
43.0	182	6.97	7.25	6.97	6.45	7.21
46.0	176	6.87	7.10	7.02	6.25	7.09
49.0	172	6.64	6.78	6.76	6.21	6.93
50.5	167	6.42	6.53	6.70	6.12	6.32
52.0	162	6.41	6.41	6.83	6.07	6.35
55.0	158	6.37	6.40	6.79	5.96	6.33
58.0	154	6.31	6.33	6.66	5.69	6.57
61.0	150	6.23	6.07	6.63	5.67	6.53
64.0	146	6.24	6.03	6.77	5.75	6.42
67.0	143	6.34	5.95	6.95	5.92	6.54
70.0	139	6.35	5.95	6.85	6.13	6.49
75.0	134	6.34	5.97	6.65	6.24	6.48

EXPERIMENT NUMBER M.12Re = 31,400

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	246	7.42	7.51	7.30	7.34	7.53
4.5	239	7.47	7.55	7.41	7.36	7.54
7.5	233	7.51	7.54	7.57	7.36	7.59
10.5	226	7.55	7.57	7.67	7.41	7.55
13.5	220	7.62	7.63	7.73	7.58	7.55
16.5	214	7.70	7.64	7.99	7.68	7.48
19.5	208	7.78	7.76	7.98	7.90	7.50
20.5	207	7.71	7.65	7.98	7.86	7.34
21.2	205	7.59	7.45	7.97	7.83	7.12
22.0	204	7.59	7.42	8.00	7.90	7.04
23.5	201	7.69	7.35	8.03	8.12	7.25
25.0	198	8.01	7.44	8.24	8.48	7.88
26.5	195	8.67	7.70	8.50	9.10	9.40
27.5	193	13.00	12.55	13.15	13.77	12.53
28.5	190	14.62	13.60	14.94	15.34	14.60
29.5	187	14.28	13.24	14.90	15.19	13.81
31.0	183	12.28	12.00	12.59	12.30	12.21
32.5	180	10.44	10.38	10.61	10.50	10.25
34.0	177	9.50	9.48	9.45	9.90	9.16
37.0	172	8.86	8.78	8.80	9.18	8.67
40.0	167	8.65	8.49	8.74	8.96	8.41
43.0	163	8.53	8.46	8.71	8.70	8.26
46.0	159	8.42	8.16	8.78	8.63	8.12
49.0	155	8.29	8.09	8.71	8.35	8.00
50.5	152	8.19	7.87	8.69	8.35	7.85
52.0	148	8.12	7.76	8.64	8.24	7.85
55.0	145	8.03	7.68	8.60	8.29	7.55
58.0	142	7.83	7.66	7.91	8.04	7.70
61.0	139	7.79	7.56	7.79	8.13	7.68
64.0	136	7.75	7.47	7.84	8.00	7.68
67.0	133	7.77	7.54	7.80	8.17	7.58
70.0	130	7.84	7.79	7.94	7.96	7.66
75.0	126	8.01	8.00	8.05	7.97	8.02

EXPERIMENT NUMBER M.14

 $Re = 36,000$

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	233	8.20	8.05	8.08	8.39	8.30
4.5	227	8.19	8.08	8.14	8.33	8.21
7.5	221	8.26	8.19	8.27	8.30	8.26
10.5	215	8.28	8.22	8.37	8.34	8.17
13.5	209	8.30	8.29	8.46	8.40	8.04
16.5	204	8.39	8.46	8.62	8.45	8.02
19.5	199	8.51	8.63	8.84	8.54	8.01
20.5	197	8.37	8.56	8.65	8.46	7.80
21.2	196	8.35	8.50	8.55	8.37	7.97
22.0	194	8.48	8.57	8.52	8.38	8.07
23.5	192	8.50	8.59	8.53	8.45	8.44
25.0	189	8.70	8.65	8.55	8.80	8.80
26.5	186	9.83	9.01	8.88	11.34	10.09
27.5	184	14.23	14.30	14.81	15.06	12.76
28.5	181	15.55	15.75	16.34	16.10	13.99
29.5	179	15.93	16.31	15.92	16.40	15.10
31.0	175	13.46	14.69	13.68	13.23	12.23
32.5	172	11.53	13.15	11.13	10.90	10.94
34.0	170	10.44	11.74	9.82	10.20	9.99
37.0	166	9.83	10.84	9.38	9.56	9.52
40.0	162	9.47	10.29	9.18	9.47	8.94
43.0	158	9.33	9.92	9.09	9.40	8.88
46.0	154	9.16	9.64	9.06	9.16	8.81
49.0	150	9.01	9.36	8.86	9.06	8.82
50.5	147	8.86	9.21	8.60	9.08	8.61
52.0	144	8.76	9.08	8.61	8.87	8.49
55.0	141	8.67	8.84	8.55	8.86	8.45
58.0	138	8.65	8.65	8.59	8.78	8.37
61.0	136	8.42	8.51	8.47	8.47	8.22
64.0	133	8.40	8.64	8.15	8.64	8.17
67.0	131	8.29	8.30	8.30	8.61	7.97
70.0	128	8.12	8.08	8.18	8.16	8.06
75.0	125	8.09	7.91	8.40	8.16	7.91

EXPERIMENT NUMBER M.17Re = 44,000

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	213	9.68	9.95	9.47	9.66	9.64
4.5	208	9.68	9.94	9.59	9.66	9.55
7.5	203	9.71	9.94	9.63	9.59	9.69
10.5	198	9.69	9.98	9.74	9.62	9.42
13.5	193	9.72	10.09	9.88	9.56	9.35
16.5	188	9.77	10.11	10.05	9.63	9.34
19.5	184	9.83	10.17	10.27	9.76	9.48
20.5	183	9.84	10.15	10.18	9.52	9.50
21.2	181	9.83	10.08	10.15	9.51	9.62
22.0	180	9.78	10.18	10.15	9.51	9.68
23.5	178	9.99	10.27	10.25	9.76	9.66
25.0	176	10.16	10.46	10.38	10.12	9.67
26.5	174	10.91	10.95	10.61	10.63	11.45
27.5	172	15.85	15.33	16.41	16.83	14.82
28.5	170	18.04	17.66	18.47	18.60	17.43
29.5	167	17.96	17.48	18.65	18.43	17.29
31.0	164	15.59	16.71	15.76	15.16	14.73
32.5	162	13.29	14.51	13.21	12.40	12.98
34.0	160	12.15	13.53	11.22	11.67	12.17
37.0	156	11.43	12.75	10.76	10.88	11.28
40.0	152	11.15	12.15	10.79	10.47	11.20
43.0	149	10.96	11.81	10.72	10.28	11.05
46.0	145	10.80	11.51	10.63	10.29	10.74
49.0	142	10.61	11.19	10.53	10.22	10.50
50.5	139	10.47	10.99	10.44	10.13	10.33
52.0	136	10.33	10.64	10.34	10.11	10.18
55.0	134	10.26	10.36	10.30	10.15	10.23
58.0	131	10.23	10.12	10.38	10.14	10.29
61.0	129	10.22	10.20	10.01	10.33	10.34
64.0	127	10.09	10.03	9.94	10.25	10.15
67.0	124	10.05	10.09	9.86	10.33	9.91
70.0	122	9.97	9.87	10.04	10.18	9.81
75.0	119	10.12	10.07	10.14	10.34	9.95

EXPERIMENT NUMBER A.1Re = 9,220

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	333	3.41	3.53	3.46	3.32	3.33
4.5	320	3.35	3.39	3.43	3.29	3.30
7.5	307	3.34	3.33	3.41	3.31	3.29
10.5	295	3.29	3.20	3.35	3.28	3.31
13.5	284	3.26	3.13	3.34	3.28	3.29
16.5	273	3.26	3.09	3.35	3.31	3.28
19.5	263	3.24	2.98	3.36	3.33	3.28
22.5	253	3.24	2.89	3.39	3.31	3.26
24.5	247	3.22	2.79	3.38	3.31	3.17
26.5	241	3.16	2.70	3.39	3.28	3.12
28.5	236	3.12	2.69	3.47	3.31	3.04
30.5	230	3.38	3.04	3.82	3.66	2.99
32.5	225	3.57	3.23	4.07	3.88	3.08
34.5	220	3.61	3.29	4.19	3.92	3.02
36.5	215	3.62	3.32	4.29	3.94	2.92
38.5	210	3.61	3.32	4.39	3.94	2.77
40.5	206	3.57	3.27	4.43	3.82	2.65
42.5	201	3.57	3.31	4.41	3.67	2.70
44.5	197	3.45	3.33	4.27	3.56	2.65
46.5	192	3.32	3.23	4.11	3.32	2.61
48.5	188	3.23	3.33	3.83	3.17	2.58
50.5	184	3.11	3.33	3.64	3.01	2.48
52.5	180	3.02	3.32	3.36	2.89	2.51
55.5	175	3.04	3.42	3.38	2.77	2.52
58.5	169	3.13	3.40	3.48	2.76	2.74
61.5	164	3.09	3.33	3.48	2.84	2.72
64.5	160	3.16	3.39	3.48	2.95	2.82
67.5	155	3.16	3.19	3.54	3.03	2.86
70.5	151	3.19	3.18	3.41	3.08	2.97
73.5	147	3.17	3.12	3.41	3.08	3.07
76.5	143	3.18	3.14	3.32	3.05	3.20
79.5	139	3.18	3.12	3.39	2.97	3.24
82.5	136	3.14	3.14	3.11	2.98	3.33
85.5	132	3.07	3.29	3.12	2.94	3.32
88.5	129	3.17	3.36	3.07	2.87	3.35
91.5	126	3.20	3.49	3.16	2.82	3.34
94.5	122	3.22	3.44	3.20	2.85	3.38
99.0	118	3.30	3.45	3.18	3.07	3.40

EXPERIMENT NUMBER A.3Re = 15,500

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	288	4.51	4.51	4.52	4.50	4.52
4.5	278	4.49	4.51	4.52	4.48	4.47
7.5	268	4.46	4.51	4.52	4.41	4.41
10.5	259	4.45	4.53	4.50	4.41	4.37
13.5	251	4.46	4.57	4.49	4.41	4.35
16.5	242	4.47	4.62	4.49	4.38	4.39
19.5	234	4.55	4.70	4.53	4.43	4.52
22.5	227	4.60	4.69	4.57	4.51	4.64
24.5	222	4.61	4.72	4.55	4.53	4.63
26.5	217	4.60	4.72	4.61	4.54	4.52
28.5	212	5.01	5.25	5.22	5.10	4.46
30.5	208	5.28	5.55	5.67	5.45	4.44
32.5	203	5.39	5.67	5.93	5.56	4.40
34.5	199	5.45	5.72	6.16	5.58	4.35
36.5	195	5.59	5.76	6.32	5.48	4.38
38.5	191	5.49	5.84	6.50	5.33	4.29
40.5	186	5.51	5.92	6.51	5.29	4.23
42.5	181	5.49	5.89	6.59	5.31	4.20
44.5	177	5.48	5.84	6.60	5.24	4.21
46.5	174	5.40	5.72	6.48	5.17	4.22
48.5	170	5.22	5.45	6.24	4.97	4.24
50.5	167	5.08	5.19	6.07	4.80	4.24
52.5	164	4.89	4.91	5.76	4.59	4.29
55.5	159	4.72	4.73	5.49	4.38	4.31
58.5	155	4.66	4.64	5.31	4.36	4.32
61.5	151	4.51	4.61	4.79	4.40	4.32
64.5	147	4.51	4.58	4.74	4.32	4.38
67.5	143	4.53	4.52	4.62	4.47	4.50
70.5	139	4.49	4.42	4.53	4.51	4.47
73.5	136	4.47	4.42	4.61	4.53	4.31
76.5	133	4.47	4.44	4.59	4.55	4.28
79.5	129	4.54	4.49	4.60	4.60	4.27
82.5	126	4.57	4.62	4.55	4.64	4.29
85.5	123	4.61	4.71	4.55	4.73	4.43
88.5	121	4.61	4.78	4.43	4.72	4.51
91.5	118	4.61	4.85	4.43	4.76	4.41
94.5	115	4.57	4.84	4.34	4.84	4.25
99.0	112	4.60	4.82	4.40	4.84	4.35

EXPERIMENT NUMBER A.6

Re = 20,600

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	228	5.50	5.68	5.45	5.51	5.35
4.5	222	5.49	5.69	5.46	5.47	5.33
7.5	216	5.52	5.72	5.55	5.44	5.37
10.5	210	5.54	5.76	5.61	5.42	5.35
13.5	205	5.56	5.80	5.68	5.43	5.32
16.5	199	5.61	5.87	5.71	5.45	5.39
19.5	194	5.64	5.92	5.64	5.50	5.42
22.5	189	5.74	5.99	5.78	5.61	5.56
24.5	186	5.74	5.98	5.80	5.65	5.53
26.5	182	5.80	5.98	5.90	5.75	5.57
28.5	179	6.11	6.33	6.45	6.24	5.48
30.5	176	6.41	6.66	6.91	6.65	5.40
32.5	173	6.55	6.82	7.21	6.81	5.34
34.5	170	6.64	6.84	7.35	6.95	5.40
36.5	167	6.65	6.75	7.53	7.03	5.33
38.5	164	6.53	6.64	7.45	6.90	5.18
40.5	161	6.49	6.64	7.32	6.90	5.11
42.5	158	6.39	6.64	7.33	6.88	5.10
44.5	156	6.45	6.65	7.28	6.73	5.15
46.5	153	6.36	6.53	7.05	6.70	5.17
48.5	151	6.28	6.48	6.96	6.46	5.20
50.5	148	6.20	6.39	6.80	6.41	5.21
52.5	146	6.03	6.27	6.55	6.05	5.27
55.5	142	6.00	6.16	6.31	6.05	5.49
58.5	139	5.93	6.07	6.15	5.93	5.56
61.5	136	5.96	6.00	6.12	5.98	5.74
64.5	133	5.90	6.02	6.06	5.74	5.80
67.5	130	5.81	5.81	6.06	5.66	5.73
70.5	127	5.77	5.71	6.04	5.68	5.65
73.5	125	5.66	5.44	5.93	5.67	5.60
76.5	122	5.55	5.37	5.85	5.58	5.42
79.5	120	5.59	5.28	5.86	5.65	5.56
82.5	118	5.51	5.18	5.80	5.65	5.40
85.5	116	5.56	5.28	5.74	5.74	5.48
88.5	113	5.65	5.34	5.62	5.96	5.67
91.5	111	5.69	5.46	5.67	5.87	5.74
94.5	109	5.72	5.70	5.60	5.75	5.82
99.0	106	5.80	5.90	5.64	5.80	5.86

EXPERIMENT NUMBER A.9Re = 26,200

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	296	6.98	6.83	6.85	6.98	7.25
4.5	288	6.97	6.79	6.84	7.02	7.24
7.5	279	7.00	6.77	6.88	7.08	7.27
10.5	271	7.06	6.79	7.01	7.13	7.32
13.5	263	7.09	6.81	7.08	7.17	7.29
16.5	255	7.12	6.86	7.18	7.17	7.27
19.5	248	7.22	6.96	7.36	7.28	7.28
22.5	240	7.32	7.08	7.55	7.39	7.26
24.5	235	7.37	7.18	7.68	7.45	7.15
26.5	231	7.39	7.22	7.78	7.47	7.09
28.5	226	7.86	7.83	8.52	8.06	7.02
30.5	222	8.27	8.27	9.15	8.57	6.98
32.5	217	8.39	8.49	9.45	8.69	6.92
34.5	213	8.48	8.47	9.71	8.81	6.92
36.5	209	8.56	8.54	9.86	8.85	6.97
38.5	204	8.63	8.57	10.12	8.91	6.90
40.5	200	8.64	8.56	10.25	8.83	6.88
42.5	196	8.56	8.38	10.30	8.70	6.87
44.5	192	8.57	8.44	10.28	8.58	6.86
46.5	188	8.47	8.47	10.05	8.51	6.84
48.5	185	8.26	8.23	9.77	8.23	6.81
50.5	181	8.08	8.16	8.97	8.03	6.85
52.5	178	7.72	7.86	8.33	7.76	6.93
55.5	173	7.53	7.62	7.72	7.69	7.09
58.5	168	7.44	7.38	7.64	7.41	7.12
61.5	163	7.28	7.17	7.54	7.23	7.18
64.5	159	7.14	6.96	7.40	7.05	7.14
67.5	155	6.96	6.85	7.17	6.75	7.06
70.5	152	6.86	6.77	7.05	6.60	7.04
73.5	148	6.73	6.74	6.87	6.34	6.96
76.5	145	6.62	6.73	6.65	6.22	6.86
79.5	142	6.63	6.74	6.56	6.33	6.87
82.5	139	6.60	6.80	6.37	6.29	6.93
85.5	136	6.55	6.68	6.27	6.28	6.98
88.5	133	6.55	6.72	6.16	6.20	7.13
91.5	130	6.60	6.91	6.13	6.21	7.11
94.5	128	6.66	6.94	6.13	6.32	7.24
99.0	124	6.72	6.96	6.19	6.34	7.19

EXPERIMENT NUMBER A.10Re = 29,400

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	272	7.53	7.44	7.55	7.71	7.44
4.5	265	7.53	7.42	7.56	7.72	7.41
7.5	258	7.56	7.49	7.57	7.74	7.43
10.5	251	7.56	7.46	7.64	7.73	7.42
13.5	244	7.63	7.49	7.71	7.75	7.56
16.5	238	7.69	7.62	7.81	7.76	7.59
19.5	231	7.76	7.71	7.97	7.81	7.56
22.5	225	7.88	7.81	8.17	7.87	7.69
24.5	221	7.83	7.79	8.25	7.76	7.51
26.5	217	7.90	7.83	8.55	7.84	7.84
28.5	213	8.71	8.47	9.62	8.61	8.12
30.5	209	8.84	8.57	10.03	8.72	8.03
32.5	205	9.20	8.84	10.77	8.78	8.21
34.5	202	9.07	8.74	10.77	8.87	7.89
36.5	198	9.12	8.84	10.84	8.95	7.86
38.5	194	9.20	8.96	10.90	9.13	7.81
40.5	191	9.26	9.04	10.93	9.24	7.82
42.5	187	9.35	9.27	10.92	9.37	7.82
44.5	184	9.34	9.39	10.86	9.34	7.74
46.5	180	9.35	9.62	10.76	9.27	7.77
48.5	177	9.30	9.57	10.64	9.22	7.78
50.5	174	9.05	9.42	10.31	8.87	7.58
52.5	171	8.90	9.30	10.06	8.71	7.54
55.5	166	8.32	8.63	8.92	8.12	7.60
58.5	162	8.02	8.28	8.50	7.75	7.57
61.5	158	7.91	8.12	8.28	7.69	7.55
64.5	154	7.80	7.99	8.20	7.44	7.55
67.5	151	7.68	7.72	8.11	7.38	7.50
70.5	148	7.71	7.81	8.05	7.34	7.63
73.5	144	7.64	7.70	7.88	7.42	7.55
76.5	141	7.59	7.69	7.81	7.32	7.53
79.5	138	7.62	7.74	7.81	7.32	7.61
82.5	136	7.65	7.85	8.28	7.28	7.20
85.5	133	7.75	7.88	8.17	7.40	7.53
88.5	130	7.84	7.84	8.14	7.56	7.62
91.5	127	7.90	7.83	8.03	7.91	7.82
94.5	125	7.84	7.82	7.94	7.84	7.78
99.0	121	7.64	7.78	7.85	7.43	7.49

EXPERIMENT NUMBER A.11Re = 31,400

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	270	8.27	8.40	7.98	8.32	8.38
4.5	263	8.24	8.26	8.03	8.29	8.37
7.5	255	8.19	8.23	8.03	8.17	8.33
10.5	248	8.16	8.20	7.96	8.15	8.34
13.5	242	8.18	8.17	8.09	8.14	8.32
16.5	235	8.19	8.15	8.26	8.12	8.25
19.5	229	8.25	8.19	8.43	8.12	8.27
22.5	223	8.34	8.24	8.65	8.23	8.25
24.5	219	8.39	8.29	8.90	8.23	8.14
26.5	215	8.40	8.16	9.19	8.24	8.02
28.5	211	8.97	8.96	10.14	8.78	8.00
30.5	207	9.47	9.54	11.03	9.34	7.98
32.5	204	9.65	9.69	11.53	9.39	7.97
34.5	200	9.70	9.82	11.72	9.38	7.90
36.5	196	9.73	9.81	11.75	9.40	7.95
38.5	193	9.62	9.64	11.66	9.25	7.93
40.5	189	9.64	9.64	11.71	9.21	7.99
42.5	186	9.70	9.70	11.76	9.22	8.09
44.5	183	9.64	9.53	11.55	9.23	8.15
46.5	179	9.48	9.42	11.36	9.20	8.15
48.5	176	9.28	9.24	10.80	8.97	8.19
50.5	173	9.06	9.09	10.17	8.74	8.24
52.5	170	8.77	8.96	9.39	8.49	8.27
55.5	165	8.57	8.71	9.18	8.13	8.25
58.5	161	8.36	8.48	9.05	7.81	8.12
61.5	157	8.12	8.26	8.88	7.43	7.92
64.5	153	7.95	7.84	8.64	7.44	7.90
67.5	150	7.98	7.87	8.55	7.52	7.98
70.5	146	7.94	7.75	8.36	7.63	8.06
73.5	143	7.89	7.65	8.12	7.72	8.07
76.5	140	7.75	7.33	7.86	7.77	8.01
79.5	137	7.83	7.54	7.86	7.81	8.11
82.5	134	7.85	7.56	7.79	7.93	8.14
85.5	131	7.88	7.68	7.81	7.96	8.08
88.5	129	7.93	7.87	7.96	7.97	7.92
91.5	126	7.98	8.11	8.07	6.85	7.90
94.5	124	7.99	8.15	8.03	7.92	7.88
99.0	120	8.08	8.14	8.11	7.92	8.14

EXPERIMENT NUMBER A.13Re = 39,700

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	224	9.53	9.28	9.52	9.90	9.40
4.5	218	9.55	9.27	9.58	9.87	9.49
7.5	213	9.57	9.24	9.56	9.94	9.54
10.5	208	9.59	9.26	9.63	9.96	9.51
13.5	203	9.60	9.26	9.68	9.99	9.48
16.5	199	9.62	9.27	9.72	10.05	9.47
19.5	194	9.70	9.34	9.86	10.08	9.53
22.5	190	9.78	9.46	9.97	10.20	9.50
24.5	187	9.80	9.53	10.05	10.19	9.42
26.5	184	9.86	9.51	10.21	10.21	9.49
28.5	181	10.57	10.33	11.36	11.03	9.53
30.5	178	11.26	11.04	12.82	11.68	9.50
32.5	175	11.61	11.26	13.75	11.85	9.59
34.5	173	11.73	11.53	13.93	11.95	9.52
36.5	170	11.76	11.59	13.91	11.95	9.35
38.5	167	11.69	11.68	13.75	11.98	9.33
40.5	164	11.73	11.65	13.56	11.98	9.32
42.5	162	11.62	11.82	13.33	12.08	9.26
44.5	159	11.53	11.78	13.06	12.01	9.28
46.5	157	11.42	11.69	12.69	12.01	9.30
48.5	154	11.23	11.35	12.31	11.91	9.35
50.5	152	11.00	11.12	12.03	11.54	9.29
52.5	150	10.57	10.53	11.43	10.96	9.28
55.5	147	9.96	10.31	10.82	10.78	9.26
58.5	144	9.87	9.70	10.09	10.38	9.30
61.5	141	9.60	9.52	9.63	9.96	9.39
64.5	138	9.50	9.33	9.49	9.74	9.44
67.5	136	9.41	9.20	9.35	9.70	9.38
70.5	133	9.28	8.90	9.38	9.51	9.32
73.5	131	9.24	8.86	9.28	9.46	9.34
76.5	128	9.20	8.82	9.28	9.18	9.51
79.5	126	9.17	8.82	9.25	9.06	9.54
82.5	124	9.11	8.79	9.29	8.91	9.47
85.5	122	9.12	8.73	9.32	9.00	9.43
88.5	120	9.09	8.77	9.46	8.85	9.30
91.5	118	9.12	8.79	9.51	8.91	9.28
94.5	116	9.21	8.98	9.55	8.93	9.39
99.0	113	9.31	9.20	9.66	9.05	9.35

EXPERIMENT NUMBER B.1Re = 10,700

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	287	3.61	3.73	3.43	3.45	3.84
4.5	276	3.50	3.61	3.39	3.40	3.61
7.5	266	3.39	3.50	3.26	3.37	3.46
10.5	256	3.29	3.38	3.14	3.30	3.34
13.5	248	3.23	3.31	3.09	3.21	3.30
16.5	239	3.17	3.20	3.12	3.16	3.18
19.5	232	3.17	3.23	3.17	3.08	3.21
22.5	224	3.26	3.26	3.33	3.16	3.30
24.5	219	3.36	3.32	3.45	3.27	3.29
26.5	214	3.56	3.52	3.89	3.60	3.25
28.5	209	4.07	4.04	4.47	4.24	3.52
30.5	204	4.37	4.37	4.70	4.78	3.62
32.5	198	4.47	4.50	4.87	4.86	3.66
34.5	193	4.44	4.50	4.92	4.75	3.58
36.5	188	4.34	4.45	4.95	4.52	3.45
38.5	184	4.14	4.31	4.81	4.20	3.24
39.5	182	4.03	4.21	4.68	4.00	3.21
40.5	180	3.96	4.11	4.43	3.89	3.40
42.5	176	3.82	3.91	4.14	3.78	3.47
44.5	172	3.76	3.72	3.94	3.78	3.60
46.5	168	3.78	3.64	3.85	3.85	3.79
49.5	163	3.62	3.33	3.78	3.77	3.61
52.5	159	3.39	3.03	3.55	3.56	3.44
55.5	154	3.29	2.88	3.42	3.44	3.43
58.5	150	3.25	2.80	3.41	3.50	3.30
61.5	146	3.27	2.85	3.53	3.54	3.14
64.5	142	3.30	2.85	3.57	3.58	3.18
67.5	138	3.33	2.90	3.66	3.53	3.23
70.5	134	3.40	3.12	3.64	3.63	3.21
73.5	130	3.43	3.24	3.62	3.58	3.28
76.5	127	3.55	3.33	3.66	3.63	3.60
79.5	123	3.56	3.42	3.45	3.64	3.75
82.5	120	3.59	3.57	3.51	3.60	3.68
85.5	117	3.62	3.70	3.56	3.56	3.67
88.5	114	3.65	3.83	3.45	3.67	3.64
93.0	110	3.68	3.88	3.46	3.66	3.73

EXPERIMENT NUMBER B.4Re = 14,500

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	251	4.35	4.45	4.07	4.43	4.49
4.5	242	4.24	4.34	4.04	4.28	4.32
7.5	235	4.20	4.29	4.02	4.26	4.24
10.5	227	4.12	4.21	4.01	4.15	4.10
13.5	220	4.07	4.21	3.98	4.09	4.01
16.5	214	4.06	4.15	3.99	4.05	4.05
19.5	208	4.09	4.10	4.09	4.07	4.09
22.5	201	4.10	4.08	4.32	4.21	4.23
24.5	197	4.28	4.07	4.48	4.36	4.23
26.5	193	4.44	4.13	4.83	4.62	4.17
28.5	189	5.01	4.70	5.45	5.34	4.56
30.5	185	5.44	5.26	5.85	5.94	4.72
32.5	181	5.70	5.69	6.08	6.29	4.73
34.5	177	5.77	5.91	6.37	6.15	4.69
36.5	172	5.66	5.90	6.36	5.80	4.60
38.5	169	5.35	5.60	6.20	5.43	4.58
39.5	167	5.20	5.33	6.10	5.26	4.53
40.5	165	5.13	5.01	5.77	5.25	4.51
42.5	162	4.90	4.71	5.59	5.07	4.46
44.5	159	4.82	4.54	5.18	5.13	4.43
46.5	156	4.67	4.31	4.98	4.98	4.40
49.5	152	4.49	4.13	4.65	4.87	4.32
52.5	147	4.40	3.95	4.63	4.77	4.25
55.5	143	4.43	4.09	4.67	4.76	4.18
58.5	140	4.37	3.98	4.69	4.68	4.15
61.5	136	4.34	4.05	4.56	4.59	4.18
64.5	132	4.31	4.04	4.46	4.48	4.26
67.5	129	4.31	4.01	4.34	4.37	4.21
70.5	126	4.32	4.25	4.37	4.45	4.17
73.5	123	4.27	4.18	4.27	4.50	4.10
76.5	120	4.26	4.24	4.14	4.59	4.05
79.5	117	4.12	4.08	4.23	4.59	3.98
82.5	115	4.18	3.82	4.32	4.52	3.98
85.5	112	4.09	3.79	4.32	4.48	3.76
88.5	110	3.99	3.63	4.20	4.58	3.53
93.0	107	3.94	3.71	4.14	4.52	3.41

EXPERIMENT NUMBER B.5Re = 20,400

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	336	6.16	6.30	5.99	6.14	6.22
4.5	325	6.09	6.27	5.93	6.08	6.10
7.5	313	6.07	6.22	5.92	6.09	6.06
10.5	303	6.02	6.09	5.87	6.07	6.04
13.5	293	5.97	6.02	5.83	6.07	5.98
16.5	284	5.94	5.91	5.85	6.05	5.97
19.5	275	5.95	5.84	5.88	6.12	5.97
22.5	266	5.97	5.73	5.93	6.26	5.98
24.5	261	5.99	5.75	6.02	6.35	5.87
26.5	255	6.19	6.11	6.29	6.64	5.73
28.5	250	7.05	7.30	7.25	7.53	6.15
30.5	244	7.59	8.06	7.98	7.97	6.36
32.5	238	7.80	8.35	8.45	8.08	6.35
34.5	232	7.79	8.24	8.64	7.94	6.36
36.5	227	7.66	8.05	8.62	7.71	6.28
38.5	222	7.46	7.67	8.44	7.32	6.42
39.5	219	7.36	7.48	8.34	7.20	6.43
40.5	217	7.31	7.30	8.24	7.25	6.46
42.5	212	7.12	7.07	7.82	7.20	6.37
44.5	208	7.00	7.03	7.32	7.23	6.40
46.5	204	6.82	6.78	7.26	7.06	6.33
49.5	197	6.66	6.56	6.86	6.95	6.29
52.5	191	6.49	6.41	6.69	6.76	6.10
55.5	186	6.45	6.45	6.43	6.82	6.09
58.5	180	6.38	6.38	6.46	6.77	5.93
61.5	175	6.33	6.24	6.46	6.77	5.85
64.5	170	6.25	6.16	6.45	6.67	5.74
67.5	165	6.23	6.14	6.44	6.53	5.80
70.5	160	6.24	6.26	6.31	6.54	5.84
73.5	155	6.20	6.14	6.30	6.44	5.90
76.5	151	6.23	6.25	6.20	6.47	5.98
79.5	147	6.24	6.27	6.17	6.52	6.02
82.5	143	6.33	6.34	6.36	6.61	6.02
85.5	139	6.33	6.41	6.26	5.57	6.07
88.5	135	6.31	6.49	6.11	6.50	6.15
93.0	130	6.33	6.59	6.10	6.47	6.14

EXPERIMENT NUMBER B.7Re = 25,500

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	303	7.14	6.91	6.91	7.61	7.13
4.5	294	7.05	6.78	6.86	7.49	7.07
7.5	285	6.99	6.76	6.87	7.38	6.97
10.5	276	6.89	6.61	6.80	7.28	6.87
13.5	267	6.88	6.53	6.85	7.30	6.85
16.5	259	6.86	6.47	6.82	7.34	6.80
19.5	252	6.88	6.44	6.88	7.39	6.80
22.5	244	6.94	6.38	6.92	7.73	6.75
24.5	239	7.08	6.57	7.09	7.97	6.69
26.5	235	7.28	6.90	7.46	8.20	6.54
28.5	230	8.29	8.10	8.72	9.13	7.20
30.5	225	8.98	8.52	9.14	9.23	7.02
32.5	220	9.07	9.31	9.93	9.69	7.37
34.5	215	8.94	9.21	9.98	9.42	7.16
36.5	210	8.81	9.05	10.01	9.18	7.00
38.5	206	8.60	8.59	9.88	8.78	7.14
39.5	203	8.35	8.32	9.47	8.62	6.98
40.5	201	8.18	8.08	9.13	8.51	6.98
42.5	197	7.94	7.84	8.50	8.42	6.99
44.5	194	7.80	7.57	8.32	8.35	6.96
46.5	190	7.65	7.39	7.85	8.30	7.07
49.5	185	7.34	7.00	7.29	8.06	7.02
52.5	179	7.19	6.68	7.08	7.80	6.98
55.5	174	7.04	6.71	7.10	7.59	6.77
58.5	169	6.97	6.75	7.14	7.27	6.71
61.5	165	7.01	6.83	7.10	7.30	6.81
64.5	160	7.00	6.83	7.00	7.36	6.81
67.5	156	6.99	6.92	6.88	7.29	6.86
70.5	152	7.04	7.00	6.86	7.37	6.94
73.5	149	7.08	7.11	6.78	7.40	7.03
76.5	145	7.06	7.22	6.53	7.44	7.06
79.5	142	7.06	7.25	6.63	7.38	7.13
82.5	138	7.13	7.25	6.64	7.47	7.17
85.5	135	7.15	7.23	6.65	7.55	7.17
88.5	132	7.16	7.18	6.66	7.62	7.20
93.0	127	7.17	7.12	6.73	7.62	7.22

EXPERIMENT NUMBER B.9Re = 32,000

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	266	8.36	8.55	7.94	8.66	8.31
4.5	258	8.30	8.49	7.82	8.65	8.24
7.5	251	8.27	8.40	7.72	8.71	8.25
10.5	243	8.23	8.33	7.80	8.62	8.15
13.5	236	8.21	8.30	7.87	8.49	8.15
16.5	230	8.18	8.14	7.91	8.57	8.13
19.5	223	8.22	8.12	7.94	8.66	8.16
22.5	217	8.19	8.17	8.11	8.84	8.04
24.5	213	8.38	8.08	8.27	8.78	8.01
26.5	209	8.54	8.16	8.71	9.41	7.89
28.5	205	9.56	9.40	10.05	10.28	8.49
30.5	201	10.25	10.52	11.08	10.64	8.77
32.5	197	10.62	11.40	11.66	10.67	8.76
34.5	193	10.68	11.51	11.90	10.61	8.70
36.5	189	10.50	11.15	11.89	10.46	8.52
38.5	185	10.10	10.39	11.50	10.16	8.37
39.5	183	9.83	9.77	11.31	10.03	8.21
40.5	182	9.61	9.30	10.96	10.05	8.14
42.5	178	9.25	8.93	10.47	9.73	7.89
44.5	175	9.06	8.86	9.89	9.73	7.76
46.5	172	8.89	8.66	9.39	9.59	7.92
49.5	168	8.75	8.56	8.82	9.44	8.16
52.5	164	8.58	8.33	8.60	9.15	8.23
55.5	160	8.42	8.23	8.52	8.93	8.00
58.5	156	8.17	7.97	8.17	8.59	7.95
61.5	152	8.13	7.95	8.03	8.51	8.01
64.5	149	8.22	8.03	8.07	8.59	8.17
67.5	145	8.19	8.01	8.07	8.45	8.24
70.5	142	8.17	8.02	7.95	8.42	8.29
73.5	138	8.16	7.99	8.10	8.31	8.26
76.5	135	8.21	8.13	8.18	8.25	8.27
79.5	132	8.11	8.03	8.10	8.00	8.31
82.5	130	8.06	8.10	8.14	7.87	8.13
85.5	127	7.94	7.84	8.13	7.92	7.85
88.5	124	7.96	8.01	8.11	7.90	7.80
93.0	121	7.86	7.91	7.96	7.87	7.70

EXPERIMENT NUMBER B.11Re = 35,600

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	256	8.83	8.55	8.76	9.37	8.62
4.5	249	8.78	8.58	8.64	9.24	8.66
7.5	242	8.73	8.53	8.54	9.16	8.68
10.5	235	8.67	8.50	8.46	9.08	8.63
13.5	229	8.62	8.46	8.42	9.03	8.59
16.5	223	8.56	8.36	8.39	9.04	8.43
19.5	217	8.58	8.28	8.41	9.11	8.54
22.5	211	8.66	8.30	8.59	9.31	8.43
24.5	207	8.81	8.46	8.89	9.52	8.25
26.5	203	9.16	8.92	9.47	9.89	8.37
28.5	199	10.37	10.37	11.00	11.10	9.01
30.5	195	11.23	11.34	12.40	12.02	9.18
32.5	191	11.68	11.91	13.17	12.39	9.25
34.5	187	11.70	12.12	13.40	12.10	9.20
36.5	183	11.38	11.75	13.23	11.44	9.12
38.5	179	10.86	11.07	12.78	10.63	8.99
39.5	177	10.48	10.65	12.20	10.30	8.80
40.5	175	10.19	10.37	11.63	10.11	8.63
42.5	172	9.88	9.86	11.05	10.01	8.61
44.5	169	9.72	9.75	10.25	9.97	8.93
46.5	166	9.57	9.52	9.97	9.93	8.91
49.5	161	9.57	9.51	9.56	9.95	9.25
52.5	157	9.31	9.35	9.58	9.75	9.37
55.5	153	8.97	8.80	9.35	9.31	8.42
58.5	149	8.62	8.65	9.05	9.23	8.36
61.5	146	8.68	8.48	8.95	8.97	8.34
64.5	142	8.77	8.61	9.00	9.04	8.43
67.5	139	8.84	8.71	9.08	9.08	8.48
70.5	135	8.85	8.45	8.98	9.18	8.78
73.5	132	8.91	8.50	8.60	9.35	9.06
76.5	129	8.85	8.43	8.80	9.37	8.65
79.5	126	8.77	8.40	8.71	9.23	8.72
82.5	123	8.78	8.45	9.09	9.21	8.74
85.5	121	8.87	8.25	9.04	9.16	9.04
88.5	118	8.89	8.23	9.03	9.10	9.21
93.0	114	8.87	8.08	8.98	9.19	9.22

EXPERIMENT NUMBER B.13Re = 40,600

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	229	9.79	9.75	9.39	10.16	9.87
4.5	223	9.65	9.62	9.35	10.03	9.61
7.5	218	9.52	9.58	9.29	9.80	9.39
10.5	212	9.39	9.42	9.17	9.74	9.25
13.5	207	9.32	9.35	9.11	9.71	9.11
16.5	202	9.06	9.32	9.21	9.70	9.04
19.5	197	9.32	9.30	9.26	9.75	8.96
22.5	192	9.44	9.39	9.47	9.84	9.09
24.5	189	9.68	9.49	9.88	10.08	9.27
26.5	186	10.04	9.66	10.46	10.48	9.54
28.5	183	11.39	11.12	12.01	11.87	10.57
30.5	179	12.39	12.08	13.26	13.14	11.10
32.5	176	12.98	12.73	14.05	14.06	11.06
34.5	173	13.05	13.10	14.49	13.48	11.12
36.5	170	12.72	12.97	14.71	12.41	10.79
38.5	167	12.12	12.52	14.11	11.50	10.34
39.5	165	11.65	12.05	13.17	11.23	10.15
40.5	164	11.35	11.76	12.40	11.13	10.08
42.5	161	10.85	11.15	11.62	10.86	9.76
44.5	159	10.61	10.89	11.08	10.75	9.71
46.5	156	10.40	10.57	10.74	10.67	9.63
49.5	153	10.19	10.20	10.40	10.57	9.57
52.5	149	9.86	9.70	10.32	10.20	9.23
55.5	146	9.31	9.39	9.68	9.86	8.82
58.5	142	9.29	9.21	9.53	9.63	8.76
61.5	139	9.29	9.22	9.58	9.54	8.83
64.5	136	9.16	8.96	9.42	9.37	8.69
67.5	133	9.21	9.08	9.56	9.31	8.68
70.5	130	9.28	9.33	9.52	9.23	9.03
73.5	127	9.32	9.46	9.54	9.15	9.13
76.5	124	9.33	9.53	9.50	9.08	9.20
79.5	122	9.31	9.52	9.37	9.05	9.32
82.5	120	9.34	9.57	9.38	8.96	9.47
85.5	118	9.40	9.58	9.45	9.15	9.43
88.5	115	9.41	9.66	9.26	9.15	9.55
93.0	112	9.41	9.65	9.33	9.18	9.49

EXPERIMENT NUMBER C.1Re = 12,600

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	313	4.39	4.41	4.32	4.48	4.35
2.5	309	4.24	4.26	4.15	4.33	4.22
3.5	305	4.07	4.09	4.00	4.14	4.15
4.5	301	3.93	3.93	3.97	3.99	3.92
7.5	290	3.90	3.86	3.86	3.95	3.91
10.5	280	3.87	3.85	3.82	3.91	3.91
13.5	270	3.84	3.83	3.78	3.83	3.91
16.5	261	3.79	3.77	3.76	3.74	3.88
19.5	252	3.78	3.78	3.76	3.68	3.90
23.0	243	3.86	3.85	3.90	3.74	3.96
25.0	237	3.96	3.99	4.13	3.84	3.90
27.0	231	3.97	4.04	4.38	3.87	3.57
28.0	229	4.77	4.82	5.51	4.75	3.98
29.0	225	5.11	5.21	6.01	5.18	4.04
30.0	222	5.38	5.49	6.38	5.46	4.17
31.0	219	5.44	5.58	6.44	5.49	4.26
33.0	213	5.37	5.53	6.27	5.41	4.28
35.0	208	5.21	5.36	5.90	5.34	4.26
37.0	203	4.99	5.22	5.33	5.17	4.24
39.0	198	4.79	5.04	4.98	4.97	4.15
41.0	193	4.65	4.91	4.66	4.84	4.20
44.0	187	4.50	4.68	4.43	4.68	4.20
47.0	180	4.48	4.64	4.35	4.67	4.26
50.0	174	4.44	4.56	4.27	4.54	4.39
53.0	169	4.34	4.34	4.20	4.41	4.44
56.0	163	4.37	4.49	4.22	4.34	4.41
59.0	158	4.30	4.43	4.20	4.21	4.36
62.0	153	4.26	4.41	4.18	4.19	4.27
65.0	148	4.24	4.40	4.16	4.17	4.23
68.0	143	4.11	4.31	4.11	3.99	4.01
71.0	138	4.02	4.22	4.08	3.85	3.91
74.0	134	4.00	4.19	4.03	3.73	4.03
77.0	130	3.93	4.17	4.01	3.66	3.86
80.0	126	4.05	4.01	4.25	3.96	3.96
83.0	122	4.17	4.16	4.51	4.02	3.98
87.5	116	4.22	4.10	4.67	3.97	4.12

EXPERIMENT NUMBER C.3Re = 16,200

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	281	5.07	5.13	5.31	5.10	4.75
2.5	277	4.90	4.93	5.10	4.90	4.67
3.5	274	4.73	4.77	4.88	4.73	4.54
4.5	271	4.56	4.52	4.67	4.59	4.45
7.5	261	4.55	4.47	4.66	4.62	4.47
10.5	253	4.58	4.46	4.64	4.68	4.55
13.5	244	4.60	4.40	4.68	4.81	4.52
16.5	236	4.67	4.35	4.74	5.01	4.57
19.5	228	4.77	4.31	4.91	5.25	4.63
23.0	219	4.99	4.41	5.19	5.62	4.72
25.0	214	5.16	4.49	5.52	5.89	4.74
27.0	209	5.33	4.63	5.70	6.30	4.68
28.0	206	5.55	4.94	6.32	6.43	4.53
29.0	204	5.90	5.55	6.82	6.64	4.59
30.0	201	6.27	6.27	7.29	6.72	4.79
31.0	198	6.43	6.83	7.48	6.55	4.87
33.0	193	6.44	6.84	7.45	6.41	5.04
35.0	188	6.25	6.53	7.19	6.27	5.05
37.0	183	6.16	6.19	7.07	6.22	5.19
39.0	179	6.07	6.00	6.78	6.17	5.32
41.0	175	5.87	5.69	6.42	6.04	5.33
44.0	169	5.76	5.50	6.24	5.97	5.35
47.0	164	5.46	5.13	5.79	5.74	5.19
50.0	158	5.23	4.82	5.53	5.46	5.11
53.0	154	5.08	4.62	5.23	5.31	5.15
56.0	149	4.74	4.25	4.87	4.97	4.87
59.0	145	4.71	4.23	4.81	4.98	4.81
62.0	141	4.64	4.19	4.75	4.92	4.70
65.0	137	4.63	4.25	4.61	4.93	4.68
68.0	133	4.63	4.39	4.77	4.89	4.46
71.0	130	4.59	4.54	4.65	4.84	4.33
74.0	126	4.65	4.71	4.73	4.84	4.33
77.0	123	4.64	4.87	4.75	4.73	4.20
80.0	120	4.60	4.84	4.77	4.60	4.20
83.0	117	4.65	4.85	4.72	4.69	4.36
87.5	113	4.68	4.87	4.67	4.68	4.50

EXPERIMENT NUMBER C.6Re = 21,000

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	314	6.68	6.87	6.60	6.76	6.48
2.5	310	6.48	6.65	6.46	6.49	6.31
3.5	306	6.30	6.43	6.30	6.36	6.10
4.5	303	6.10	6.17	6.05	6.21	5.97
7.5	293	6.07	6.05	6.05	6.20	5.98
10.5	284	6.07	6.04	6.04	6.21	5.97
13.5	275	6.04	5.98	6.05	6.16	5.96
16.5	267	6.00	5.87	6.07	6.15	5.92
19.5	259	6.01	5.82	6.10	6.19	5.92
23.0	250	6.11	5.84	6.24	6.37	6.00
25.0	244	6.17	5.75	6.40	6.59	5.94
27.0	239	6.56	6.00	6.90	7.10	6.20
28.0	237	7.06	6.74	7.61	7.67	6.22
29.0	234	7.62	7.58	8.42	8.22	6.27
30.0	231	8.21	8.58	9.28	8.59	6.38
31.0	228	8.54	9.21	9.91	8.62	6.43
33.0	223	8.76	9.76	10.29	8.55	6.44
35.0	217	8.66	9.63	10.21	8.33	6.49
37.0	212	8.40	9.10	9.88	8.14	6.46
39.0	207	8.21	8.60	9.50	8.12	6.63
41.0	202	7.81	8.04	8.90	7.82	6.46
44.0	196	7.46	7.59	8.37	7.58	6.49
47.0	190	7.17	7.17	8.00	7.19	6.30
50.0	185	6.82	6.75	7.53	6.84	6.14
53.0	180	6.60	6.52	7.19	6.53	6.18
56.0	174	6.36	6.10	6.77	6.11	6.36
59.0	170	6.27	6.16	6.60	6.07	6.27
62.0	165	6.14	6.03	6.40	5.88	6.24
65.0	160	6.68	6.13	6.29	5.77	6.14
68.0	156	6.21	6.11	6.44	5.83	6.48
71.0	152	6.34	6.16	6.50	5.98	6.72
74.0	148	6.25	5.94	6.44	5.88	6.71
77.0	144	6.23	5.95	6.44	5.89	6.61
80.0	140	6.14	5.84	6.24	5.88	6.56
83.0	136	6.14	5.84	6.32	5.84	6.54
87.5	130	6.24	5.94	6.50	5.96	6.42

EXPERIMENT NUMBER C.10Re = 30,000

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	266	7.98	8.38	7.73	8.07	7.74
2.5	263	7.78	8.09	7.61	7.90	7.51
3.5	261	7.59	7.92	7.36	7.72	7.36
4.5	258	7.39	7.68	7.26	7.55	7.07
7.5	251	7.37	7.61	7.24	7.58	7.07
10.5	244	7.36	7.51	7.32	7.54	7.06
13.5	237	7.38	7.49	7.35	7.59	7.11
16.5	231	7.38	7.45	7.45	7.58	7.04
19.5	225	7.45	7.43	7.54	7.64	7.17
23.0	218	7.47	7.36	7.64	7.72	7.15
25.0	214	7.46	7.29	7.83	7.68	7.04
27.0	209	7.85	7.58	8.54	8.14	7.13
28.0	207	9.14	8.99	10.08	9.42	8.08
29.0	205	9.82	9.86	11.12	9.99	8.33
30.0	203	10.56	10.68	12.00	10.81	8.75
31.0	201	11.00	11.06	12.54	11.51	8.90
33.0	196	11.32	11.32	13.01	11.72	9.22
35.0	192	11.17	11.11	12.79	11.49	9.28
37.0	187	10.76	10.60	12.31	10.99	9.14
39.0	183	10.22	10.01	11.47	10.39	8.99
41.0	180	9.76	9.62	10.64	9.91	8.87
44.0	174	9.47	9.36	10.24	9.54	8.74
47.0	170	9.27	9.18	9.89	9.20	8.80
50.0	165	8.93	8.83	9.47	8.73	8.68
53.0	160	8.56	8.48	9.02	8.26	8.40
56.0	156	8.29	8.20	8.67	7.90	8.40
59.0	152	8.12	7.93	8.40	7.75	8.40
62.0	148	8.04	7.86	8.32	7.53	8.45
65.0	145	8.06	7.95	8.25	7.55	8.52
68.0	141	7.97	8.04	8.17	7.39	8.29
71.0	138	7.84	7.82	7.96	7.46	8.13
74.0	135	7.87	8.10	8.00	7.37	8.03
77.0	132	7.85	8.20	7.95	7.37	7.90
80.0	129	7.84	8.21	7.84	7.40	7.91
83.0	126	7.95	8.20	8.10	7.49	8.03
87.5	122	8.02	8.17	8.08	7.73	8.08

EXPERIMENT NUMBER C.12Re = 34,400

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	252	8.55	8.57	8.56	8.71	8.36
2.5	249	8.65	8.64	8.61	8.81	8.54
3.5	247	8.75	8.74	8.69	8.87	8.70
4.5	245	8.52	8.47	8.37	8.73	8.50
7.5	238	8.48	8.32	8.35	8.67	8.58
10.5	232	8.41	8.42	8.19	8.49	8.52
13.5	226	8.46	8.48	8.33	8.43	8.61
16.5	220	8.49	8.42	8.32	8.58	8.66
19.5	215	8.56	8.54	8.41	8.59	8.71
23.0	208	8.69	8.51	8.58	8.84	8.85
25.0	205	8.89	8.90	8.76	9.79	8.82
27.0	201	9.24	8.36	9.39	10.27	8.94
28.0	199	10.02	9.32	10.49	11.03	9.24
29.0	197	10.78	10.34	11.50	11.83	9.45
30.0	195	11.74	11.64	12.88	12.70	9.77
31.0	193	12.33	12.49	13.69	13.21	9.94
33.0	189	12.85	13.17	14.45	13.39	10.39
35.0	185	12.88	12.94	14.17	14.02	10.38
37.0	181	12.14	12.34	13.75	12.29	10.34
39.0	177	11.27	11.06	12.54	11.27	10.21
41.0	174	10.63	10.15	11.61	10.63	10.14
44.0	169	10.08	9.81	10.90	10.16	9.44
47.0	165	9.72	9.40	10.38	9.78	9.33
50.0	160	9.16	8.87	9.66	9.18	8.92
53.0	157	8.87	8.57	9.37	8.86	8.70
56.0	153	8.58	8.29	8.85	8.58	8.60
59.0	150	8.54	8.32	8.63	8.58	8.65
62.0	146	8.48	8.40	8.47	8.33	8.72
65.0	143	8.53	8.55	8.35	8.24	8.98
68.0	140	8.63	8.65	8.24	8.26	9.19
71.0	137	8.70	8.68	8.34	8.47	9.31
74.0	134	8.70	8.91	8.34	8.42	9.26
77.0	131	8.75	9.06	8.28	8.41	9.23
80.0	128	8.76	9.10	8.31	8.43	9.20
83.0	126	8.78	9.11	8.34	8.51	9.17
87.5	122	8.79	9.13	8.33	8.56	9.15

EXPERIMENT NUMBER C.14Re = 39,800

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	237	9.97	10.22	10.14	10.04	9.45
2.5	235	9.65	9.83	9.71	9.77	9.28
3.5	233	9.26	9.43	9.39	9.55	9.07
4.5	231	9.06	9.04	9.04	9.32	8.86
7.5	225	8.99	8.86	8.93	9.27	8.90
10.5	220	8.95	8.80	8.89	9.17	8.92
13.5	214	8.91	8.73	8.80	9.19	8.94
16.5	209	8.94	8.78	8.80	9.21	8.98
19.5	204	9.06	8.99	9.01	9.29	8.96
23.0	198	9.30	9.22	9.32	9.53	9.14
25.0	195	9.64	9.87	9.70	9.84	9.15
27.0	192	9.80	10.21	9.84	9.87	9.26
28.0	190	10.91	11.63	11.36	11.18	9.48
29.0	188	11.96	12.73	12.83	12.32	9.96
30.0	186	12.91	13.70	14.21	13.25	10.50
31.0	185	13.56	14.09	15.86	13.72	10.58
33.0	181	14.02	14.77	16.39	14.02	10.90
35.0	177	13.78	14.54	15.86	13.77	10.96
37.0	173	13.14	13.59	14.83	13.30	10.83
39.0	170	12.38	12.66	13.57	12.73	10.57
41.0	167	11.81	11.84	12.78	12.33	10.29
44.0	163	11.44	11.32	12.08	12.12	10.23
47.0	159	11.17	11.06	11.77	11.74	10.11
50.0	155	10.83	10.56	11.32	11.50	9.93
53.0	151	10.38	10.09	10.87	11.00	9.55
56.0	148	10.10	9.85	10.40	10.70	9.47
59.0	145	9.47	9.20	9.66	10.09	8.92
62.0	142	9.37	9.07	9.52	9.90	8.98
65.0	139	9.37	9.10	9.35	9.88	9.14
68.0	136	9.39	9.06	9.26	9.90	9.33
71.0	133	9.44	9.23	9.14	9.94	9.48
74.0	130	9.55	9.47	9.14	9.85	9.75
77.0	128	9.52	9.51	9.12	9.85	9.61
80.0	125	9.58	9.45	9.27	9.93	9.69
83.0	122	9.63	9.45	9.32	9.97	9.78
87.5	118	9.65	9.52	9.36	9.91	9.80

EXPERIMENT NUMBER C.16Re = 45,200

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	233	11.22	11.43	11.07	11.09	10.72
2.5	231	10.92	11.11	10.70	10.81	10.41
3.5	229	10.59	10.82	10.40	10.58	10.23
4.5	227	10.30	10.50	10.22	10.22	10.00
7.5	221	10.22	10.41	10.19	10.23	9.93
10.5	216	10.16	10.25	10.16	10.19	10.06
13.5	210	10.11	10.18	10.18	10.25	10.10
16.5	205	10.19	10.09	10.17	10.30	10.19
19.5	200	10.26	9.98	10.23	10.45	10.21
23.0	194	10.49	10.16	10.57	10.74	10.31
25.0	191	10.76	10.36	10.79	10.96	10.38
27.0	188	11.21	10.93	11.55	11.53	10.48
28.0	186	12.29	12.48	12.63	12.49	11.54
29.0	185	13.19	13.36	14.19	13.43	11.77
30.0	183	14.28	14.31	15.95	14.64	12.23
31.0	181	14.93	14.64	17.05	15.58	12.44
33.0	177	15.30	14.91	17.56	15.96	12.78
35.0	173	15.02	14.63	17.04	15.38	13.01
37.0	170	14.47	14.11	16.12	14.67	12.98
39.0	167	14.01	13.82	15.09	14.23	12.88
41.0	164	13.61	13.52	14.38	13.60	12.93
44.0	160	13.00	12.98	13.65	12.84	12.53
47.0	156	12.55	12.60	12.96	12.40	12.22
50.0	152	11.93	12.06	12.24	11.73	11.70
53.0	148	11.27	11.47	11.37	11.02	11.22
56.0	145	10.76	11.20	10.88	11.05	10.87
59.0	141	10.39	11.17	10.51	10.69	10.11
62.0	138	10.23	11.10	10.29	10.44	10.00
65.0	135	10.43	11.05	10.21	10.35	10.10
68.0	132	10.35	10.97	10.23	10.15	10.21
71.0	130	10.34	10.85	10.24	10.16	10.32
74.0	127	10.33	10.76	10.25	10.01	10.54
77.0	124	10.42	10.77	10.22	9.96	10.55
80.0	122	10.39	10.72	10.34	10.04	10.45
83.0	119	10.44	10.69	10.60	10.12	10.35
87.5	116	10.56	10.60	10.73	10.63	10.30

EXPERIMENT NUMBER D.1Re = 11,900

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	329	3.99	4.28	3.76	3.70	4.19
4.5	316	3.98	4.28	3.78	3.70	4.17
7.5	303	3.96	4.26	3.74	3.69	4.14
10.5	291	3.93	4.17	3.74	3.67	4.14
13.5	280	3.92	4.15	3.76	3.67	4.10
16.5	269	3.90	4.08	3.71	3.70	4.10
19.5	259	3.87	3.97	3.67	3.67	4.14
22.5	250	3.87	4.00	3.75	3.64	4.09
24.0	245	3.76	3.81	3.60	3.62	4.02
25.5	241	3.70	3.64	3.53	3.63	4.00
26.2	239	3.76	3.94	3.45	3.65	3.99
27.0	236	4.18	4.99	3.83	3.97	3.92
28.5	231	5.28	5.83	5.67	5.34	4.27
30.0	226	5.99	6.32	6.54	6.31	4.81
31.5	220	6.32	6.47	6.90	6.64	5.25
33.0	215	6.35	6.36	6.68	6.75	5.59
34.5	210	6.05	6.13	6.03	6.47	5.58
36.0	205	5.77	5.92	5.61	6.06	5.49
37.5	201	5.44	5.62	5.15	5.67	5.33
39.0	197	5.16	5.25	4.86	5.34	5.20
42.0	190	4.89	5.00	4.54	5.11	4.89
45.0	183	4.68	4.72	4.50	4.88	4.61
48.0	176	4.32	4.32	4.10	4.48	4.38
51.0	170	4.19	4.12	4.05	4.21	4.36
54.0	164	4.07	4.07	3.87	4.08	4.24
57.0	159	3.95	3.99	3.78	3.99	4.04
60.0	154	3.81	3.94	3.60	3.88	3.83
63.0	149	3.71	3.89	3.49	3.78	3.68
66.0	145	3.66	3.88	3.46	3.68	3.61
69.0	141	3.67	3.95	3.57	3.57	3.61
72.0	137	3.68	4.02	3.57	3.49	3.53
75.0	133	3.73	4.06	3.66	3.48	3.72
78.0	130	3.68	3.82	3.62	3.31	3.86
82.5	125	3.69	3.86	3.69	3.43	3.86

EXPERIMENT NUMBER D.3Re = 16,400

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	297	5.04	5.37	4.92	5.00	4.87
4.5	286	5.01	5.27	4.90	5.01	4.87
7.5	275	5.02	5.25	4.88	5.05	4.92
10.5	265	4.97	5.12	4.81	4.97	4.97
13.5	256	4.96	5.09	4.80	4.99	4.98
16.5	247	4.95	5.00	4.82	4.97	5.03
19.5	238	4.98	5.01	4.84	4.96	5.12
22.5	230	5.02	5.03	4.91	4.95	5.17
24.0	226	5.00	5.02	4.87	4.90	5.20
25.5	222	5.01	5.10	4.76	4.94	5.23
26.2	220	5.01	5.28	4.66	4.95	5.15
27.0	218	5.41	5.70	5.37	5.53	5.04
28.5	214	6.56	6.35	7.89	6.72	5.28
30.0	209	7.55	7.45	8.78	8.12	5.85
31.5	204	8.01	7.97	9.13	8.60	6.33
33.0	200	8.01	8.13	8.61	8.54	6.74
34.5	195	7.55	7.77	7.48	8.07	6.81
36.0	191	7.03	7.27	6.54	7.34	6.60
37.5	187	6.50	6.74	6.06	6.78	6.41
39.0	183	6.08	6.12	5.76	6.29	6.19
42.0	177	5.82	5.91	5.68	6.02	6.06
45.0	171	5.66	5.61	5.42	5.85	5.76
48.0	165	5.59	5.51	5.43	5.75	5.66
51.0	160	5.28	5.25	5.28	5.45	5.16
54.0	155	5.25	5.20	5.26	5.36	5.19
57.0	150	5.26	5.19	5.24	5.29	5.31
60.0	145	5.16	5.08	5.18	5.18	5.19
63.0	141	4.97	4.78	5.09	5.06	4.97
66.0	137	4.88	4.86	4.97	5.03	4.65
69.0	133	4.78	4.81	4.92	4.92	4.48
72.0	130	4.80	4.89	4.99	4.77	4.56
75.0	127	4.83	4.86	4.99	4.72	4.78
78.0	124	4.80	4.72	5.12	4.68	4.68
82.5	119	4.76	4.62	5.05	4.71	4.67

EXPERIMENT NUMBER D.6Re = 22,200

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	248	6.38	6.92	6.31	5.87	6.44
4.5	240	6.31	6.73	6.22	5.85	6.43
7.5	232	6.28	6.62	6.22	5.86	6.41
10.5	224	6.20	6.48	6.15	5.74	6.42
13.5	217	6.14	6.35	6.08	5.69	6.44
16.5	210	6.11	6.24	5.97	5.71	6.50
19.5	204	6.06	6.12	5.94	5.71	6.46
22.5	198	6.00	5.97	5.81	5.64	6.58
24.0	195	5.86	5.79	5.70	5.56	6.39
25.5	192	5.80	5.77	5.77	5.63	6.04
26.2	191	5.75	5.76	5.54	5.47	6.22
27.0	189	6.34	6.60	6.26	6.15	6.36
28.5	186	7.80	7.80	8.69	8.20	6.63
30.0	183	9.00	9.00	10.02	9.59	7.28
31.5	180	9.74	9.74	10.95	10.30	7.85
33.0	176	9.98	9.98	11.21	10.43	8.27
34.5	173	9.68	9.68	10.42	10.20	8.27
36.0	170	9.15	9.15	9.53	9.72	8.05
37.5	167	8.52	8.52	8.60	9.15	7.69
39.0	164	7.92	7.92	7.98	8.37	7.33
42.0	159	7.55	7.55	7.48	7.95	7.21
45.0	154	7.41	7.41	7.28	7.67	7.34
48.0	150	7.24	7.24	7.06	7.54	7.25
51.0	146	7.04	7.04	6.91	7.28	7.28
54.0	142	6.83	6.83	6.48	7.00	7.33
57.0	138	6.63	6.18	6.36	6.77	7.19
60.0	134	6.29	6.09	6.13	6.58	6.36
63.0	131	6.08	5.84	5.98	6.36	6.13
66.0	128	5.98	5.73	5.98	6.13	6.10
69.0	125	5.80	5.64	5.83	5.88	5.85
72.0	122	5.71	5.54	5.88	5.56	5.83
75.0	119	5.55	5.47	5.61	5.44	5.69
78.0	117	5.43	5.47	5.99	5.05	5.24
82.5	114	5.29	5.39	5.89	4.80	5.08

EXPERIMENT NUMBER D.10Re = 29,600

1/d	t _g	h _{pm}	h _A	h _B	h _C	h _D
1.5	296	7.94	8.22	8.01	7.60	7.93
4.5	287	7.97	8.08	7.98	7.71	8.08
7.5	278	7.98	8.10	7.98	7.76	8.10
10.5	270	8.01	8.08	7.97	7.89	8.10
13.5	262	8.03	8.07	7.98	7.87	8.21
16.5	254	8.09	8.03	8.02	7.99	8.31
19.5	246	8.15	8.13	8.02	8.08	8.38
22.5	239	8.15	8.04	8.04	8.11	8.40
24.0	235	8.11	7.99	7.95	8.15	8.36
25.5	232	8.02	7.83	7.80	8.10	8.37
26.2	230	7.92	7.76	7.61	8.11	8.30
27.0	228	8.48	7.91	9.40	8.49	8.14
28.5	224	10.17	10.51	10.68	10.58	8.90
30.0	220	11.54	11.86	13.04	12.12	9.14
31.5	216	12.39	12.88	14.22	12.50	9.98
33.0	212	12.52	12.76	14.40	12.48	10.46
34.5	208	11.96	12.07	13.31	12.08	10.38
36.0	205	11.18	11.25	12.03	11.31	10.14
37.5	201	10.34	10.41	10.89	10.45	9.59
39.0	198	9.89	9.91	10.29	10.02	9.33
42.0	192	9.57	9.62	9.85	9.67	9.13
45.0	186	9.25	9.23	9.36	9.45	8.96
48.0	181	9.00	8.98	9.03	9.15	8.84
51.0	176	8.77	8.68	8.77	8.89	9.45
54.0	172	8.42	8.32	8.36	8.52	8.46
57.0	167	8.20	8.11	8.05	8.37	8.28
60.0	163	8.06	7.91	7.86	8.35	8.13
63.0	159	7.95	7.76	7.81	8.14	8.09
66.0	155	7.91	7.74	7.69	8.13	8.09
69.0	151	7.81	7.59	7.66	8.06	7.95
72.0	147	7.75	7.59	7.52	7.92	7.96
75.0	144	7.65	7.45	7.33	7.90	7.92
78.0	141	7.50	7.28	7.26	7.73	7.73
82.5	136	7.50	7.20	7.32	7.60	7.85

EXPERIMENT NUMBER D.12Re = 35,300

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	271	8.77	8.91	8.57	8.78	8.82
4.5	263	8.71	8.87	8.54	8.60	8.84
7.5	255	8.74	8.76	8.52	8.71	8.97
10.5	248	8.68	8.71	8.42	8.62	8.97
13.5	241	8.73	8.63	8.50	8.65	9.12
16.5	234	8.64	8.45	8.40	8.56	9.13
19.5	227	8.66	8.57	8.46	8.49	9.13
22.5	221	8.66	8.55	8.58	8.49	9.01
24.0	218	8.51	8.26	8.42	8.45	8.92
25.5	215	8.50	8.17	8.50	8.47	9.86
26.2	214	8.75	8.85	8.55	8.52	9.08
27.0	212	9.16	9.08	7.97	8.50	9.09
28.5	209	10.74	10.74	11.37	10.80	9.34
30.0	205	12.30	12.30	13.07	13.24	9.83
31.5	202	13.14	13.14	14.20	13.78	10.67
33.0	198	13.34	13.34	14.53	13.72	11.20
34.5	195	12.90	12.90	13.92	13.15	11.13
36.0	192	12.15	12.15	12.88	12.32	10.85
37.5	189	11.26	11.26	11.71	11.39	10.31
39.0	186	10.43	10.43	10.66	10.67	9.79
42.0	180	9.94	9.94	9.93	10.12	9.57
45.0	175	9.72	9.72	9.49	10.00	9.60
48.0	171	9.49	9.49	9.10	9.87	9.45
51.0	166	9.41	9.41	8.89	9.81	9.51
54.0	162	9.47	9.47	8.79	9.97	9.64
57.0	157	9.35	9.08	8.67	9.99	9.66
60.0	154	9.12	9.10	8.68	9.12	9.56
63.0	150	8.97	8.80	8.60	9.06	9.41
66.0	146	9.07	8.84	8.61	9.37	9.48
69.0	143	9.02	8.78	8.65	9.34	9.30
72.0	140	9.04	8.79	8.70	9.41	9.26
75.0	136	9.03	8.86	8.72	9.45	9.10
78.0	134	9.03	8.87	8.81	9.36	9.06
82.5	129	9.03	8.87	8.81	9.36	9.06

EXPERIMENT NUMBER D.14Re = 39,700

l/d	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	246	10.29	10.81	10.38	10.12	9.86
4.5	240	10.27	10.62	10.36	10.04	10.04
7.5	233	10.24	10.50	10.28	10.06	10.10
10.5	227	10.23	10.36	10.19	10.17	10.19
13.5	221	10.18	10.24	10.16	10.00	10.30
16.5	215	10.13	10.11	10.07	9.93	10.40
19.5	209	10.04	10.07	10.09	9.86	10.13
22.5	204	10.00	9.99	10.02	9.78	10.21
24.0	201	9.58	9.62	9.86	9.61	10.23
25.5	199	9.70	9.59	9.64	9.40	10.19
26.2	198	9.66	9.28	9.86	9.33	10.19
27.0	196	10.78	11.01	10.71	10.42	10.91
28.5	193	11.99	12.20	13.70	11.02	11.03
30.0	190	13.38	15.59	15.89	14.45	12.63
31.5	187	15.16	15.72	16.70	15.37	12.84
33.0	184	15.98	16.10	17.11	17.67	13.06
34.5	181	15.56	16.30	16.56	16.10	13.25
36.0	179	14.77	15.60	15.60	14.70	13.20
37.5	176	13.70	14.32	14.10	13.92	12.47
39.0	173	12.39	12.87	12.68	12.50	11.51
42.0	169	11.61	11.97	11.86	11.72	10.88
45.0	164	11.31	11.62	11.44	11.39	10.78
48.0	160	10.98	11.07	11.11	11.11	10.63
51.0	156	10.83	10.49	11.04	11.13	10.70
54.0	153	10.39	10.31	10.25	10.72	10.30
57.0	149	10.33	10.34	10.30	10.50	10.15
60.0	145	10.26	10.26	10.50	10.22	10.05
63.0	142	10.12	9.90	10.31	10.13	10.13
66.0	139	10.13	9.94	10.09	10.23	10.26
69.0	136	10.12	9.87	10.04	10.28	10.28
72.0	133	10.02	9.49	9.96	10.15	10.48
75.0	130	9.98	9.63	9.83	10.21	10.25
78.0	128	10.01	9.43	9.87	10.15	10.60
82.5	124	9.80	9.35	9.33	10.06	10.45

EXPERIMENT NUMBER D.17Re = 47,500

$1/d$	t_g	h_{pm}	h_A	h_B	h_C	h_D
1.5	223	11.23	11.92	11.62	10.65	10.88
4.5	217	11.13	11.65	11.33	10.61	10.97
7.5	212	11.08	11.47	11.21	10.62	11.04
10.5	207	11.09	11.64	11.08	10.61	11.07
13.5	202	11.11	11.62	11.12	10.59	11.16
16.5	197	11.14	11.66	11.04	10.60	11.31
19.5	193	11.17	11.78	10.97	10.57	11.45
22.5	188	11.19	11.81	10.86	10.53	11.59
24.0	186	11.12	11.80	10.73	10.37	11.62
25.5	184	11.07	11.65	10.62	10.48	11.60
26.2	183	11.14	11.66	10.76	10.55	11.52
27.0	182	12.66	13.76	13.56	11.49	11.82
28.5	179	13.68	14.86	15.17	12.47	12.26
30.0	177	15.49	17.02	16.94	15.00	13.01
31.5	174	16.73	18.21	17.45	17.52	13.79
33.0	172	17.10	18.52	17.59	17.92	14.41
34.5	169	16.51	17.66	17.02	17.19	14.20
36.0	167	15.50	16.33	15.99	16.01	13.68
37.5	165	14.36	15.03	14.75	14.90	12.78
39.0	163	13.80	14.19	14.14	14.38	12.50
42.0	159	13.15	13.45	13.39	13.72	12.09
45.0	156	12.75	13.10	12.88	13.19	11.84
48.0	152	12.46	12.79	12.44	12.94	11.71
51.0	149	12.06	12.50	11.85	12.46	11.41
54.0	146	11.63	12.09	11.25	11.97	11.19
57.0	143	11.20	11.94	10.69	11.36	11.06
60.0	140	10.83	11.45	10.21	10.98	10.77
63.0	137	10.58	10.70	10.62	10.52	10.50
66.0	134	10.59	10.77	10.51	10.37	10.70
69.0	132	10.59	10.88	10.38	10.16	10.94
72.0	129	10.61	11.02	10.26	10.12	11.04
75.0	127	10.58	11.23	10.13	9.96	11.02
78.0	124	10.49	11.24	9.99	9.89	10.85
82.5	121	10.57	11.60	9.89	9.94	10.84

APPENDIX B

Computer Programs

PROGRAM 7

CALCULATION OF VELOCITY AND TEMPERATURE PROFILES.

```

begin real r,h,EMF,tF,rhoa,v;

integer i,k,m;

switch s:=again;

integer array Is[1:20];

print 'Is1?r?',sameline,'Is10?h?', 'Is10?EMF?', 'Is10?tF?', 'Is10?rhoa?',
      'Is10?v?';

k:=1;

again : m:=1;

instring(Is,m);

m:=1;

outstring(Is,m);

for i:=1 step 1 until 4 do
begin read r,h,EMF;

tF:=33.848+44.672*(EMF)-0.623*(EMF)12;

rhoa:=(0.08071*492)/(460+tF);

v:=18.28*(h/rhoa)10.5;

print 'I1??',aligned(4,4),r,sameline,h,EMF,tF,rhoa,v,'I1??';

end;

k:=k+1;

if k<134 then goto again else

end;

```


PROGRAM 2

AVERAGE HEAT TRANSFER CALCULATIONS.

```

begin real W,tm,tx,rhoU,rhoD,VMU,VMD,Q,Re,G,MU;
  integer i,j,k,h,g,m;
  array v,tF,R,R1,rhoa,P,P1[1:22],S1,S2,S3,S4,S5[0:22],rm1[1:10],
    dp1,dp2[0:200],tG2[1:2],r[1:11];
  integer array Is[1:20];
  switch s:=L1,L2,L3,L4;

  g:=1;
  L4: m:=1;
  instring(Is,m);
  m:=1;
  outstring(Is,m);
  r[1]:=0.0;
  r[2]:=0.2;
  r[3]:=0.4;
  r[4]:=0.6;
  r[5]:=0.7;
  r[6]:=0.75;
  r[7]:=0.8;
  r[8]:=0.85;
  r[9]:=0.9;
  r[10]:=0.95;
  r[11]:=1.0;
  h:=0;
  L1: for i:=1 step 1 until 11 do
    begin read v[i+h],tF[i+h];
      rhoa[i+h]:=(0.08071*492)/(460+tF[i+h]);
      P[i+h]:=v[i+h]*rhoa[i+h]*r[i];
      P1[i+h]:=P[i+h]*tF[i+h];
      S1[i+h]:=S2[i+h]:=S3[i+h]:=S4[i+h]:=S5[i+h]:=0;
    end;
    for i:=1 step 1 until 10 do
      begin R[i+h]:=(P[i+h+1]-P[i+h])/10;
        R1[i+h]:=(P1[i+h+1]-P1[i+h])/10;
        rm1[i]:=(r[i+1]-r[i])/10;
      end;

```

PROGRAM 2(cont.)

```

    j:=0;
    k:=1;
L2:  for i:=0 step 1 until 10 do
      begin dp1[i+j+h]:=P[h+k+1]-i*R[k+h];
          dp2[i+j+h]:=P1[h+k+1]-i*R1[k+h];
      end;
      j:=j+11;
      k:=k+1;
      if k<10 then goto L2;
      j:=0;
      k:=1;
L3:  for i:=0 step 2 until 8 do
      begin S1[k+h]:=S1[k+h]+dp1[i+j+h]+4*dp1[i+j+h+1]+dp1[i+j+h+2];
          S2[h+k]:=S2[k+h]+dp2[i+j+h]+4*dp2[i+j+h+1]+dp2[i+j+h+2];
      end;
      S3[h+k]:=S3[h+k]+rm1[k]*S1[k+h]/3;
      S4[h+k]:=S4[h+k]+rm1[k]*S2[h+k]/3;
      j:=j+11;
      k:=k+1;
      if k<10 then goto L3;
      h:=h+11;
      if h<11 then goto L1;
      for i:=1 step 1 until 10 do
      begin S5[1]:=S5[1]+S3[i];
          S5[2]:=S5[2]+S3[i+10];
          S5[3]:=S5[3]+S4[i];
          S5[4]:=S5[4]+S4[i+10];
      end;
      W:=(S5[1]+S5[2])*(2*3.14159/144)/2;
      tG2[1]:=(2*3.14159/144/W)*S5[3];
      tG2[2]:=(2*3.14159/144/W)*S5[4];
      rhoU:=(0.08071*492)/(460+tG2[1]);
      rhoD:=(0.08071*492)/(460+tG2[2]);
      VMU:=(W*144)/(rhoU*3.14159);
      VMD:=(W*144)/(rhoD*3.14159);

```

PROGRAM 2(cont.)

```

Q:=W*(tG2[1]-tG2[2])*0.25*3600;
tm:=(tG2[1]-tG2[2])/ln(tG2[1]/tG2[2]);
tx:=((tm-32)/1.8)+273;
G:=(144*W)/3.14159;
MU:=(15010-7*(tx↑1.5))/(tx+124)*0.0672;
Re:=G/(6*MU);
printffl?Wl=?,sameline,S5[1]*(2*3.14159/144),ffs2?W2=?,
      S5[2]*(2*3.14159/144),ffs2?W=?,W,ffs2?tG1=?,tG2[1],
      ffs2?tG2=?,tG2[2],ffl?tm=?,sameline,tm,ffs2?VMU=?,
      VMU,ffs2?VMD=?,VMD,ffs2?Q=?,Q,ffs2?Re=?,Re,ffl??;
g:=g+1;
if g<180 then goto L4 else
end;

```

PROGRAM 3

CALCULATION OF LOCAL AND PERIPHERAL MEAN HEAT TRANSFER COEFFICIENTS.

```

begin real F,G,W,Q,T0;
    array AR,A,B,C,D,E[0:36],h,ha,hb,hc,hd,T,TD,S1,dx[1:36];
    integer i,b;
    switch L:=L1;
        b:=1;
L1: for i:=0 step 1 until 36 do
    begin read A[i];
    end;
    AR[0]:=0;
    for i:=0 step 1 until 36 do
    begin read B[i];
    end;
    for i:=0 step 1 until 36 do
    begin read C[i];
    end;
    for i:=0 step 1 until 36 do
    begin read D[i];
    end;
    dx[1]:=3;  dx[2]:=6;  dx[3]:=6;  dx[4]:=6;  dx[5]:=6;  dx[6]:=6;
    dx[7]:=6;  dx[8]:=6;  dx[9]:=4;  dx[10]:=4;  dx[11]:=4;  dx[12]:=4;
    dx[13]:=4;  dx[14]:=4;  dx[15]:=4;  dx[16]:=4;  dx[17]:=2;  dx[18]:=2;
    dx[19]:=4;  dx[20]:=4;  dx[21]:=4;  dx[22]:=6;  dx[23]:=6;  dx[24]:=6;
    dx[25]:=6;  dx[26]:=6;  dx[27]:=6;  dx[28]:=6;  dx[29]:=6;  dx[30]:=6;
    dx[31]:=6;  dx[32]:=6;  dx[33]:=6;  dx[34]:=6;  dx[35]:=6;  dx[36]:=9;
    read Q,W,T0;
    for i:=0 step 1 until 36 do
    begin E[i]:=((A[i]+B[i]+C[i]+D[i])-(4*358))/(4*1336);
    end;
    for i:=0 step 1 until 35 do
    begin S1[i+1]:=(E[i]+E[i+1])*dx[i+1]/2;
        AR[i+1]:=AR[i]+S1[i+1];
    end;

```

PROGRAM 3(cont.)

F:=Q/AR[36];

G:=72*F/3.14159;

print $\text{\textcircled{E}}\text{\textcircled{E}}1?B?$, (b+4), $\text{\textcircled{E}}\text{\textcircled{E}}1?F=?$, sameline, F, $\text{\textcircled{E}}\text{\textcircled{E}}G=?$, G,

$\text{\textcircled{E}}\text{\textcircled{E}}1?T$ h ha hb hc hd?;

for i:=1 step 1 until 36 do

begin T[i]:=T0-((AR[i]*F)/(900*W));

TD[i]:=T[i]-60;

h[i]:=E[i]*G/TD[i];

ha[i]:=(A[i]-358)*G/(TD[i]*1336);

hb[i]:=(B[i]-358)*G/(TD[i]*1336);

hc[i]:=(C[i]-358)*G/(TD[i]*1336);

hd[i]:=(D[i]-358)*G/(TD[i]*1336);

print $\text{\textcircled{E}}\text{\textcircled{E}}1??$, aligned(3,3), sameline, T[i], h[i], ha[i], hb[i], hc[i], hd[i];

end;

b:=b+1;

if b<17 then goto L1;

end;

PROGRAM 4

CALCULATION OF $(Nu/Pr^{0.4})_{av}$.

```

begin real SU, SU1, SU2, W, G, Dd;
  array h, t, tx[0:15], dx, L2, H, L3, T, Re, Mu, k, Pr, Nu[1:15];
  integer i, b;
  switch s:=L1;
    b:=1;
L1:  for i:=0 step 1 until 15 do
    begin read h[i];
    end;
    dx[1]:=4;  dx[2]:=4;  dx[3]:=4;  dx[4]:=4;  dx[5]:=4;  dx[6]:=4;
    dx[7]:=2;  dx[8]:=2;  dx[9]:=4;  dx[10]:=4;  dx[11]:=4;  dx[12]:=6;
    dx[13]:=6;  dx[14]:=6;  dx[15]:=6;
    SU:=0;
    SU1:=0;
    SU2:=0;
    read W, Dd;
    for i:=0 step 1 until 15 do
    begin read t[i];
    end;
    for i:=1 step 1 until 15 do
    begin SU:=SU+dx[i];
      L2[i]:=SU;
      SU1:=SU1+(h[i-1]+h[i])*dx[i]/2;
      H[i]:=SU1/L2[i];
      L3[i]:=L2[i]/2;
      SU2:=SU2+(t[i-1]+t[i])*dx[i]/2;
      tx[i]:=SU2/L2[i];
      T[i]:=(tx[i]-32)/1.8+273;
      Mu[i]:=(15010-7*(T[i]1.5))/(T[i]+124)*0.0672;
      k[i]:=(2.03310-5)*tx[i]+1.21310-2;
      G:=(144*W)/3.14159;
      Re[i]:=G/(6*Mu[i]);
      Nu[i]:=H[i]/(6*k[i]);
      Pr[i]:=(900*Mu[i])/k[i];
    print 'L1??', (Nu[i]/Pr[i]0.4), 'sameline, Re[i], Dd, L3[i];
    end;
    b:=b+1;
    if b<20 then goto L1;
end;
```

PROGRAM 5

LEAST SQUARES POLYNOMIAL FITS.

```

begin real array x,y,z[0:1339],a[1:7];
  real k,sigma;
  integer N,n,p,b;
  comment please insert F4/2,E2/1;
  read N;
    for n:=0 step 1 until N do
      begin read y[n],x[n];
      end;
  begin a[1]:=a[2]:=a[3]:=a[4]:=a[5]:=a[6]:=a[7]:=0;
    for n:=1 step 1 until 6 do
      begin LSQFIT(x,y,N,a,n);
      print %E14?ORDER=?,sameline,digits(1),n,%E12??;
      print %COEFFICIENTS?;
      for p:=1 step 1 until n+1 do
        print sameline,aligned(1,8),a[p];
      k:=0;
      for b:=0 step 1 until N do
        begin z[b]:=a[1]+a[2]*x[b]+a[3]*(x[b]2)+a[4]*(x[b]3)+a[5]*(x[b]4)
          +a[6]*(x[b]5)+a[7]*(x[b]6);
          k:=k+(y[b]-z[b])2;
        end;
      sigma:=(k/(N+1))0.5;
      print %E1?STANDARD ERROR?,sameline,aligned(1,8),sigma;
      end;
    end;
  end;

```

APPENDIX C

Bibliography

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