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THE EFFECT OF TURBULENCE PARAMETERS AND SUPPORT POSITION ON THE HEAT TRANSFER FROM SPHERES

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Abstract—Measurements are reported which show the influence of the turbulence intensity, the scale of turbulence, and the position of the support, on the average heat transfer from spheres to an air stream. The Reynolds number range was from about $3{\cdot}6 \times 10^3$ to $5{\cdot}2 \times 10^4$. The turbulence intensity and the scale of turbulence distributions downstream from three grids, behind which the heat-transfer measurements were later made, were measured for velocities from 4·6 to 18·3 m/s. The heat-transfer measurements showed that the average Nusselt number increased with the turbulence intensity, and with the ratio of the sphere diameter to the scale of turbulence for values up to at least five. Nusselt numbers, obtained using a crossflow support, were found to be about 10 per cent higher than those obtained using a rear support. Equations relating the average Nusselt number to the Reynolds number, for a low-turbulence free stream, are given.

NOMENCLATURE

D, sphere diameter;
$f(x)$, longitudinal two-point velocity correlation;
$g(x)$, transverse two-point velocity correlation;
L_f, longitudinal integral scale of turbulence, $L_f = \int_0^\infty f(x)\,dx$;
L_g, transverse integral scale of turbulence, $L_g = \int_0^\infty g(x)\,dx$;
$L_{g,i}$, a transverse scale of turbulence obtained by integrating $g(y)$ to the ith zero crossing;
M, grid mesh dimension;
Nu, Nusselt number, with property values evaluated at the film temperature;
Re, Reynolds number, with property values evaluated at the film temperature;
Tu, the component turbulence intensity in the x direction, $Tu = \sqrt{(u^2)}/U$;
T_s, temperature of the air stream;
u, fluctuating component of velocity in the x direction;
U, mean velocity in the x direction;
x, dimension in the direction of mean flow (Fig. 2);
y, dimension in the direction normal to the mean flow;
$\delta(\Delta T)$, maximum variation in ΔT, as determined by thermocouples at the sphere surface;
ΔT, the temperature difference between the free stream and the sphere surface at some thermocouple location;
$\overline{\Delta T}$, the average value of ΔT.

INTRODUCTION

In many engineering problems a knowledge of the heat or mass transfer from spherical bodies, particles, or droplets is required. To fulfill this need many experiments have been conducted. Most of the experiments have been aimed at determining the heat transfer between heated spheres and air streams. Unfortunately, there are considerable disagreements in the results.

This work was undertaken in an attempt to understand the reasons for the discrepancies in the measurements, and to determine as accurately as possible the dependence of the heat transfer on the Reynolds number, the turbulence intensity, the scale of turbulence, and the position of the sphere support. The measurements were carried out in an air stream.

In order to determine the influence of the turbulence in the free stream on the heat transfer from spheres, it was necessary to measure the turbulence intensity and scale of turbulence downstream from grids. These measurements were carried out over a large range of velocity, and for different types of grids. In order that the correlation of the Nusselt number with these quantities would be as reliable as possible, considerable care was taken in making the measurements. Therefore, it is hoped that these results alone would be a worthwhile addition to the available information on the change in turbulence quantities downstream from grids.

REVIEW OF PREVIOUS RESULTS AND OBJECTIVES

In order to show the pertinence of the present investigation, a brief literature survey will be given. This will exclude the measurements at Reynolds numbers lower than 10^3 since a complete and excellent review has already been given by Rowe, Claxton and Lewis [1]. In addition, Williams [2] has reviewed the measurements obtained prior to 1943. The correlation equation proposed by him is, despite the large disagreements in the data, probably the most commonly referenced in the modern literature, and in textbooks. The curve representing his equation is shown in Fig. 1.

Curves 2, 3, and 6 in Fig. 1 represent respectively the experimental data of Xenakis, Amerman and Michelson [3], Wadsworth [4], and Cary [5]. The data were obtained by integrating local heat-transfer rates measured at positions on the equators of spheres with crossflow supports. Cary's results can be seen to be in substantial disagreement with those of the other two. In addition, there is an uncertainty in the measured local heat-transfer rates in the wake region of the sphere since the presence of a crossflow support has been shown [6, 7] to appreciably affect the flow pattern, and thus presumably the heat transfer.

Curve 4 represents the measurements of Yuge [8] for Reynolds numbers larger than $1{\cdot}8 \times 10^3$. For lower Reynolds numbers a different equation was used. His data were obtained using spheres with small rear supports.

More recently Zhitkevich and Simchenko [9] used a sphere with a single crossflow support for Nusselt number measurements over a wide range of Reynolds numbers. The authors represented their data by a single equation over the whole range of Reynolds numbers investigated. From the data, it appears to be more appropriate to follow Yuge's example and use two equations, with the change in equations occurring at a Reynolds number of about $1{\cdot}7 \times 10^3$. Curve 5 in Fig. 1 appears to best represent their data over the Reynolds number range shown.

It is interesting that the Reynolds number, at which a change in the equation representing the data is needed, is approximately the same as that reported by Yuge. It seems possible that the change in the vortex shedding pattern, which occurs at about this Reynolds number [10], could be responsible.

Effect of turbulence parameters

A considerable amount of work has been done to determine the effect of turbulence intensity on the heat transfer from flat plates and cylinders. In general, no influence of the turbulence intensity of the free stream on the Nusselt number for a flat plate has been found except when a favorable pressure gradient is imposed. Qualitatively, but not quantitatively, this may be explained by Lin's theory [11].

A substantial increase in the Nusselt number with the turbulence intensity of the free stream

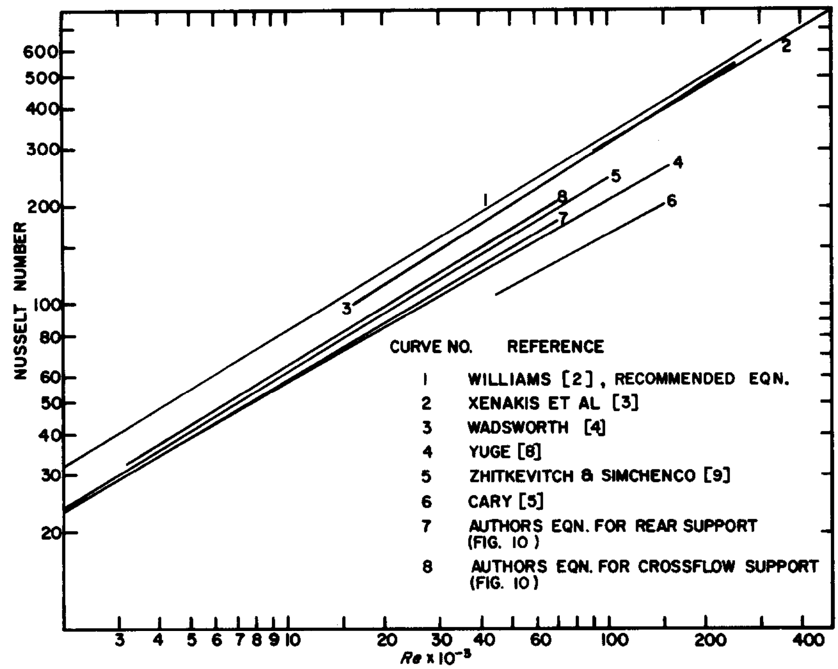


FIG. 1. A comparison of measurements of the average Nusselt number for spheres, made by various investigators.

has been found for cylinders, the increase being largest at the stagnation point. There is disagreement concerning the dependence of the Nusselt number on the turbulence intensity, but it has definitely emerged that the influence becomes more pronounced at higher Reynolds numbers, at least over the range of Reynolds numbers that has been investigated. Measurements have been reported by Comings, Clapp and Taylor [12], Maisel and Sherwood [13], Giedt [14], Van der Hegge Zijnen [15], Seban [16], and Kestin, Maeder and Sogin [17].

Van der Hegge Zijnen also used the ratio of the scale of turbulence to the cylinder diameter, L_f/D, in correlating his Nusselt number measurements. He found that there was an "optimum" value of L_f/D for which the increase in the Nusselt number with the turbulence intensity was a maximum. This has been attributed to resonance which is thought to occur when the frequency of the energy-containing eddies in the free stream is one-half the frequency at which the vortices were shed from the cylinder [18].

It appears that the large increase in the Nusselt number with turbulence intensity at the stagnation point may arise from the stretching of large scale vortices, as suggested by Sutera, Maeder and Kestin [19]. Although their analysis represented a highly idealized case, the predicted increases in the heat transfer and the surface shear were of the correct order of magnitude.

The effect of turbulence intensity on the heat transfer from spheres is not as well established. Loitzianski and Schwab [2] and Maisel and Sherwood [13] both found substantial increases in the average Nusselt number with increasing turbulence intensity of the free stream. However, the shape of the curve relating these two parameters was very different, and both sets of results appear to be only semi-quantitative [7].

In disagreement with the above results, Wadsworth [4] found no consistent dependence of the average Nusselt number on the turbulence intensity. Yuge [20] found a much smaller increase than did Loitzianski and Schwab. In sharp contrast to the measurements for circular cylinders, Short, Brown and Sage [21] found that the stagnation point Nusselt number *decreased* with increasing turbulence intensity in the range from 0·01 to 0·10. However, the Nusselt number in the wake was found to increase so sharply over this range of turbulence intensity that the net effect was a monotonical increase in the average Nusselt number.

Lavender and Pei [22] reported some measurements, near the conclusion of the present investigation, on the effect of turbulence intensity and scale of turbulence on the average Nusselt number for a sphere. In these measurements the sphere had a large brass crossflow support which was not guard heated. The measured Nusselt numbers were generally lower than Williams correlation and consistently higher than Yuge's measurements. A regression analysis showed that the Nusselt number increased with the parameter $Re \times Tu$, proposed by Van der Hegge Zijnen [15], and that the ratio of the scale of turbulence to the diameter of sphere "exhibited some significance". The magnitude of the influence was not specified.

From this brief survey it becomes evident that there remains considerable uncertainty in the dependence of the Nusselt number on the Reynolds number for the simple case of a sphere immersed in a moving air stream with a low turbulence intensity. In addition, the effect of the support position on the Nusselt number has not been determined. The more difficult problem of accurately determining the influence of the turbulence intensity has not been at all conclusively resolved, and nothing certain is known about the influence of the scale of turbulence on the Nusselt number, except that it is probably small. The objective of this investigation was, at least to some degree, to clarify each of these points.

APPARATUS AND PROCEDURE

The experiments were carried out in the Heat Transfer Laboratory low-turbulence wind tunnel. Air filters were installed to maintain a clean air stream in which turbulence measurements could be made. A schematic diagram of the test section is shown in Fig. 2. A slot was provided at the entrance to the test section into which either a turbulence-generating grid, or a blank which smoothly filled the slot, could be inserted. The air temperature in the test section was for all experiments between 26 and 50°C.

Three turbulence-generating grids were used. One, referred to in the text as a perforated plate, was constructed by punching square holes in a flat plate 0·193 cm in thickness. The mesh dimension was 2·54 cm, and the width of the strips between the holes was 0·635 cm. The grid solidarity was 0·440. The other two were made from commercially produced woven-wire grids with mesh dimensions of 1·91 cm and 1·27 cm, wire diameters of 0·357 cm and 0·159 cm, and solidarities of 0·340 and 0·234 respectively.

Two hot-wire probes were mounted in a probe holder which permitted the probes to be individually moved in arcs, with approximate radii of 38 cm, in a plane parallel to, and midway between the largest two surfaces of the rectangular test section. In order to make correlation measurements, a method was provided to accurately determine the distance between the hot wires.

The turbulence intensity measurements were taken with one of the probes located approximately at the center of the test section. Both a constant-current anemometer and a constant-temperature anemometer were used to measure the x component of the turbulence intensity. A more detailed description of the apparatus and procedure has been given elsewhere [7].

The longitudinal scale of turbulence, L_f, was measured by the single-wire method proposed by Townsend. A complete description of

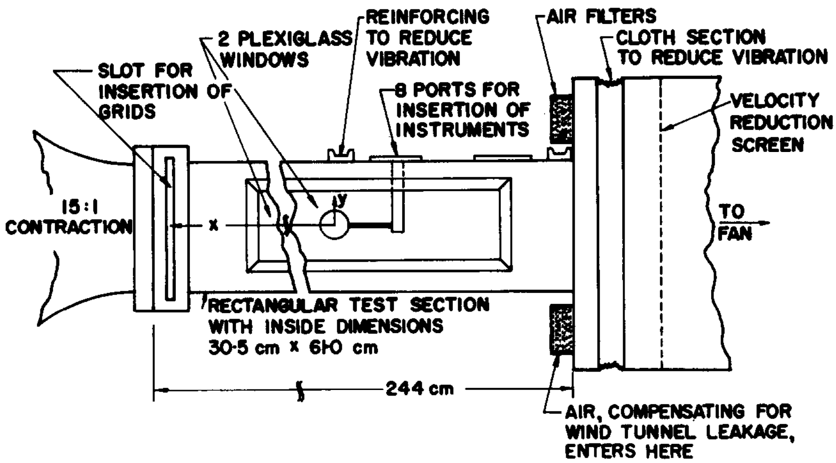


FIG. 2. Schematic drawing of test section.

the method, as well as some extensions to improve the accuracy in the measurement, have been given in [7].

Using the two probes in the holder described above, two-point velocity correlation curves, $g(y)$, were measured for values of y which were large enough to include the second zero crossing of $g(y)$. Transverse scales of turbulence $L_{g,1}$ and $L_{g,2}$ were defined by

$$L_{g,1} = \int_0^{y_1} g(\xi)\, d\xi$$

and

$$L_{g,2} = \int_0^{y_2} g(\xi)\, d\xi$$

where y_1 and y_2 are the probe separations at the first and second zero crossing of $g(y)$ respectively. $L_{g,1}$ and $L_{g,2}$ are only approximations of the desired transverse scale of turbulence, L_g, but it was not possible to accurately determine $g(y)$ for larger probe separations. This is one of the inherent problems in using this method of measurement. The details of the measurements may be found elsewhere [7].

In reference to the heat-transfer measurements from spheres, it has already been mentioned that there are large discrepancies in the results in the literature. These may be partly due to problems connected with design and instrumentation of the heat-transfer models. In view of this, a fairly detailed description of the present apparatus will be given.

A schematic drawing of the heat-transfer models has been given in Fig. 3. Three geometrically similar spheres, with respective diameters of 1·270, 2·540 and 5·080 cm, were constructed from solid blocks of copper. Each sphere was heated internally by passing current through a fine resistance wire which had been wound on a spool of boron nitride. The choice of sphere materials, and the design of the heater, was such that almost a uniform outside wall temperature was achieved in the experiments.

Heat conduction from the sphere via the stem was eliminated by using the guard heater shown in Fig. 3. Heat transfer from this heater to the wake of the sphere (which could substantially alter the heat transfer from the sphere if the air flowed back over the rear surface of the sphere) was reduced by coating the outside of the heater with a low thermal conductivity ceramic cement. The amount of current through the guard heater was adjusted until four thermocouples, located on the stem and on the back portion of the sphere, indicated that no appreciable amount of heat was flowing either into, or away from, the sphere. Only one of the thermocouples is shown in Fig. 3.

The surface temperature of the sphere was measured using thermocouples 1, 2, 3, 4 and 9, whose junctions were located at the positions indicated by the numbers. The fine lines perpendicular to the stem, passing through the thermocouple junction positions, represent circles drawn on the surface of the sphere. The angles to these circles, lying in the plane of the paper, are shown in the figure. The thermocouple junctions were placed in shallow 0·3-mm holes drilled in the sphere, and the copper surface was crimped around the junctions to hold them in place. The wires were placed in shallow grooves, represented by the heavy lines in Fig. 3, cut in the surface along the circles mentioned above. Upon reaching the line parallel to the support, the wires were turned and brought out along the stem by conducting them through another shallow groove. All the grooves containing the wires were smoothly filled with high thermal conductivity copper oxide cement. The lead wires were tied to the outside of the stem with thread, and a thin coating of heat-resistant low-conductivity paint was applied to smooth the surface.

The stem diameters, d, were originally very close to 0·1 D. After the thermocouple wires were brought out along the stems, tied down with thread, and coated with paint, the d/D ratios were approximately 0·17, 0·13 and 0·11 for D values of 1·270, 2·540 and 5·080 cm respectively.

The completed spheres were highly polished and a thin coating of chromium was evaporated onto the surfaces. This ensured that the surface emittance was low and essentially unchanging with time. The emittance was found by direct measurement [7] to be 0·10.

The sphere was held in the test section in either of two configurations: (1) the sphere support was parallel to the free stream and behind the sphere, or (2) the support was perpendicular to the direction of the free stream. The general procedure in carrying out the heat-transfer measurements is probably well known

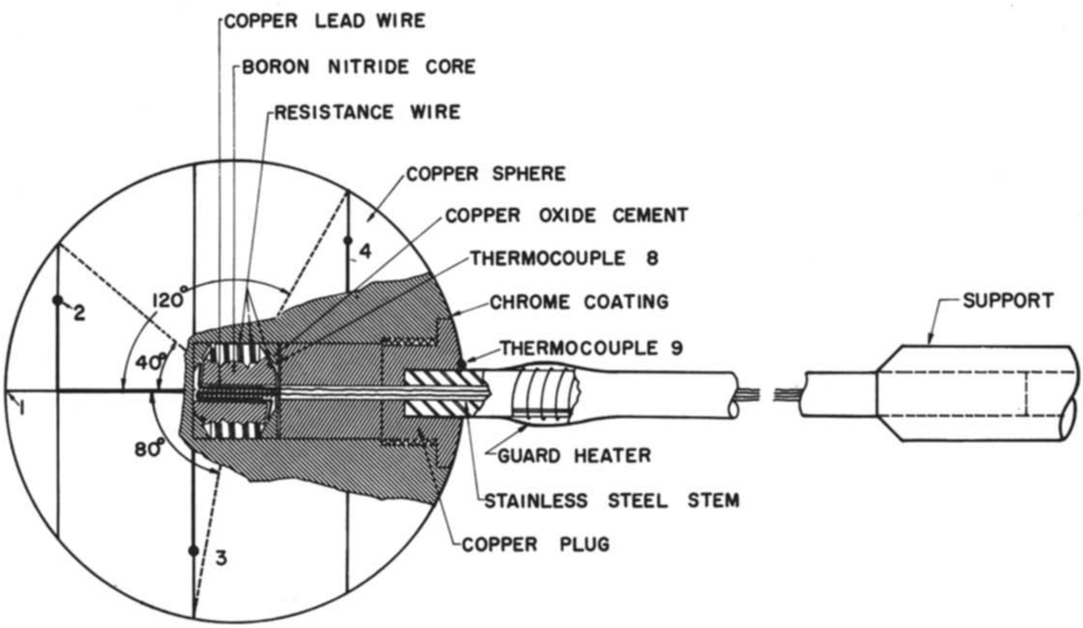


FIG. 3. Schematic drawing showing construction of heat-transfer models.

to the reader. A detailed account may be found in [7]. It is only important to note here that care was taken in the measurements that the free-stream temperature, the temperature of the sphere, and the free-stream velocity were held constant over a long period of time preceding each measurement. Also, visual observations revealed that there were no noticeable sphere vibrations during the experiments.

The power dissipation in the sphere heater was determined by measuring the voltage drop across, and current through, the heater. The current, supplied from a battery, was measured to an accuracy of better than 0·1 per cent. For the two largest spheres the voltage drop was also determined to an accuracy of about $\pm 0{\cdot}1$ per cent; due to an appreciable lead wire resistance, the voltage drop across the heater in the smallest sphere was accurate to only about $\pm 0{\cdot}5$ per cent.

Only a small temperature difference between the sphere and the free stream was maintained in these experiments ($5{\cdot}1$ degC $< \overline{\Delta T} <$ $12{\cdot}2$ degC). There was a maximum error of about 2 per cent in determining $\overline{\Delta T}$. Measurements from the sphere thermocouples indicated that the variation in the surface temperature usually amounted to less than 1 per cent of $\overline{\Delta T}$.

With the heated sphere in the moving air stream, the quantities required to calculate the energy dissipation in the sphere heater, the temperature difference between the sphere surface and the air stream, and the heat loss by radiation (calculated in the usual way [23]), were determined. With these, and the property values [24] evaluated at the film temperature, the Nusselt number was calculated. The Reynolds number was computed using the same property value equations and the free-stream velocity (determined using a pitot tube).

Based on the above error estimates, the maximum error in the Nusselt number determination was, in the worst case, about 2·6 per cent. The scatter in the data was much smaller than this. The maximum possible error in the Reynolds number was less than 1 per cent.

No corrections have been applied to account for the increase in velocity, at the position of the model, due to blockage of the test section. Applying the correction equation recommended by Pankhurst and Holder [36], it can be seen that at the largest section of the largest sphere (with a rear support) the free-stream velocity increased by only approximately 0·1 per cent.

RESULTS

Turbulence intensity measurements

The turbulence intensity measurements obtained using the constant-current anemometer are shown in Fig. 4. The turbulence intensity may be seen to depend strongly on the solidarity of the grid, and the grid geometry. However, essentially no dependence of the turbulence intensity on the velocity of the free stream was found. For velocities of 9·1 and 18·3 m/s the results for each grid were found to agree within 5 per cent. The slightly poorer agreement in the measurements at a velocity of 4·6 m/s, at large distances from the grid, was probably due to the inaccuracy of the correction equation used [7] to account for the decrease in the gain of the amplifier in the constant-current anemometer at low frequencies.

If the measured turbulence intensities are to be correct, it is necessary that the length of the hot-wire is much smaller than the integral scale of turbulence. This criterion was not always fulfilled in the present measurements. Therefore, the correction equation derived by Skramstad [25] was applied to the turbulence intensities represented by the solid lines in Fig. 4. The corrected measurements are represented by the dotted lines. The scale of turbulence data, required in the application of the Skramstad correction, were those reported in the following section.

Frenkiel [26] has postulated that far downstream from a grid the turbulence intensity should decay proportionally to $(x/M)^{-5/7}$. The present measurements showed this to be approximately true for values of x/M greater than about fifty. A line with a slope of $-\frac{5}{7}$ has been drawn in Fig. 4.

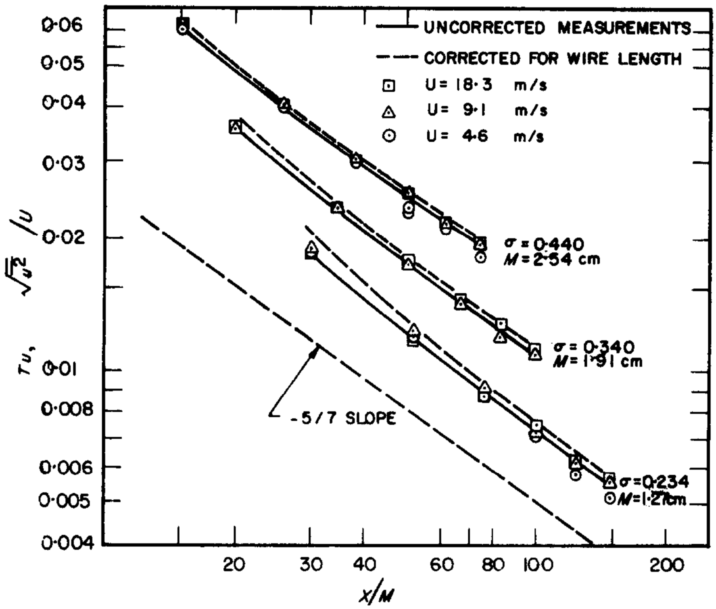


FIG. 4. Turbulence intensity measurements downstream from grids, obtained using a constant-current anemometer.

The solid lines from Fig. 4 have been transferred to Fig. 5. However, in this figure, the data points were obtained using a constant-temperature anemometer. For turbulence intensities greater than 0·01 the independent measurements agreed within 5 per cent, and there was agreement to within 10 per cent at the lowest measured turbulence intensity (0·005). In addition, it may be seen that there is no consistent dependence of the turbulence intensity on the free-stream velocity. The data points in Fig. 5 have not been corrected to account for the finite wire length. However, the wire was of the same length as that used to obtain the measurements reported in Fig. 4.

It was found that equations of the form

$$Tu = A\left(\frac{x}{M} - \frac{x_0}{M}\right)^{-n} \quad (1)$$

fit the experimental data very well over the limited range of x/M in the present experiments. The constants required to fit the data, which have been corrected to account for the finite wire length, are tabulated below.

Table 1. Constants in equation (1) for different grids

M	A	x_0/M	n
2·54	0·314	3	0·645
1·91	0·203	6	0·633
1·27	0·168	9	0·686

Measurements indicated that the free stream turbulence intensity, with no grid, varied between 0·0005 and 0·002 depending on the fan speed in the wind tunnel. This variation was not surprising since Schubauer and Skramstad [27] showed previously that the turbulence intensity in a low-turbulence wind tunnel depends on the operating noise of the tunnel. For all the test conditions, the average free-stream turbulence intensity, with no grid, was about 0·0015.

Grant and Nisbet [28] have reported that there are substantial variations in the turbulence

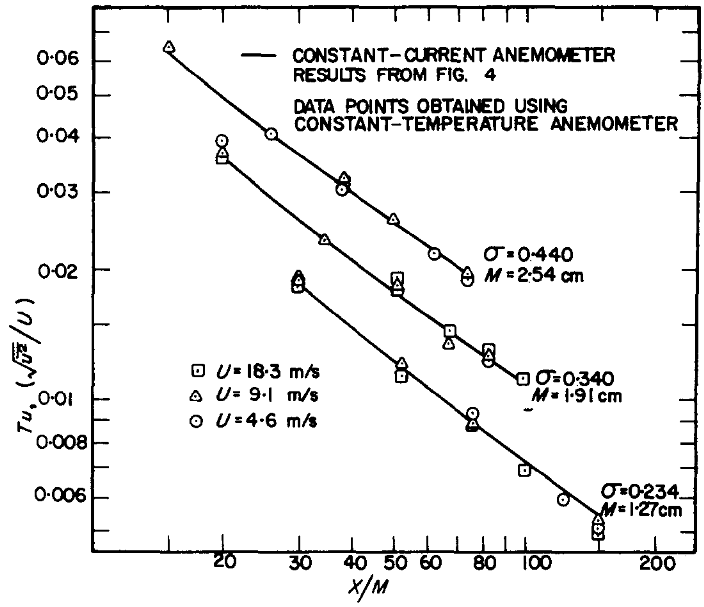


FIG. 5. Comparison of the turbulence intensity measurements obtained using constant-current and constant-temperature anemometers.

intensity, downstream from grids, in planes parallel to the grid. In the present experiments these variations were not found. This is shown in Fig. 6 for one set of conditions.

There are very few measurements in the literature for grids geometrically similar to the ones used in these experiments. The comparison of the available measurements has been given in Fig. 7. A more extensive comparison including other types of grids, has been given in reference [7].

Scale of turbulence measurements

The measurements of the integral scales of turbulence, L_f, in the longitudinal direction behind the three grids are presented in Fig. 8. The measurements behind the perforated plate ($M = 2{\cdot}54$ cm) indicated that the scale of turbulence did not change with velocity over the range investigated. On the other hand, the measurements behind the woven-wire grids ($M = 1{\cdot}91$ cm and $M = 1{\cdot}27$ cm) showed a definite, but not completely consistent, dependence on velocity. Repeated measurements confirmed the fact that the data for different velocities did indeed lie on separate curves. Therefore, in Fig. 8, solid lines have been drawn through the data points obtained for each velocity for both of the woven-wire grids. The broken lines labeled "average for all velocities" are curves which best fit all the data for each grid. The curves labeled "+10%" and "−10%" lie respectively 10 per cent above and below this average curve. It may be seen that all but two of the thirty-six measurements for the 1·91 and the 1·27 cm grids lie within ±10 per cent of the average curve.

The results of the measurements of the transverse scale of turbulence L_g, behind the perforated plate grid are shown in Fig. 9. As pointed out earlier, two scales of turbulence, $L_{g,1}$ and $L_{g,2}$, corresponding to integration of the correlation curve to the first and second zero crossing, have been used.

Very close agreement of the present $L_{g,2}$ measurements [7] with the corresponding

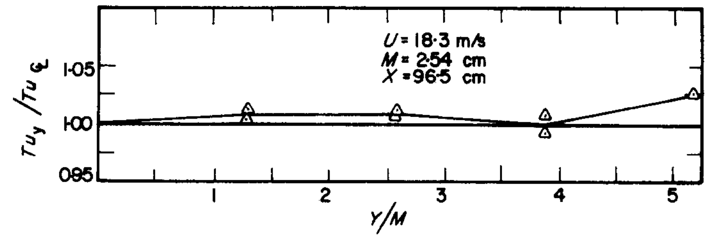


FIG. 6. The variation of turbulence intensity with distance from the centerline of the test section.

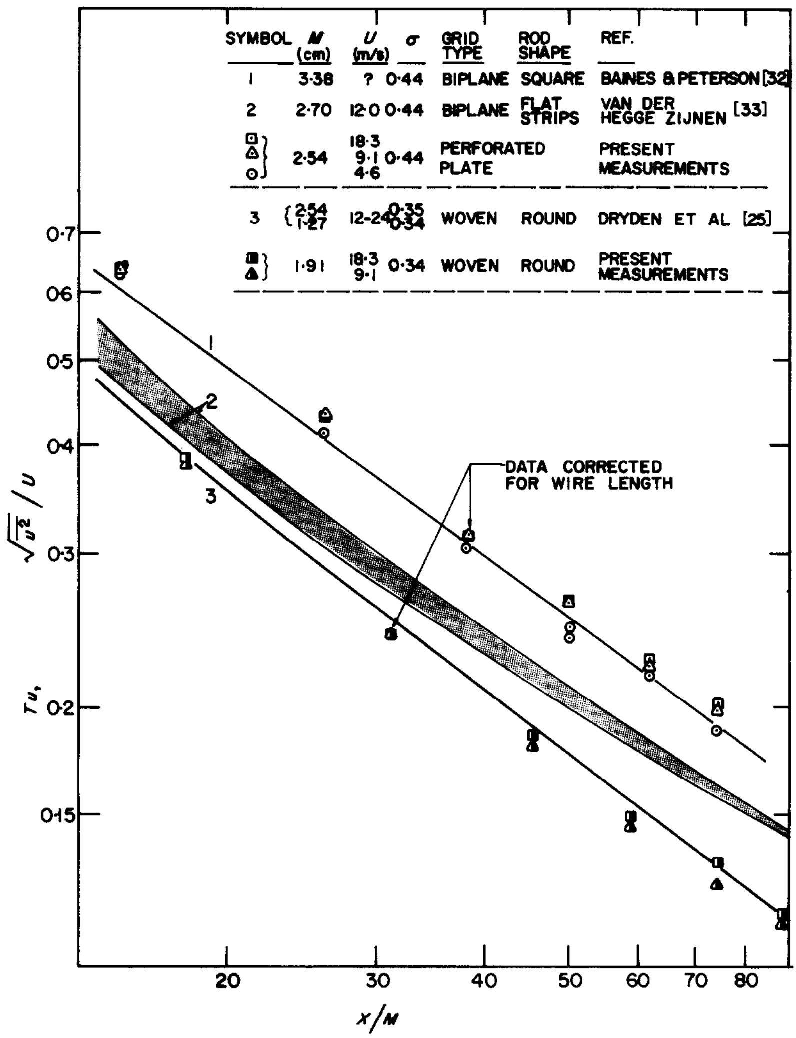


FIG. 7. Comparison of various turbulence intensity measurements.

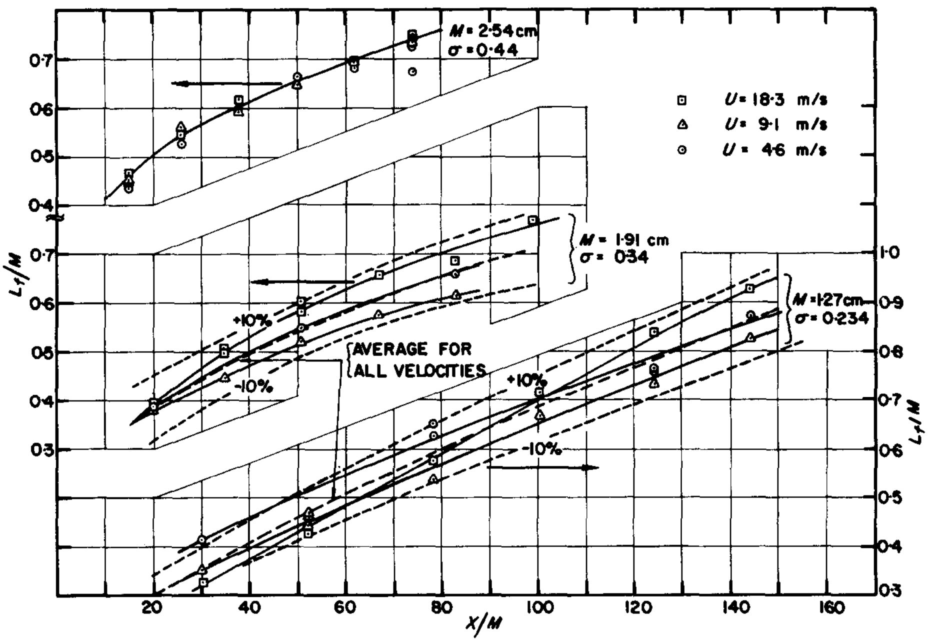
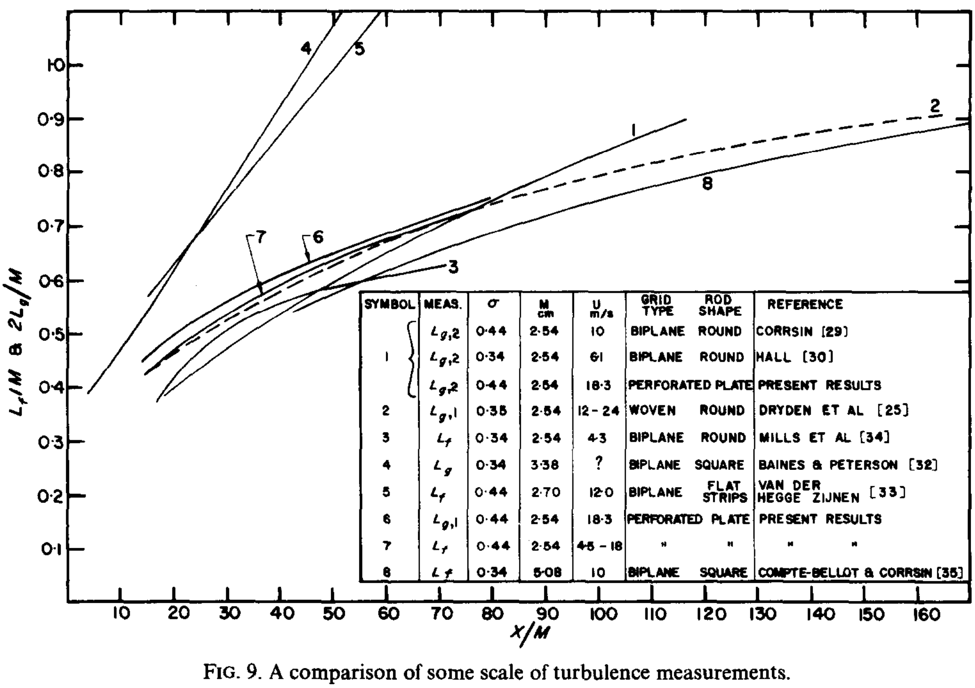


FIG. 8. Measurements of the longitudinal scale of turbulence, L_f.



SYMBOL	MEAS.	σ	M cm	U m/s	GRID TYPE	ROD SHAPE	REFERENCE
1	$L_{g,2}$	0·44	2·54	10	BIPLANE	ROUND	CORRSIN [29]
	$L_{g,2}$	0·34	2·54	6·1	BIPLANE	ROUND	HALL [30]
	$L_{g,2}$	0·44	2·54	18·3	PERFORATED PLATE		PRESENT RESULTS
2	$L_{g,1}$	0·35	2·54	12–24	WOVEN	ROUND	DRYDEN ET AL [25]
3	L_f	0·34	2·54	4·3	BIPLANE	ROUND	MILLS ET AL [34]
4	L_g	0·34	3·38	?	BIPLANE	SQUARE	BAINES & PETERSON [32]
5	L_f	0·44	2·70	12·0	BIPLANE	FLAT STRIPS	VAN DER HEGGE ZIJNEN [33]
6	$L_{g,1}$	0·44	2·54	18·3	PERFORATED PLATE		PRESENT RESULTS
7	L_f	0·44	2·54	4·5 – 18	"	"	" "
8	L_f	0·34	5·08	10	BIPLANE	SQUARE	COMPTE-BELLOT & CORRSIN [35]

FIG. 9. A comparison of some scale of turbulence measurements.

measurements of Corrsin [29] and Hall [30] was found. Therefore, a single curve has been used to represent the results of the three investigations. The $L_{g,1}$ measurements agreed closely with the measurements of $L_f/2$ ($L_g = \frac{1}{2}L_f$ for isotropic turbulence [31]) which were transferred to this figure from Fig. 8.

Several curves representing the results of other investigators, who used grids with about the same mesh size as the perforated plate, have also been given in Fig. 9. The reason for the large discrepancy between the results obtained by Baines and Peterson [32] (curve 4) and Van der Hegge Zijnen [33] (curve 5), from the other investigators, is not known. However, this figure gives some idea of the uncertainties existing in the published scale of turbulence measurements.

Heat-transfer results

Measurements in a low-turbulence stream. The average Nusselt number measurements using the three spheres with rear supports, for velocities from 4·3 to 18·9 m/s, are grouped around the lower curve in Fig. 10. All these measurements were made in the tunnel without a turbulence-generating grid. The average turbulence intensity was about 0·0015. The data for this, and the other conditions discussed below, are given in [7]. Flow studies discussed in [6, 7] indicate that all measurements occurred in the subcritical range.

The constants, in the two types of equations usually used to represent the dependence of the Nusselt number on the Reynolds number, were determined using the available regression analysis subroutine from the computer library at the University of Minnesota. The average deviation of the data from the equation

$$Nu = 2{\cdot}0 + 0{\cdot}210\, Re^{0{\cdot}606}$$

was 0·8 per cent. The maximum deviation was 2·0 per cent, and the standard error in the Reynolds number exponent was 0·0027.

The equation

$$Nu = 0{\cdot}257\, Re^{0{\cdot}588} \qquad (2)$$

was found to fit the data slightly better. The average deviation in this case was 0·7 per cent, the maximum deviation was 1·9 per cent, and the standard error in the exponent was 0·0022.

The upper curve in Fig. 10 represents the data obtained for the crossflow support configuration. The corresponding equations fitting these data were

$$Nu = 2{\cdot}0 + 0{\cdot}244\, Re^{0{\cdot}600}$$

and

$$Nu = 0{\cdot}291\, Re^{0{\cdot}585} \qquad (3)$$

where the average deviation of the data from either equation was 0·8 per cent. The maximum deviations were 2·3 and 2·4 per cent respectively, and the standard error in both of the Reynolds number exponents was 0·0040.

From these results it is clear that the presence of the crossflow support increased the Nusselt number by approximately 10 per cent in the range of Reynolds numbers investigated. The increase probably arises from the flow disturbance produced by the crossflow support.

For a comparison with the results of other investigators, equations (2) and (3) are plotted in Fig. 1. The data for the rear support configuration are shown to agree very well with Yuge's results. Curve 5, representing the data of Zhitkevich and Simchenko for a sphere with a crossflow support, corresponds quite closely to the results obtained from these experiments when a crossflow support was used.

Effect of turbulence intensity and scale of turbulence. Figures 11(a–d) present the dependence of the average Nusselt number on the turbulence intensity at Reynolds numbers of $3{\cdot}60 \times 10^3$, $1{\cdot}40 \times 10^4$, $2{\cdot}70 \times 10^4$ and $5{\cdot}20 \times 10^4$ respectively. The turbulence intensities were evaluated from equation (1), where the x value used was the distance from the grid to the center of the sphere. Different symbols on the graphs, defined on Fig. 11(a), represent different ranges of D/L_f, the ratio of the sphere diameter to the longitudinal scale of turbulence. The L_f values were taken from the curves

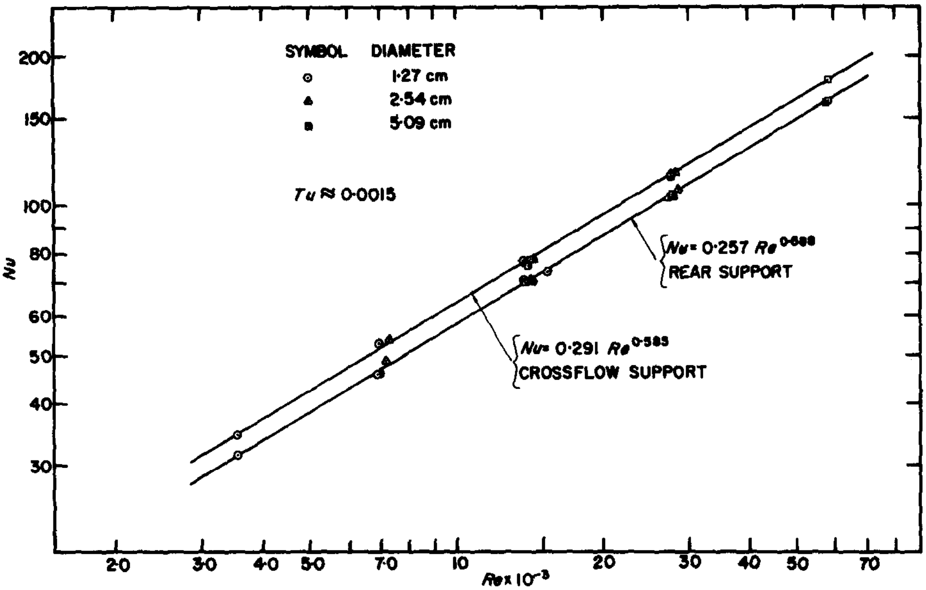


FIG 10. Nusselt number measurements in a low-turbulence stream using two methods of sphere support.

presented in Fig. 8; the x values used were the same as for the turbulence intensity determination. The figures present the measurements corresponding to both support configurations. The Nusselt numbers for the rear support geometry always lie below those obtained using the crossflow support.

The measured Reynolds numbers were not precisely those shown on the graphs. Therefore, each measured Nusselt number, Nu_m, was altered to account for the discrepancy between the desired Reynolds number, Re, and the measured Reynolds number, Re_m, by the following equation, which is based on equation (2):

$$Nu = Nu_m \left(\frac{Re}{Re_m}\right)^{0\cdot 588}$$

Figure 11(a) presents the results for the lowest Reynolds number. For the rear support geometry, the effect of the turbulence intensity is seen to be greatest in the range from 0 to 0·02. The sharp increase in the Nusselt number with turbulence intensity at low values of turbulence intensity was observed previously by Van der Hegge Zijnen who measured the effect of turbulence intensity on the heat transfer from circular cylinders ([15], Fig. 1). The reason for this, or even the portion of the surface (wake, stagnation point area, etc.) responsible for it, is not known. However, it is interesting to note that the effect disappears when the sphere has its support normal to the stream, as seen in the upper portion of the figure. Also, reference to Figs. 11(b, c, d) shows that the effect becomes smaller at larger values of Reynolds number. Figure 11 also shows that the presence of the crossflow support resulted in an increased Nusselt number over the range of turbulence intensities investigated.

Figure 11(b) presents results similar to those in Fig. 11(a) except that at this Reynolds number a large range of the D/L_f ratio was obtained as a result of being able to use all three spheres. In addition, all three grids were used.

Turning attention first to the data points in Fig. 11(b) corresponding to the rear support geometry, it is evident that the solid curve represents the data quite well over the whole

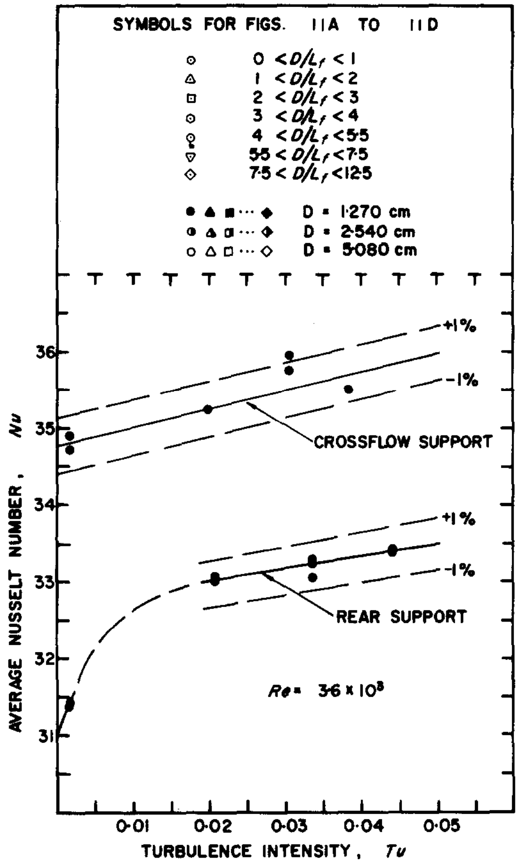


FIG. 11(a). The dependence of the average Nusselt number on the turbulence intensity for $D/L_f < 1$ and $Re = 3{\cdot}6 \times 10^3$.

range of turbulence intensity. It shows that the Nusselt number was increased by approximately 9 per cent as a result of increasing the turbulence intensity from near zero to 7 per cent. The broken lines, labeled "+1%" and "−1%" have been drawn to show that all the data are within ±1 per cent of the solid line. However, a closer look reveals that this scatter is not entirely random, but depends on the D/L_f ratio.

To show this more clearly, three cross plots were made at turbulence intensity values of 0·02, 0·04 and 0·07 respectively. This was done by extrapolating the data points near these values to the desired turbulence intensity along lines parallel to the solid line. The results are shown in the upper portion of Fig. 12. A small, but definite increase in Nusselt number with increasing D/L_f values can be seen. In addition, the rate of increase is larger with higher values of turbulence intensity. Therefore, in Fig. 11(b), the data should really be represented by a family of curves for different ratios of D/L_f. The broken line labeled "Extrapolated curve for $D/L_f \rightarrow 0$" would be the lowest curve in the family, and corresponds to the case where the sphere diameter is much smaller than the scale of turbulence.

The measurements obtained at the same Reynolds number using crossflow supports are indicated in the upper portion of Fig. 11(b). In this case, the measurements were found to lie mostly within a ±1 per cent band about the mean curve for each sphere, and again there is a definite trend with the D/L_f ratio. However, as opposed to the rear support geometry, a different curve must be drawn for each sphere. It was noted earlier that the stem-to-sphere diameter ratio, d/D, varied as a result of the thermocouple wires that were brought out along the stem. The d/D ratios for the three spheres are shown in the figure. Increasing this ratio appeared to appreciably increase the Nusselt number, especially at the higher values of turbulence intensity.

For $Re = 2{\cdot}70 \times 10^4$, the measurements were obtained using the two largest spheres. Similar results to those discussed above are presented in Fig. 11(c). For the rear support geometry, the increase in the Nusselt number was about 13 per cent for an increase in turbulence intensity to 7 per cent. The data can be seen to lie mostly within ±1 per cent of an average curve. However, the cross plots in the lower portion of Fig. 12 show that, once again, the scatter is not random but rather depends on the D/L_f ratio. At this Reynolds number, however, the increase in the Nusselt number with D/L_f is more important. A family of curves for different D/L_f ratios would again be needed to more accurately represent the data in Fig. 11(c). The lowest

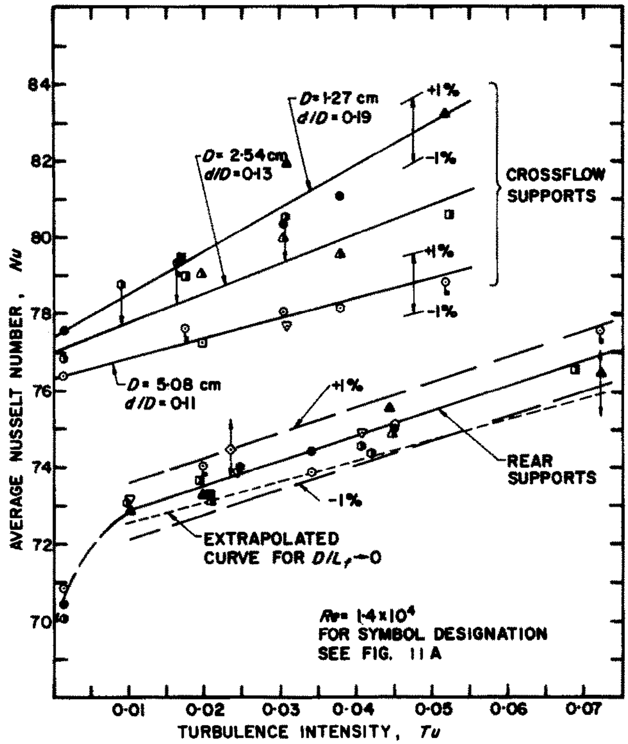


FIG. 11(b). The dependence of the average Nusselt number on the turbulence intensity for various D/L_f values and $Re = 1{\cdot}4 \times 10^4$.

curve in the family has been shown in the figure as a broken line.

The highest Reynolds number obtainable was $4{\cdot}9 \times 10^4$. Figure 11(d) shows that at this Reynolds number the results are similar to those obtained for lower Reynolds numbers. However, the increase in turbulence intensity to 5 per cent now results in approximately a 17 per cent increase in the Nusselt number. This may be caused by the fact that the separation line, though still indicating subcritical flow, started to exhibit fluctuations [6].

At this point it may be interesting to recall that Van der Hegge Zijnen [15] found an "optimum" value of the ratio L_f/D for which the heat transfer from circular cylinders, for a given turbulence intensity and Reynolds number, was a maximum. The optimum L_f/D value was about 1·6.

Hinze [18] showed analytically that there would be resonance between the energy-containing eddies and the shedding frequency when $L_f/D \approx 1{\cdot}2$. Using Hinze's method, and assuming that the shedding frequency for a sphere is ten times that for a circular cylinder [10], one obtains a value of $L_f/D \approx 0{\cdot}12$ as the condition for resonance. Therefore, if this hypothesis is correct, a maximum in the Nusselt number for a given Reynolds number and turbulence intensity should occur at about $D/L_f \approx 8{\cdot}4$. The number of data points in Fig. 12 are not sufficient to confirm the existence of the maximum. However, this would explain the fact that Van der Hegge Zijnen found an increase in the Nusselt number with D/L_f for cylinders only up to $D/L_f = 0{\cdot}63$ while the results of this investigation show the increase to continue up to at least $D/L_f = 5$.

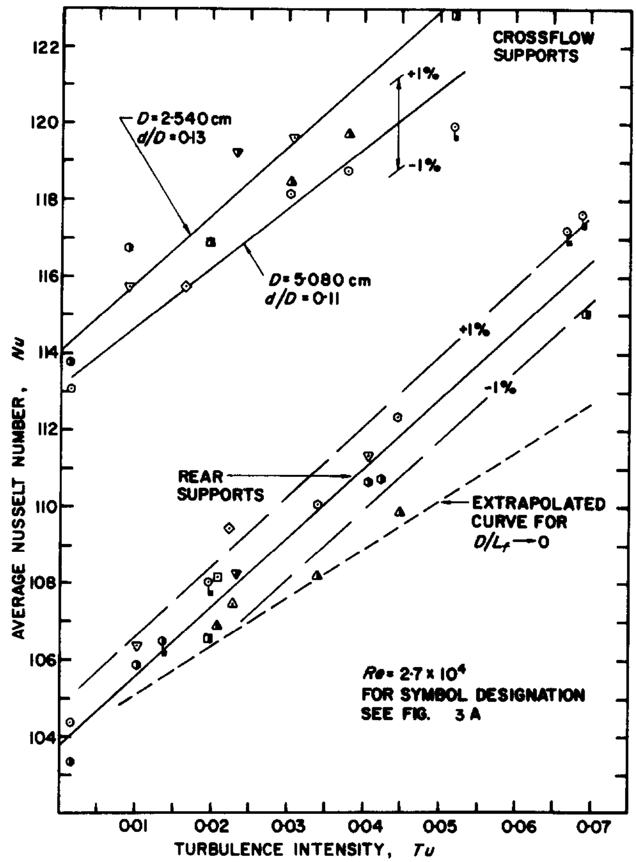


FIG. 11(c). The dependence of the average Nusselt number on the turbulence intensity for various D/L_f values and $Re = 2{\cdot}7 \times 10^4$.

Another interesting point of comparison is the fact that Van der Hegge Zijnen found the increase of the Nusselt number with D/L_f to be greater at higher turbulence intensities and higher Reynolds numbers, exactly as shown in Fig. 12.

Finally, it was shown in Fig. 9 that Van der Hegge Zijnen's scale of turbulence measurements were considerably higher than the corresponding measurements made in this investigation for quite similar grids. This could explain the discrepancy of 30 per cent between the value of D/L_f for resonance predicted by Hinze and the "optimum" value found by Van der Hegge Zijnen.

The effect of guard heating. A few Nusselt number measurements were taken with the guard heater turned off. It was found that the Nusselt numbers without guard heating were from 7 to 11 per cent higher for the rear support geometry and 8 to 13 per cent higher using the crossflow support, than the corresponding values obtained using the guard heater. In view of the increase in the Nusselt number due to the presence of crossflow support (about 10 per cent), and the additional increase due to heat conduction along the support, it is not surprising that Lavender and Pei [22] obtained Nusselt numbers more than 20 per cent higher than those of Yuge, and those from this thesis using

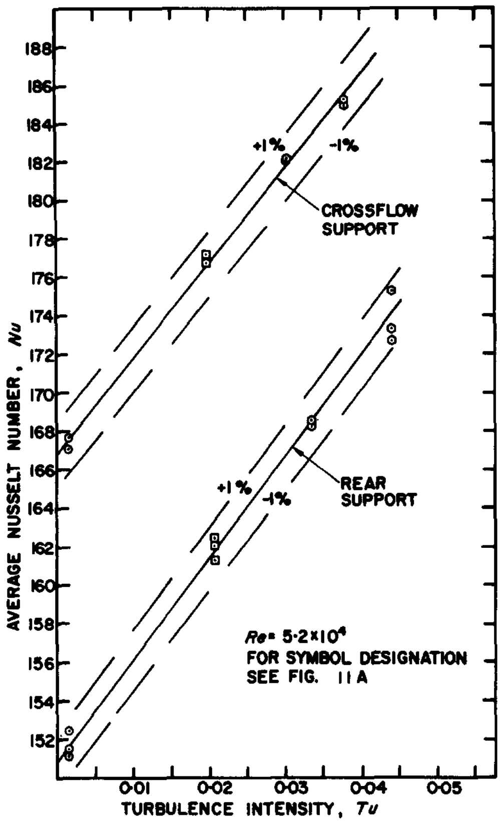


FIG. 11(d) The dependence of the average Nusselt number on the turbulence intensity for a small range in D/L_f and $Re = 5{\cdot}2 \times 10^4$.

a rear guard heated support. The crossflow support on the sphere used by Lavender and Pei was made of brass, was not guard heated and appeared to be quite large compared to the sphere diameter.

Some discussion should be devoted to the specification of the turbulence parameters used in correlating the heat-transfer results. If a sphere were placed in an infinite air stream in which the turbulence was completely homogeneous, it would be most logical to determine the required turbulence parameters far enough upstream of the model that the presence of the sphere would not be felt. When the turbulence changes in the direction of the air flow, it would appear to be best to measure the distribution of the turbulence parameters far upstream of the sphere and extrapolate to some reference point on the sphere (the center, for example). Provided the turbulence far upstream is not altered by the presence of the sphere, these values of the turbulence parameters should correspond to the values measured when the sphere has been removed and a probe is inserted at the reference point, i.e. as done in these experiments.

One cannot exclude *a priori* the possibility that the turbulence parameters far upstream could have been affected by the presence of the model. The mechanism for such a distant upstream disturbance would most likely be a vibration transmitted from the sphere to the tunnel wall, and back to the air stream. However, as mentioned earlier, careful observations of the spheres were made during the experiments and no vibrations were observed except for a slight tremor at high fan speeds.

If the upstream turbulence, far from the sphere, was disturbed by the presence of the sphere, there would be some dependence of the turbulence on the size of the sphere. Thus the parameters Re, Tu, and D/L_f (with Tu and L_f defined as the measured values with no sphere present) would not be sufficient to correlate the results. Figure 12 (especially the data points on the $Tu = 0{\cdot}02$ curve for $Re = 1{\cdot}4 \times 10^4$) shows that, for given values of Re, Tu, and D/L_f, there is no further consistent dependence of the Nusselt number on the diameter D. This tends to confirm that, to the accuracy of these measurements, measuring the turbulence parameters prior to the insertion of the model was satisfactory.

SUMMARY

Turbulence intensities were measured at several stations downstream from three grids of different geometry at velocities of 4·6, 9·1 and 18·3 m/s. Independent measurements were made using both a constant-current anemometer and a constant-temperature anemometer. The two sets of results agreed very closely. The turbulence

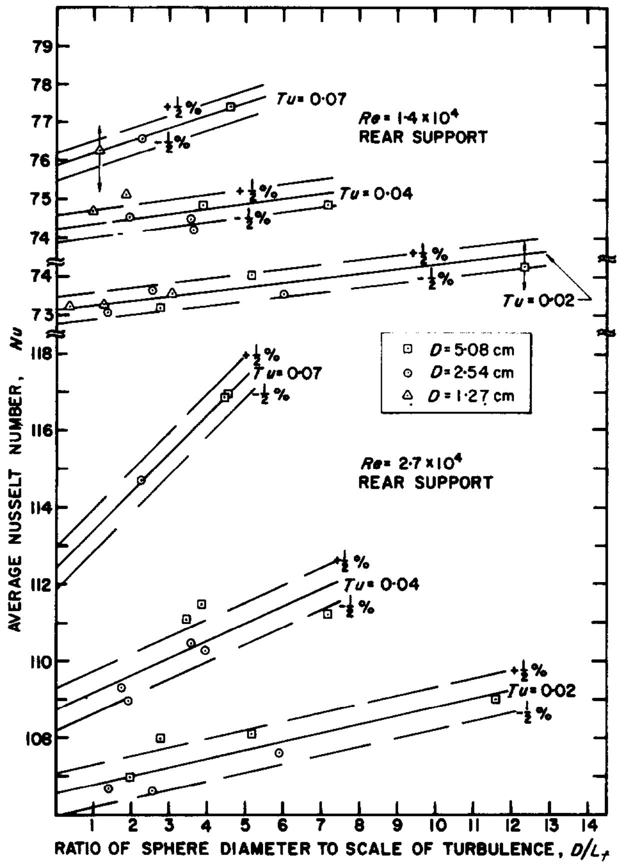


FIG. 12. The dependence of the average Nusselt number, for spheres with rear supports, on the D/L_f ratio for $Re = 1{\cdot}4 \times 10^4$ and $2{\cdot}7 \times 10^4$.

intensity was found to be essentially independent of the velocity of the air stream. Also, there were only slight variations in the turbulent intensity at positions off the centerline of the test section in planes normal to the flow direction. A brief comparison of the present results with those reported by other investigators was shown in Fig. 7.

The longitudinal scale of turbulence, L_f, was measured at various stations behind the same grids for the same range in velocities. Behind the perforated plate grid there was no dependence of L_f on the air speed; behind the woven-wire grids there was a slight dependence. In addition, a few measurements of the transverse scale of turbulence behind the perforated plate were reported. These measurements were compared to the L_f measurements and the measurements of others in Fig. 9.

Measurements of the Nusselt number were made for spheres both in a low-turbulence stream, and in a stream made turbulent using the grids for which the above measurements were made. Both rear support and crossflow support geometries were used.

In the low-turbulence stream, and using the rear support geometry, the following equations were obtained for Reynolds numbers in the range from $3{\cdot}6 \times 10^3$ to $5{\cdot}2 \times 10^4$.

$$Nu = 2{\cdot}0 + 0{\cdot}210\, Re^{0{\cdot}606}$$

or

$$Nu = 0{\cdot}257\ Re^{0{\cdot}588}.$$

The average deviation of the measured Nu values from the equations was 0·8 and 0·7 per cent respectively. Figure 1 compares these results with earlier measurements.

The effect of both the turbulence intensity and the ratio of the sphere diameter to the longitudinal scale of turbulence, D/L_f, was studied. Increasing the turbulence intensity was found to cause an increase in the average Nusselt number. By drawing an average curve through the data, without regard to the D/L_f ratio, it would appear that an increase in the turbulence intensity to 5 per cent caused the Nusselt number to increase by 7·5 and 17·5 per cent for Reynolds numbers of $3{\cdot}6 \times 10^3$ and $5{\cdot}2 \times 10^4$ respectively. At the lower Reynolds numbers, the most pronounced increase was in the range of turbulence intensities below 2 per cent.

At Reynolds numbers of $1{\cdot}4 \times 10^4$ and $2{\cdot}7 \times 10^4$, the number of data points was sufficient to determine the dependence of the Nusselt number on the ratio of the sphere diameter to the longitudinal scale of turbulence, D/L_f, for given values of turbulence intensity. Values of D/L_f were varied from near zero to twelve. The Nusselt number was found to increase with D/L_f, the increase becoming larger at higher turbulence intensities and higher Reynolds numbers. Figure 12 summarizes these results.

The crossflow support resulted in an increase in average Nusselt number of about 10 per cent for heat transfer in a low turbulence stream. The difference was approximately the same at higher turbulence intensities. The ratio of the stem diameter to the sphere diameter also had an influence. In addition, failure to guard-heat the support was found to result in an additional 10 per cent increase in the Nusselt number.

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Résumé—On décrit des mesures montrant l'influence de l'intensité et de l'échelle de la turbulence ainsi que de la position du support sur le transport de chaleur moyen à partir de sphères dans un écoulement d'air. La gamme de nombres de Reynolds allait d'environ $3{,}6 \cdot 10^3$ à $5{,}2 \cdot 10^4$. Les distributions de l'intensité et de l'échelle de la turbulence en aval de trois grilles derrière lesquelles on a mesuré ensuite le transport de chaleur, ont été déterminées pour des vitesses allant de 4,6 à 18, 3m/s. Les mesures de transport de chaleur ont montré que le nombre de Nusselt moyen augmentait avec l'intensité de la turbulence et avec le rapport du diamètre de la sphère à l'échelle de la turbulence pour des valeurs allant jusqu'à 5 au moins. On a trouvé que les nombres de Nusselt, obtenus avec un support perpendiculaire à l'écoulement, étaient environ 10 pour cent plus élevés que ceux obtenus avec un support placé à l'arrière. On donne des équations reliant le nombre de Nusselt moyen au nombre de Reynolds, pour un écoulement libre à faible turbulence.

Zusammenfassung—Es wird über Messungen berichtet, welche den Einfluss von Turbulenzintensität, Turbulenzgrad und Lage der Aufhängung auf den mittleren Wärmeübergang von Kugeln, an einen Luftstrom zeigen. Der Bereich der Reynolds-Zahlen erstreckt sich von etwa $3{,}6 \times 10^3$ bis $5{,}2 \times 10^4$. Die Turbulenzintensität und die Turbulenzgradverteilung wurden für Geschwindigkeiten von 4, 6 bis 18,3 m/s gemessen, stromabwärts von 3 Gittern, hinter welchen später Wärmeübergangsmessungen durchgeführt wurden. Die Wärmeübergangsmessungen zeigten eine Vergrösserung der mittleren Nusselt-Zahlen mit der Turbulenzintensität und dem Verhältnis von Kugeldurchmesser zu Turbulenzgrad bis zu Werten von mindestens 5. Nusselt-Zahlen, die bei Queraufhängung ermittelt wurden, waren etwa 10% grösser, als solche bei Aufhängung vom rückwertigen Teil der Kugel. Beziehungen zwischen den mittleren Nusselt-Zahlen und der Reynolds-Zahlen werden für geringe Freistromturbulenz angegeben.

Аннотация—В статье приводятся результаты по определению влияния интенсивности турбулентности, масштаба турбулентности и положения державки на средний теплообмен от сфер к потоку воздуха. Число Рейнольдса изменялось приблизительно от $3{,}6 \times 10^3$ до $5{,}2 \times 10^4$. Распределения интенсивности и масштаба турбулентности вниз по потоку от трех решеток, где позднее проводились измерения теплообмена, определялись при скоростях от 4,6 до 18,3 м/сек. Из измерений теплообмена следует, что среднее число Нуссельта увеличивается с увелечением как интенсивности турбулентности, так и отношения диаметра сферы к масштабу турбулентности, по крайней мере, до величины этого отношения, равного 5. Найдено, что числа Нуссельта при расположении державки перпендикулярно направлению течения приблизительно на 10% больше, чем числа Нуссельта при её расположении в кормовой части сферы.

Приводятся уравнения, связывающие среднее число Нуссельта с числом Рейнольдса для свободного потока с малой турбулентностью.