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THE EFFECT OF FREE STREAM TURBULENCE ON THE HEAT TRANSFER FROM THE STAGNATION POINT OF A SPHERE

VINCENT J. GOSTKOWSKI and FREDERICK A. COSTELLO

Department of Mechanical and Aerospace Engineering, University of Delaware, Newark, Delaware, U.S.A.

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An experimental investigation was conducted to define quantitatively the effect of free stream turbulence on the heat transfer to the stagnation point of a sphere. The present data expands the existing heat-transfer results for turbulence intensities up to 36 per cent. It is shown that the heat transfer remains generally constant for the low turbulence intensities (1–10 per cent), following existing data, but at higher intensities a significant increase in heat transfer is noted.

INTRODUCTION

Heat transfer from solid bodies immersed in a stream of fluid is of importance in many engineering problems. For most common cases, heat-transfer rates can be adequately predicted from available engineering analyses or correlations. One serious shortcoming of the available techniques is that there is no systematic way of predicting the effects of the stream turbulence on heat transfer; yet experiments by Giedt [1] have shown that even moderate turbulence levels may increase the heat transfer by as much as 70 per cent over the theoretical value.

Many analytical models have been attempted to describe turbulence effects, including vorticity stretching models [2] and eddy diffusion models [3]. Of the many models proposed, only these two have been successful in predicting the dramatic effect of turbulence on the heat transfer from the stagnation line of a cylinder.

Neither theory has been applied, however, to other geometries; therefore an analytical prediction of the heat transfer from the stagnation point of a sphere for high turbulence intensities cannot be made.

The current investigation was prompted by experimental results showing the stagnation line heat-transfer rate on cylinders to increase by 40 per cent for free stream turbulence levels increasing from approximately 0·05 to 2 per cent. Prior to this study, no such trend was evident for heat transfer from a spherical stagnation point, since the existing data for the spherical stagnation point falls on both sides of theory.

EXPERIMENTAL EQUIPMENT

The test model was constructed from a 1·5 in. dia. aluminum–bronze bearing spherical to 10^{-6} in. The heat transfer was measured by an equilibrium method similar to that used in guarded-hot-plate thermal-conductivity measurements. A portion at the stagnation region of the sphere, called the center calorimeter, was insulated thermally from the rest of the electrically heated sphere by an air gap of 0·005 in., as shown in Fig. 1. The calorimeter was provided with a heater and thermocouple.

The sphere was heated by a series of four electrical resistance heaters; four thermocouples were used to measure the temperature within the sphere. The sphere heaters and thermocouples were molded to four cylindrical capsules that fit machined shafts in the sphere.

The turbulence was generated by a series of 50 per cent porosity perforated drilled plates with holes ranging from $\frac{1}{4}$ to 4·5 in. The range in turbulence intensity produced by

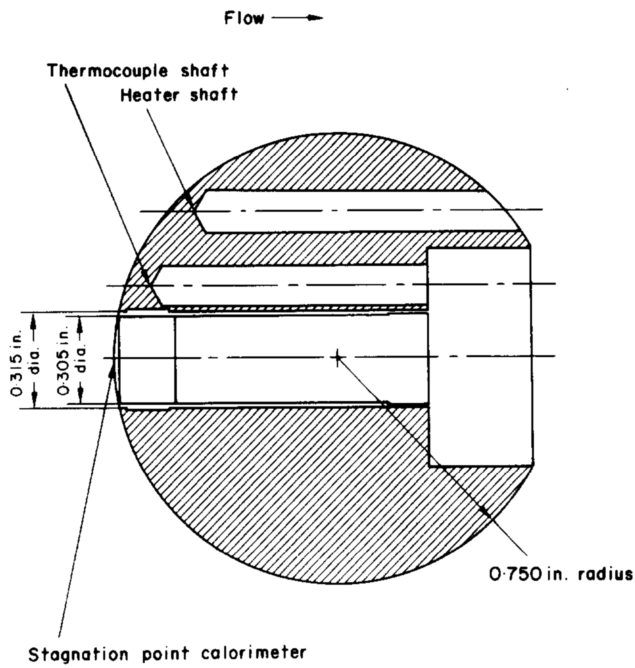

FIG. 1.

these grids was ½–36 per cent and agreed well with the data presented by Raithby and Eckert [4]. The turbulence intensities were measured using a single-wire DISA Constant Temperature hot-wire anemometer with a 0·0005 in. dia. wire. The measurements were made 1·5 in. in front of the sphere, which was sufficiently far from the sphere for there to be no difference in intensity measurements made with the sphere in or not in place. The velocities and intensities were uniform over a 4 by 8 in. core in the 6 by 10 in. wind tunnel. The turbulence was mildly anistropic, the ratio of lateral intensity, u'_2, to longitudinal intensity, u'_1, being approximately 0·63.

EXPERIMENTAL PROCEDURE

Under experimental conditions the sphere heaters were supplied with electrical energy at a steady and constant rate and the temperature of the entire sphere was allowed to attain equilibrium. The current supplied to the sphere heaters was adjusted to give a temperature difference of approximately 30°F between the free stream and the sphere. The temperature difference was measured by thermocouples in the wind tunnel and in the sphere.

When equilibrium had been established within the sphere, the stagnation-point calorimeter was supplied with heat and adjusted to such a rate that the temperature difference between the calorimeter and the sphere was 0·0 ± 0·1°F. The equalization of the calorimeter and sphere temperatures to within 0·1°F ensured that less than 2 per cent of the calorimeter input could be lost to the sphere.

Heat transfer tests were conducted at wind tunnel velocities of 120, 100, 50 and 30 ft/s for a range of turbulent intensities.

RESULTS AND DISCUSSION

The results are illustrated in a series of graphs. In Fig. 2 the dimensionless quantity $Nu/Re^{0\cdot5}$ was plotted v. the turbulence intensity; Nu is the Nusselt number based on the sphere diameter and Re is the Reynolds number based on the free-stream velocity and the sphere diameter. A distinct correlation curve showing $Nu/Re^{0\cdot5}$ against turbulent intensity, Tu, could be drawn for each velocity. The data with the free stream velocity approximately equal to 120 f/s shows an increase in the $Nu/Re^{0\cdot5}$ value of almost 100 per cent over the theoretical value for turbulence intensities near 40 per cent. Lesser increases were noted with the data at 100 and 50 ft/s. The data for 30 ft/s stream velocity also shows an increasing trend.

The heat transfer results were therefore seen to be dependent primarily on the stream velocity (or Reynolds number) and the turbulent intensity (Tu). Although the integral scale was not measured, published data for similar turbulence generators [4] can be used to show that within the range of

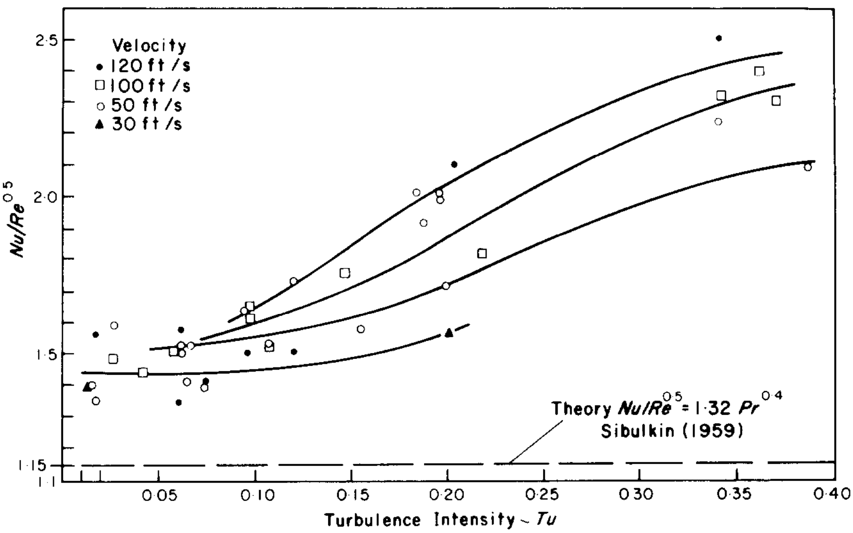

FIG. 2.

0·32–1·70 in. the integral scale had no effect. A correlation in terms of the turbulent Reynolds number $Re_T = (Re \times Tu)$ was sought. To this end, the ratio $Nu/Re^{0.5}$ was plotted vs. Re_T in Fig. 3. The results show that the relation is essentially linear in the low turbulent Reynolds number range; however, a sharp increase occurs in the heat-transfer rates in the vicinity of $Re_T = 7 \times 10^3$. The result is very similar to the published results of Lavender and Pei [5], who found a sharp increase in overall heat transfer from the complete sphere at $Re_T = 10^3$. The dependence of $Nu/Re^{0.5}$ on Re_T is also similar to that found in the data of Smith and Kuethe [3] for the stagnation line of a cylinder; however, for cylinders the sharp increase occurs at Re_T equal to 1000. In neither the sphere nor the cylinder case is the cause of the sharp increase understood at present.

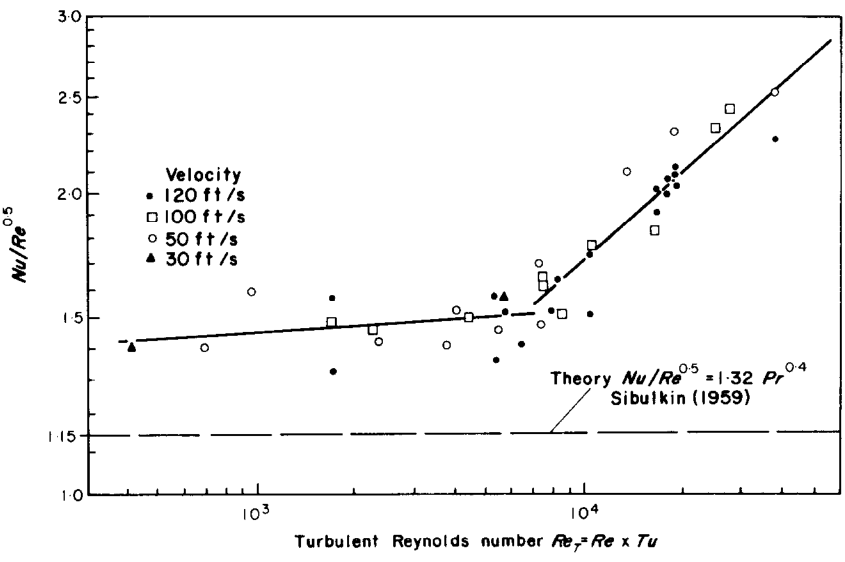

FIG. 3.

A "least squares" method of curve fitting yielded the following relations:

$$\frac{Nu}{Re^{0.5}} = 1.255\, Re_T^{0.0214} \qquad Re_T < 7 \times 10^3$$

$$\frac{Nu}{Re^{0.5}} = 1.128\, Re_T^{0.2838} \qquad Re_T > 7 \times 10^3.$$

When the previously published data is compared with the $Nu/Re^{0.5}$ vs. Re_T correlation, as in Fig. 4, it is seen to follow the trend of the curves. The data of Short *et al.* [6], Hsu and Sage [7] and Venezian *et al.* [8] for high turbulence intensity but extremely low Re_T values is found to have the same trend as the calculated curve. Costello's [9] data obtained with a model similar to that used in the present work is found to fit excellently onto the curve. Xenakis' [10]* and Wadsworth's [11] data fit well in the low Re_T range but lack the pronounced increase noted in the present work $Re_T = 7 \times 10^3$.

The consistent difference between the present data and that obtained from the references brings into question the effects of the present model design, especially with respect to the use of an air gap for insulation. As a check of the insulation technique, the model was re-tested while covered with a thin rubber membrane. The results of these tests confirmed the data obtained with the uncovered model. Possibly the side mounting of the sphere, as used by previous investigators, influences the effects of stream turbulence.

The results show that there is a slight increase in $Nu/Re^{0.5}$ in the lower turbulent Reynolds number range but that a significant increase in heat transfer existed for turbulent Reynolds numbers greater than 7×10^3.

In regards to a validation of the transition Re_T point, additional tests could be conducted with a larger test model. Thus with the original stream velocities and with lower turbulence intensities any shifts in the Re_T transition point could be noted.

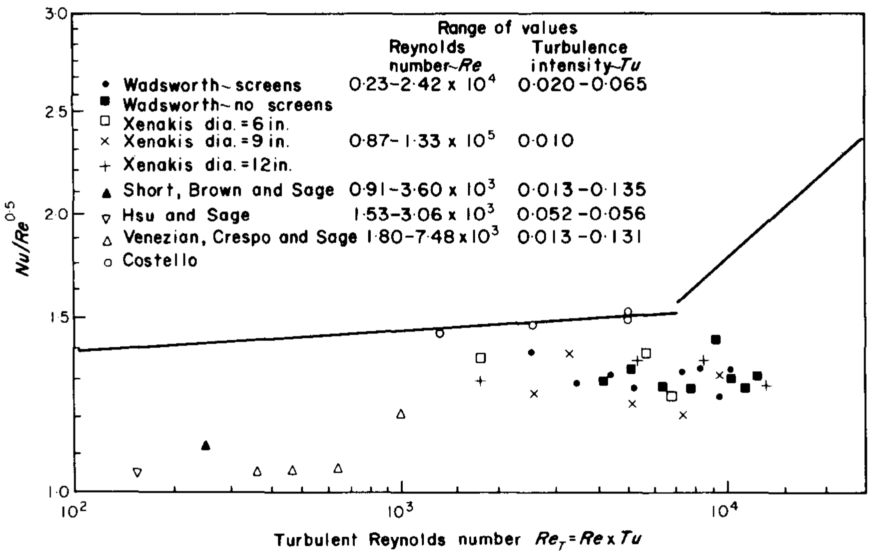

FIG. 4.

CONCLUSION

The relationship of $Nu/Re^{0.5}$ to Re_T was found to be an adequate correlation of the heat transfer at the stagnation point of a sphere. The heat transfer increase was dependent primarily on the Reynolds number and the turbulence intensity whereas effects of the scale of the turbulence, Λ_f, were not discernible.

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