JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
45, 3, pp. 505-511, Warsaw 2007

ESTIMATION OF THE INFLUENCE OF INFLOW TURBULENCE ON HEAT CONVECTION FROM A SPHERE SURFACE

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In the paper, results of an experimental investigation of a heat transfer coefficient on a sphere for different inflow turbulence levels have been presented. The average heat transfer coefficient on the sphere surface appear to be dependent on the turbulence level of flow around the sphere. This effect of influence of the flow structure near the sphere surface on the heat transfer process have been presented. Distributions of heat transfer on spheres of different diameters for different turbulence levels of the inflow have been analyzed. It has been shown that an increase of the inflow turbulence level caused an increase of the average heat transfer coefficient on the sphere surface. The maximum increase of the heat transfer due to growing turbulence has been found to be about 30%.

Key words: convective heat transfer, turbulence, sphere

1. Introduction

The heat transfer process from a surface to flow is a function of many parameters. For forced convection of heat from the surface, the main parameter which stimulates this process is the average flow velocity. Much more difficult is the problem with description of the flow structure.

A flow generated by different flow sources can be characterised by different flow structures for turbulent flows. The average velocity can be the some, but the level of turbulence, as the simplest parameter of the turbulent flow structure, can be different. Very often, the average flow velocity is not good enough to describe turbulent flow structures when they influence heat transfer processes on surfaces.

Many literature data indicate that an increase of the turbulence level causes an increase of the heat transfer coefficient even when the average velocity does not change. Next, problems of the vortex structure of turbulent flows still remain. Influence of the flow turbulence level on average heat transfer on spheres of different diameters is tested.

To estimate the influence of the turbulence level of flow on the average heat transfer coefficient, experimental tests were performed. The flow was generated by a nozzle. For different distances from the nozzle, the outlet turbulence level in free jet was varied from about 0.5% to about 25% with no change of the average flow velocity. A constant temperature anemometer was used to measure the level of flow turbulence. The average heat transfer coefficient on spheres was measured in steady state thermal conditions by means of an electrical heating system.

2. Measurement technique and apparatus

Heat transfer convection from spheres diameters of 0.01 m, 0.02 m and 0.03 m were measured for different turbulence levels of inflow. The average heat transfer from spheres made of copper to ambient flow was measured by the use of a DC power supply. The electrical power was recorded in steady-state conditions. The difference between temperature of the isothermal sphere surface and ambient flow of about $60°C$ was measured by making use of a thermocouple with accuracy of $0.1°C$ and then recorded. The information was used for calculations of the average heat transfer. The tested spheres were mounted on round, long supports. The support cross-section covered less than 0.5% of the sphere surface. Heat losses by supports was neglected because they were of the order of heat convection from free sphere surfaces. The influence of radiation was corrected using the radiation transfer equation from the surface to surroundings. The copper surface emissivity of 0.6 was taken into account.

An open wind tunnel was used to perform the experimental test. The flow was generated by a free round jet outflow from nozzles of different diameters. The level of turbulence, in the jet axis, changed from about 0.5% near the nozzle outlet to about 20% far away from the nozzle. By changing the average flow velocity at the nozzle outlet it was possible to keep a constant value of velocity at different distances from the nozzle outlet where the tested spheres were located. Distribution of the average flow velocity and flow velocity turbulent fluctuations were measured by means of a TSI hot wire probe connected to a Constant Temperature Anemometer (CTA) bridge TSI 1050. The influence of average velocity profile irregularity was tested by nozzles of different diameters. The nozzles of diameters $D > 2d$ were used.

The reference flow velocity and turbulent level of jet flow was measured at a distance x from the nozzle outlet of diameter D, where the sphere stagnation point was located. The Reynolds number of average flow defined on the sphere diameter was 32 000 for all presented measurements. As the reference value of heat transfer measurements, the values obtained for the lowest level of external flow turbulence ($\sim 0.5\%$) was taken into account.

A diagram of the experimental setup and apparatus is shown in Figure 1.

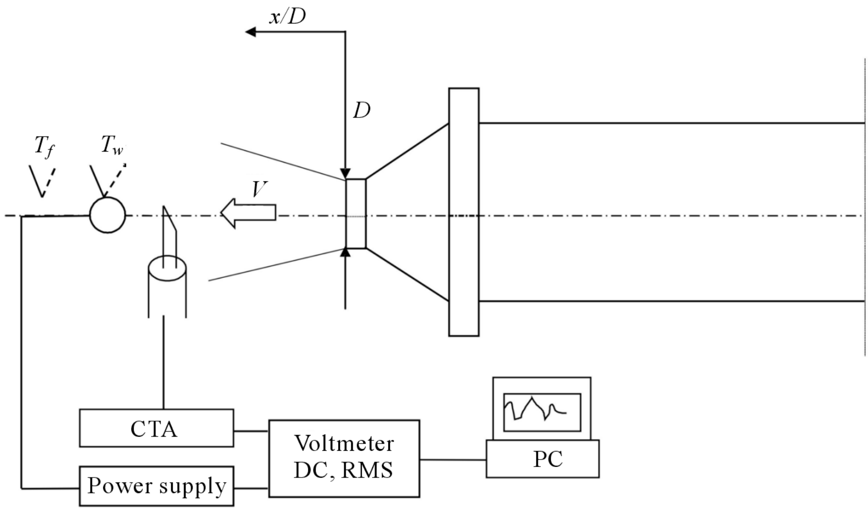

Fig. 1. Experimental setup and apparatus

3. Results of experimental investigations

A turbulent flow generated by different flow sources can be characterised by different turbulent flow structures. The average velocity can be the some, but the level of turbulence, as the simplest parameter of the turbulent flow structure, can be different. So, the average flow velocity in the Reynolds number is not good enough to describe turbulent flow structures when they influence heat transport processes from surfaces.

Many literature data indicate that an increase of the turbulence level causes an increase of the heat transfer coefficient even when the average velocity does not change (Bogusławski, 1996; Incropera and Witt, 2001; Whitaker, 1972).

As the reference heat transfer coefficient to indicate the influence of turbulence, the value of heat transfer obtained for a low turbulence level of about 0.5% was taken into account. This flow conditions occurs when the spheres were located at the half distance of the nozzle outlet diameter. The relations between experimental data obtained for spheres diameters of 0.01 m, 0.02 m and 0.03 m and literature data are presented in Fig. 2. For comparison, the following equations were taken into account.

The Ranz and Marshall equation (Ranz and Marshall, 1952)

$$\mathrm{Nu} = 2 + 0.6\mathrm{Re}^{0.5}\mathrm{Pr}^{0.33} \tag{3.1}$$

The Whitaker equation (Whitaker, 1972)

$$\mathrm{Nu} = 2 + (0.4\mathrm{Re}^{0.5} + 0.06\mathrm{Re}^{0.666})\mathrm{Pr}^{0.4}\Big(\frac{\mu_f}{\mu_w}\Big) \tag{3.2}$$

The Kancnelson and Timofiejewa equation (Wiśniewski and Wiśniewski, 2000)

$$\mathrm{Nu} = 2 + 0.03\mathrm{Pr}^{0.33}\mathrm{Re}^{0.54} + 0.35\mathrm{Pr}^{0.356}\mathrm{Re}^{0.58} \tag{3.3}$$

The obtained data are in good agreement with Ranz and Marshall equation (3.1). Two other equations give results which are above own experimental data.

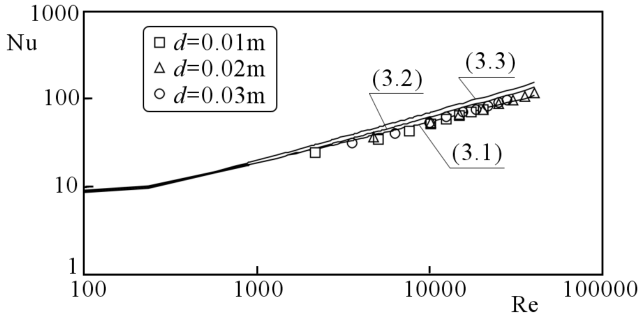

Fig. 2. Distribution of experimental data of the heat transfer coefficient on spheres in comparison with literature data

For the sphere, an increase of the turbulence level of flow causes an increase of the average heat transfer from the isothermal surface of the sphere to ambient air as shown in Fig. 3. This figure illustrates the process of heat transfer intensification for the sphere diameter of 0.03 m in a turbulent flow generated by nozzles of diameters $D = 0.06$ m, 0.12 m and 0.15 m. An increass of the flow turbulence by 22% causes an increase of the heat transfer by about 30%. The average flow velocity around the sphere does not change. The observed increase of average heat transfer can be interpreted as a result of the increase of flow turbulence. In this case (i.e. $d = 0.03$ m), the plot of experimental data looks to be independent of the nozzle diameter. This suggests that the scale of turbulent flow structures generated by nozzles of different diameters does not influence heat transfer processes.

For the sphere diameter of 0.0 2m, the plot of experimental data is shown in Fig. 4. Again, the increase of flow turbulence increases the heat transfer process from the isothermal sphere surface. The plot of data indicates, a nearly linear trend. Intensification of the heat transfer is smaller because for the turbulence of about 15%, the increase of heat transfer reaches 20%.

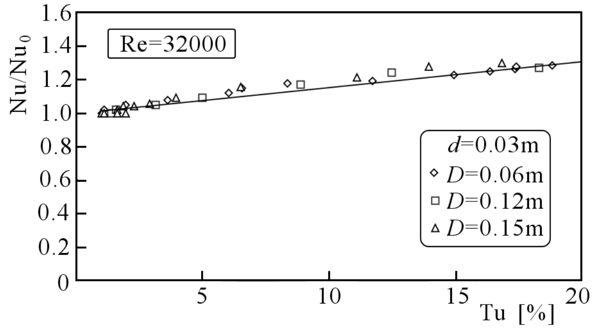

Fig. 3. Distribution of the average heat transfer coefficient on the sphere surface diameter of 0.03 m for different inflow turbulence levels

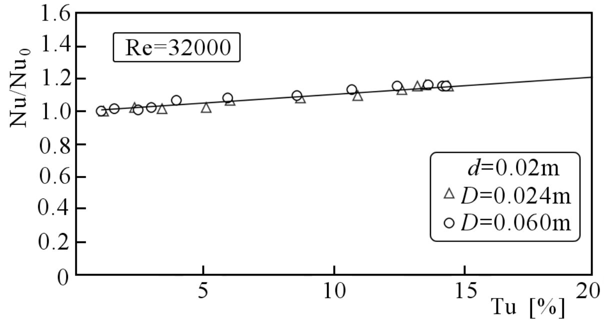

Fig. 4. Distribution of the average heat transfer coefficient on the sphere surface diameter of 0.02 m for different inflow turbulence level

For a smaller sphere with the diameter of 0.01 m, the plot of experimental data gets more complicated as shown in Fig. 5. For the nozzle diameter of 0.01 m, the influence of flow turbulence on heat transfer is much lower. For turbulence below 10%, the heat transfer increase is rather weakly visible. For the turbulence level beyond 15%, the heat transfer increases and reaches about 18% above the reference value at the turbulence level equal 20%.

The Reynolds numbers of average flow over spheres is the some for all spheres and nozzles.

The trend lines of increasing heat transfer coefficients for the tested spheres are presented in Fig. 6. A comparison between the trend lines for different diameters of spheres indicates that for smaller spheres the influence of intensity of turbulence is lower. There is no clear evidence that the scale of turbulent structures generated by nozzles of different diameters effects heat transfer phenomena in the tested range of the nozzle-to-sphere diameter ratio. Nevertheless, the diameter of spheres and its interaction with the flow structure cause that the influence of turbulent flow intensity on heat convection is lower when the diameter becomes smaller.

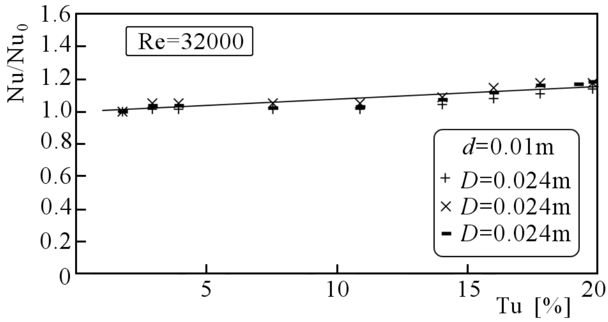

Fig. 5. Distribution of the average heat transfer coefficient on the sphere surface diameter of 0.01 m for different inflow turbulence level

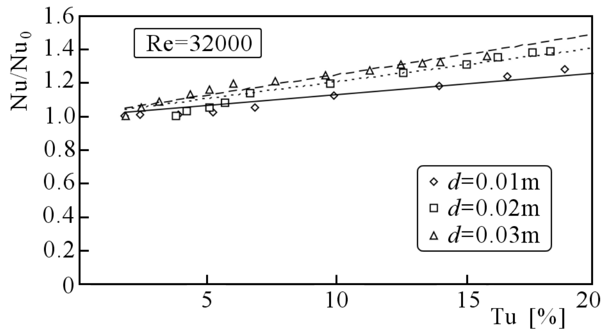

Fig. 6. Trend lines of increasing average heat transfer coefficient on spheres with the surface diameter of 0.01 m, 0.02 m and 0.03 m for different inflow turbulence levels

We can initially assume that turbulent vortexes are not able to effectively influence the increase of transport phenomena in the boundary layer on small diameter spheres. In this case, the boundary layer is thin. Because of this, the boundary layer is not so sensitive to turbulent perturbations. When the size of spheres grows, the possibility of affecting the heat transfer process by increasing flow turbulence grows essentially as well.

4. Conclusions

The increase of turbulence of the external inflow intensifies heat transfer phenomena on the sphere in an essential way. This effect is more visible when the diameter of spheres grows in the tested range. The boundary layer on spheres of smaller diameters is less sensitive to intensification of the heat transfer by external flow turbulence. Local heat transfer distributions indicate that for spheres of large diameters the external flow turbulent vortex is able to influence the boundary layer transport phenomena more intensively.

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Oszacowanie wpływu turbulencji napływu na konwekcję ciepła z powierzchni kuli

Streszczenie

W pracy przedstawiono wyniki badań eksperymentalnych współczynników przejmowania ciepła na kuli przy różnych stopniach turbulencji napływającej strugi. Średni współczynnik przejmowania ciepła na powierzchni kuli jest zależny od stopnia turbulencji przepływu wokół kuli. Jest to rezultat zmiany struktury przepływu w pobliżu ścianki kuli wpływającej na procesy transportu ciepła. Przeprowadzono analizę zmian wymiany ciepła na kulach o różnych średnicach przy zmianie stopnia turbulencji napływającej strugi. Wzrost stopnia turbulencji napływu powoduje wzrost średniego współczynnika przejmowania ciepła na powierzchni kuli. Maksymalny wzrost wymiany ciepła spowodowany wzrostem turbulencji przepływu był rzędu 30%.

Manuscript received February 21, 2007; accepted for print April 13, 2007