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Experimental and numerical investigation of heat transfer from a heated horizontal cylinder rotating in still air around its axis

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KEYWORDS

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Abstract In the present paper, the experimental system under consideration is a rotating cylinder of 50 mm diameter placed in still air. The numerical calculations are carried out by using a finite volume method based computational fluid dynamics solver FLUENT. The results of the heat transfer are characterized in terms of the non-dimensional parameters: Nusselt number (Nu), Reynolds number (Re), and Grashof number (Gr). The experimental measurements are carried out for Reynolds number range of 1880–6220 and Grashof numbers range of 14,285–714,285, while the numerical calculations are carried out for Reynolds number range of 0–100,000 and Grashof numbers range of 100–1,000,000. The effects of rotation on the heat transfer characteristics are presented in terms of the isotherm patterns, streamlines, local and the average Nusselt numbers. The results correlated as: $Nu = 0.022Re^{0.821}$ which compares very well with the data available for air in published works.

1. Introduction

Heat transfer from a rotating cylinder is one of the problems which is drawing attention due to its wide range of engineering and industrial applications. These include cooling of turbine rotors or electrical motor shaft, cooling of high speed gas bearings, rotating condensers for sea water distillation. Also include space vehicle technology, spinning projectiles, drying of paper on rollers in the paper industry.

In a heated rotating system the buoyancy and the centrifugal forces are of importance. The resultant combination of these determines the flow pattern and the heat transfer mechanism. In the mixed convection system the flow and heat transfer characteristics are determined by the buoyancy and the centrifugal forces which are characterized by Grashof number and Reynolds numbers, respectively. Of particular relevance is the ratio Gr/Re^2, which indicates the relative importance of buoyancy and rotational effects. At low rotational Reynolds number, buoyancy forces play an important role in determining the flow regime. In this paper a study is presented for simple configuration. The specific system under consideration is a rotating cylinder placed in still air.

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Nomenclature

L	cylinder length (m)	k	air thermal conductivity (W/m K)
D	cylinder diameter (m)	β	coefficient of thermal expansion of air (K^{-1})
R	cylinder radius (m)	v	air kinematic viscosity (m^2/s)
A	cylinder surface area where $A = \pi DL$ (m^2)	g	acceleration due to gravity (m/s^2)
I	input currant to the heater circuit (A)	Nu	Nusselt number where $\mathrm{Nu} = (hD)/k$
V	Voltage drop across the heater circuit (V)	Re	where $\mathrm{Re} = (\Omega D^2)/2v$
q	electric power to the heater where $q = IV$ (W)	Gr	Grashof number where $\mathrm{Gr} = (g\beta(t_s - t_\infty)D^3)/v^2$
t_∞	air temperature (°C)	φ	angular position on cylinder circumference (°)
t_s	arithmetic mean of cylinder surface temperatures (°C)	ψ	stream function (m^2/s)
h	heat transfer coefficient where $h = q/A(t_s\text{-}t_\infty)$ (W/m^2 K)	Ψ	dimensionless stream function where $\Psi = \psi/v$
Ω	rotational speed of the cylinder (s^{-1})	Θ	dimensionless temperature where $\Theta = (t - t_\infty)/(t_s - t_\infty)$

Convective heat transfer from a horizontal cylinder rotating in air, water and oil has been studied experimentally by several investigators, Anderson and Saunders [1], Etemad [2], Dropkin and Carmi [3], Ozerdem [4], Ball and Farouk [5], Becker [6], and Sebanand and Johnson [7].

Anderson and Saunders [1] investigated the heat transfer from horizontal cylinders rotating in still air and found that up to a critical value of the Reynolds number based on surface velocity the Nusselt number is almost independent of the Reynolds number and the rate of heat transfer is then mainly determined by the free convection. Using theoretical considerations the critical Reynolds number was found to be equal to $\mathrm{Re}_{cr} = 1.09\mathrm{Gr}^{1/2}$. Above the critical Reynolds number it was found that the Nusselt number increased with the Reynolds number and that the Grashof number had a negligible effect on the rate of heat transfer. They derived an expression for the heat transfer from a cylinder rotating in still air as $\mathrm{Nu} = 0.1\mathrm{Re}^{2/3}$. This equation compared excellently with the measurements.

Etemad [2] studied experimentally the heat transfer and flow around horizontal cylinders rotating in air. A range of Reynolds numbers from 0 to 65.400 was studied. From interferometric observations he found that the laminar motion broke down at a critical Reynolds number of 900 compared with 1080 computed from the relation established by Anderson and Saunders. The heat transfer results by Etemad compared excellently with the data of Anderson and Saunders. For Reynolds numbers above 8000, the heat transfer rates were independent of the Grashof number and the experimental data correlated as: $\mathrm{Nu} = 0.076\mathrm{Re}^{0.7}$. For Reynolds numbers below 1000 the Nusselt numbers depended almost entirely on the Grashof numbers and in the intermediate range between 1000 and 8000 both the Grashof and the Reynolds numbers influenced the rate of heat transfer and the a correlation was recommended as: $\mathrm{Nu} = 0.11(\mathrm{Pr}(0.5\mathrm{Re}^2 + \mathrm{Gr}))^{0.35}$.

Dropkin and Carmi [3] studied experimentally the problem of natural convection from a rotating cylinder in air. The experimental results covered the range of Reynolds number up to 43,300 and rotational speed up to 150 rpm. The results indicated that the rotational motion of the cylinder opposes the free convection currents on the downward moving side and aids those on the upward moving side. The effect of rotation was negligible up to the critical Reynolds number at which turbulence is established around the cylinder. For Reynolds numbers larger than 15,000 they correlated the data as: $\mathrm{Nu} = 0.073\mathrm{Re}^{0.7}$ which compares extremely well with the results mentioned earlier. In the region where both rotation and natural convection influenced the heat transfer their data were correlated by the equation as: $Nu = 0.095(0.5\mathrm{Re}^2 + \mathrm{Gr})^{0.35}$.

Ozerdem [4] has studied experimentally the convection around a rotating horizontal cylinder rotating in quiescent air. The average convective heat transfer coefficients have been measured by using radiation pyrometer. All the measurements have been obtained in the region where the natural convection effect was negligible. Therefore, heat transfer rate is assumed to depend on the rotational Reynolds number only. According to the experimental results, a correlation in terms of the average Nusselt number and rotating Reynolds number has been established. The equation $\mathrm{Nu} = 0.318\mathrm{Re}^{0.571}$, has been found valid for a range of the rotating Reynolds number from 2000 to 40,000. The average Nusselt number increased with an increase in the rotating speed. Comparison of the results, with the previous studies, has been showed a good agreement with each other.

Ball and Farouk [5] conducted experimental and numerical studies on the mixed convective flows around a rotating isothermal cylinder. The numerical solution was obtained for the range of $\mathrm{Gr} = 1.39\times10^3$ to 1.39×10^6, with $\mathrm{Pr} = 0.7$. They found that the average Nusselt number was generally decreasing with the increase of the rotational speed. They have obtained results up to $\mathrm{Re} = 50$, and faced instability problems near $\mathrm{Gr}/\mathrm{Re}^2 = 1.0$. They claimed that these instabilities were due to the presence of a three-dimensional secondary flow near the value $\mathrm{Gr}/\mathrm{Re}^2 = 1.0$, as a result they restricted their calculations to the values of $\mathrm{Gr}/\mathrm{Re}^2$ greater than unity. On the other hand, the experimental results they obtained showed that for the values of $\mathrm{Gr}/\mathrm{Re}^2$ from 0.0 up to 1.0, the average Nusselt number was almost uniform. They have concluded that, although the local Nusselt number is highly influenced by $\mathrm{Gr}/\mathrm{Re}^2$, the effect on the average Nusselt number was insignificant.

Becker [6] measured the convection heat transfer from a horizontal cylinder rotating in a tank of water. Results were correlated in terms of Nusselt, Reynolds and Prandtl numbers as: $\mathrm{Nu} = 0.111\mathrm{Re}^{2/3}\,\mathrm{Pr}^{1/3}$, for $1000 < \mathrm{Re} < 46{,}000$ and $2.2 < \mathrm{Pr} < 6.4$. This equation compared well with the experimental and theoretical data reported by Anderson and

Saunders [1]. All measured data were obtained in the region where the effects of natural convection are negligible and heat transfer rates were dependent only on Reynolds and Prandtl numbers.

Seban and Johnson [7], measured experimentally the heat transfer from a horizontal cylinder rotating about its axis in oil as the surrounding fluid. The results embrace a Prandtl number range from about 150 to 660, with Reynolds numbers up to 5×10^4, and show an increasing dependence of free-convection heat transfer on rotation as the Prandtl number is increased by reducing the oil temperature. Some correlation of this effect, which agrees with the prior results for air, has been achieved. They deduced that in the free-convection region, where the flow is laminar, the effect of rotation depends on the Prandtl number and the Reynolds number, and a representation of the results has been found which produces a fair correlation and is at the same time in agreement with the results for air. At higher rotative speeds the flow becomes turbulent, the free-convection effect vanishes, and the results with oil can be correlated generally with those for air.

Convective heat transfer from a horizontal rotating cylinder has been studied analytically and numerically by several investigators such as: Kendoush [8] and Abu-Hijleh and Heilen [9].

Kendoush [8] has presented an approximate solution for the calculation of the convective heat transfer rates through a laminar boundary layer over a rotating circular cylinder in a fluid of unlimited extent. By using the appropriate velocity components in the energy equation and by neglecting free convection effects, a solution was derived for the average Nusselt number as: $\mathrm{Nu} = 0.6366(\mathrm{Re\ Pr})^{1/2}$. The solution compares well with the available experimental data.

Abu-Hijleh and Heilen [9] have solved numerically the problem of laminar mixed convection from a rotating isothermal cylinder. The study covered a wide range of parameters: $5 < \mathrm{Re}_D < 450$ and $0.1 < \mathrm{Gr}_D/\mathrm{Re}_D < 10.0$. A correlation for the average Nusselt number, as a function of Reynolds number and buoyancy parameter $\mathrm{Gr}_D/\mathrm{Re}_D$, has been proposed. The correlation obtained was $\mathrm{Nu}_D = 1.586 + 0.05189\mathrm{Re}_D^{0.7072}[-0.4497 + 2.254\mathrm{Gr}_D/\mathrm{Re}_D^{0.5978}]$. The correlation gives an accurate estimate of the Nusselt number over the range of Reynolds numbers and buoyancy parameter values studied.

Some studies have been carried out on the problem of convective heat transfer from a rotating cylinder in a cross-stream such as: Kays and Biorklund [10], Badr and Dennis, [11], Ryohachi et al. [12], Chiou and Lee [13], Smyth and Zurita [14], Abdella and Magpantay [15], Sharma et al. [16], Yan [17] and Singh et al. [18].

Most of the previous studies, especially experimental ones, have focused on average Nusselt number especially in the region where the natural convection effect was negligible. One of the important objectives of the CFD model as applied in the present work is to predict the behavior of the flow in terms of flow patterns and the isothermal lines around the cylinder as well as local distribution of heat transfer for wide range of rotational Reynolds numbers including natural and mixed convection. A test rig is designed and constructed for performing the experimental investigation. For numerical investigation, a two-dimensional model representative of cylinder geometry has been developed which consists of an infinite long circular cylinder having diameter D maintained at a constant temperature of T_s and is rotating in a counter-clockwise direction The computational grid is generated by using a commercial grid generator GAMBIT and the numerical calculations are performed in the full computational domain using CFD modeling package, FLUENT.

2. Experimental details

The aim of the present study is to investigate experimentally and numerically the effect of rotation on the heat transfer from a heated horizontal cylinder rotating in still air around its axes. For this reason, an experimental test rig is being designed and constructed, Fig. 1.

As shown in Fig. 1, the main components of the test rig are rotation mechanism (parts 1–5), slip ring (part 6), rotating cylinder (part 7) and measuring equipments. The rotation mechanism consists of motor, gearbox, pulleys, and type belt. The rotation mechanism is used to control the rotational speed. The rotating motion is transmitted to the slip ring and then to the rotating cylinder through circular flanges. By this way different rotational speed and in turn different Reynolds numbers can be obtained.

The slip ring is used to supply the power from fixed source to the rotating heater and also used to connect the thermocouples which rotate with rotating cylinder with the fixed measuring apparatus. As shown in Fig. 2 the slip ring consists of a steel shaft. The shaft has two grooves; one of them is used to put the power cables inside and the other to put thermocouples wires in. Ten brass rings are mounted on the shaft, eight of them are used to connect the thermocouple ends to measuring unit and the other two rings are used to connect the power cables from the heater to power supply. All brass rings are completely insulated from each other and also from the rotating shaft. Ten carbon brushes are used to connect the rotating brass rings with the fixed measuring units and power supply. Each carbon brush is mounted in a seat and the seats are insulated from each other.

The rotating cylinder is made of hollow-aluminum cylinder with of 500 mm length, 20 mm inner diameter and 50 mm outer diameter. A cylindrical electrical heater of 20 mm outer diameter is inserted through the rotating cylinder. The heater is connected to the power supply through the slip ring. The surface temperature of rotating cylinder is measured using 8 thermocouples which are connected to measuring device through the slip ring. Two disks of an insulating material are fitted at the cylinder ends to prevent the heat transfer from the cylinder ends. The cylinder is mounted on two journal bearing.

The measurements necessary for the heat-transfer determination are the steady-state values of electric power to the heater, q, the air temperature, t_∞, the arithmetic mean of cylinder surface temperatures, t_s, the rotational speed of the cylinder, Ω. and cylinder surface area, A. Air properties are evaluated at the arithmetic mean of the surface and the air temperatures From these measured and calculated values, the heat transfer coefficient, h can be determined as: $h = q/A(t_s - t_\infty)$. From measured and calculated values Nusselt number, Reynolds number and Grashof number are calculated as:

$$\mathrm{Nu} = \frac{hD}{k}$$

$$\mathrm{Re} = \frac{\Omega D^2}{2\nu}$$

$$\mathrm{Gr} = \frac{g\beta(t_s - t_\infty)D^3}{\nu^2}$$

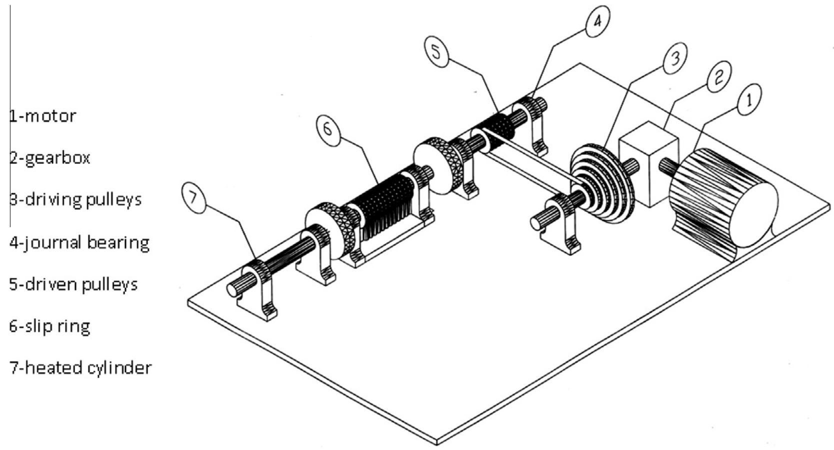

Fig. 1 Schematic diagram of the test rig.

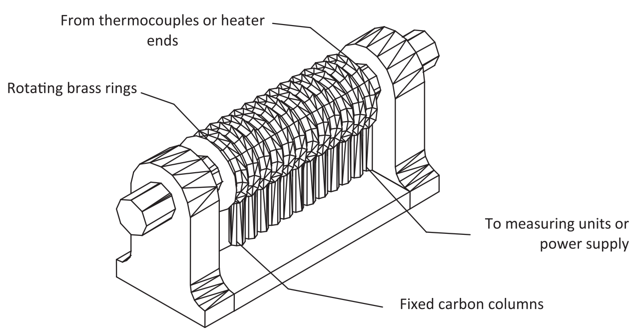

Fig. 2 Details of slip ring, part 6.

The measuring equipments are used to measure the output of thermocouples in (m), the input currant to the heater circuit (A), the voltage drop across the heater circuit (V) and the angular velocity of the rotating cylinder (S^{-1}).

3. Numerical details

The first task in any numerical work is to validate the codes ability to accurately reproduce published results. FLUENT is validated by many researchers before. The second important point is the grid dependence examination of the numerical results. This examination consists of four parts.

The first part is the effect of distribution of the grid density on the results. The present and all of the previous examinations concluded that for the considered problem, the highest gradient is in the boundary layer around the cylinder and gradually reduces as we go far from the cylinder. So non-uniform grid is used for the solution domain with the grid near the surface of the cylinder is sufficiently fine to resolve the boundary layer around the cylinder.

The second part is the normal distance, Δn, between the first nodes around the cylinder and cylinder surface, Fig. 3a. The importance of this distance is that it used for calculating the local Nusselt numbers and in turn average Nusselt number which represent the amount of heat released from the cylinder for different angular velocity and temperature difference between the cylinder surface and ambient temperature.

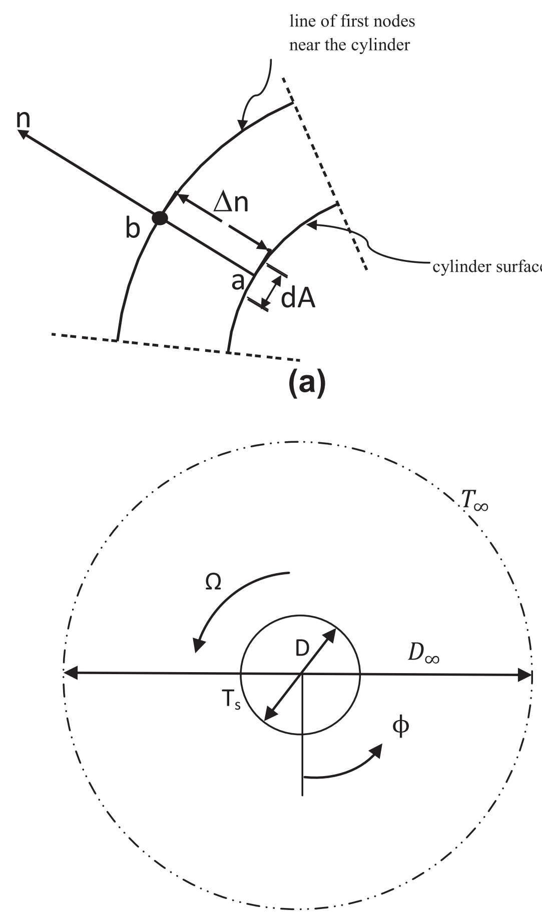

Fig. 3 Schematic diagram of the numerical system.

3.1. Local Nusselt number

At cylinder surface

$$h(dA)(T_s - T_\infty) = -k(dA)\frac{\partial T}{\partial n}\bigg|_{r=\frac{D}{2}}$$

where n is the normal direction

Rearranging the equation yields

$$\frac{hD}{k} = -\left.\frac{\partial\Theta}{\partial N}\right|_{r=D/2}$$

where $\theta = \frac{T-T_\infty}{T_S-T_\infty}$ and $N = n/D$
then

$$Nu = -\left.\frac{\partial\Theta}{\partial N}\right|_{r=D/2}$$

3.2. Average Nusselt number

$$\bar{Nu}\,\frac{1}{2\pi}\int_o^{2\pi} Nu\, d\varphi$$

In the present study local Nusselt number is calculated numerically as:

$$Nu = -\left.\frac{\partial\Theta}{\partial N}\right|_{r=D/2} = \frac{\theta_a - \theta_b}{\Delta N}$$

where

$$\Delta N = \Delta n/D$$

and the average Nusselt is calculated using numerical integration.

Evidenced by above equations that the accuracy of local Nusselt number and in turn the accuracy of average Nusselt number depend on the value of n/D.

The average Nusselt is calculated using numerical integration and the numerical integration depends on the number of points on the cylinder surface. So the third part of the grid dependence examination is the number of points on the cylinder surface. The fourth part, which is special for the present problem, is the domain size i.e. the ratio of far away diameter to the cylinder diameter D_∞/D, Fig. 3b.

Is clear from the above analysis that the results of average Nusselt number depends on the following parameters.

(a) The relative normal distance between the first nodes and cylinder surface, $\Delta n/D$
(b) Grid resolution (number of cells in solution domain).
(c) Domain size D_∞/D.
(d) Number of points on the outer surface of cylinder.

Different values of the above parameters are tested and the percentage differences in the average Nu number are found to be less than 5% for different values of the Re and Gr. The domain of size $D_\infty/D = 10$ with grid resolution of 10,000 quadrilateral cells and 100 points on the outer surface of cylinder and having a relative normal distance $\Delta n/D$ of .001 is used in all the calculations in the present work.

The system here consists of an infinite long circular cylinder having diameter D which is maintained at a constant temperature of T_s and is rotating in a counter-clockwise direction with a constant angular velocity of Ω, Fig. 3b. A two-dimensional model representative of cylinder geometry has been developed. The computational grid for the problem under consideration is generated by using a commercial grid generator GAMBIT and the numerical calculations are performed in the full computational domain using FLUENT for varying conditions of Reynolds number Re and Grashof number Gr. Standard k–ϵ model with standard wall function is used. The second order upwind scheme is used to discretize both of momentum and energy equations, while The first order upwind

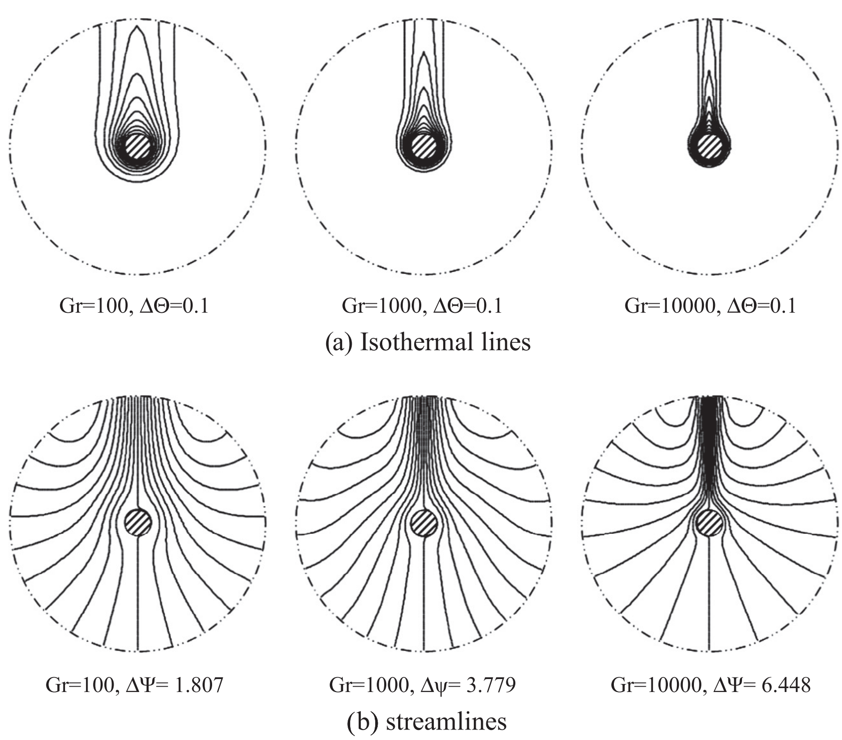

Fig. 4 Isotherm profiles and streamlines for a stationary cylinder (Re = 0).

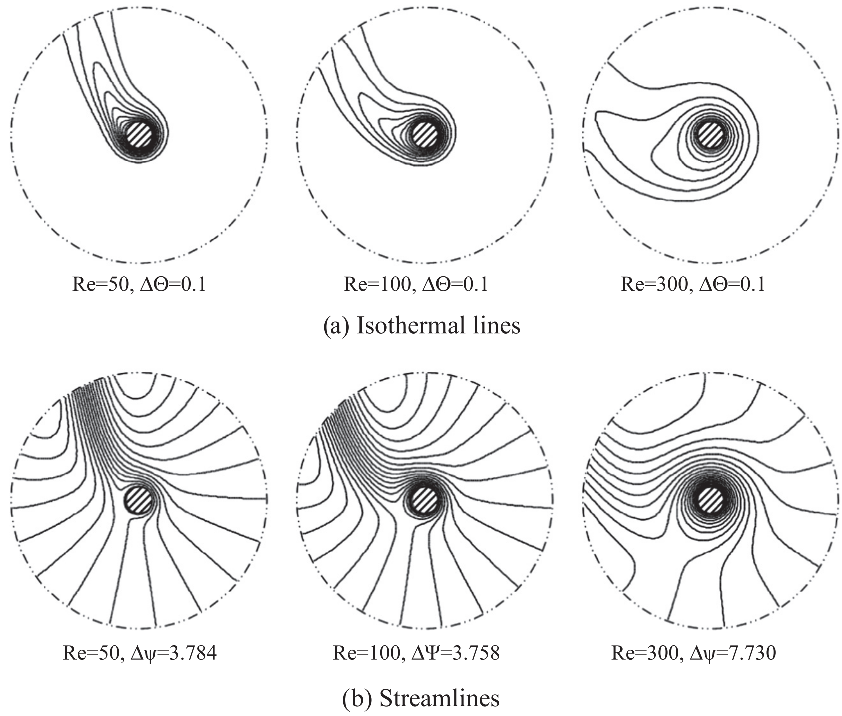

Fig. 5 Isotherm profiles and streamlines for a rotating cylinder (Re = 50, 100 and 300) and (Gr = 1000).

scheme is used to discretize both of turbulent kinetic energy and turbulent dissipation rate. The semi implicit method for the pressure linked equations (SIMPLE) has been used to pressure-velocity coupling. A convergence criterion of 10^{-3} is used for continuity, turbulent kinetic energy and turbulent dissipation rate while 10^{-5} is used for the *x*- and *y*-components of momentum equation and 10^{-6} is used for energy equation.

4. Results and discussion

4.1. Isotherms and streamlines patterns

The representative isotherm profiles and streamlines around the rotating cylinder for different values of Re and Gr are presented. For a stationary cylinder (Re = 0), Fig. 4, isotherms have maximum density close to the bottom surface of the cylinder. This indicates high temperature gradients or in other words, the higher values of local Nu number near the bottom stagnation point on the bottom surface as compared to other points on the cylinder surface. Also, as the value of Gr number increases, the thermal boundary layer becomes thinner which leads to an increase in the temperature gradients close to the top surface.

On increasing the value of the Re, Fig. 5, the maximum density of isotherms shifts from bottom surface towards the right surface of the rotating cylinder and the density of isotherms close to the top surface of the cylinder increases (the cylinder rotating counter-clock wise). This effect can be explained as on increasing the Re, the recirculation region increases.

Fig. 5 gives also that at low Re the temperature gradient is least at the top and greatest at the bottom, but at the critical Re the gradient at the top is much steeper than at the downward side, suggesting that the breakaway region of the flow has shifted in the direction of rotation to the downward side. At the higher Re the gradients near the surface differ little in the four positions. Farther away from the surface, however,

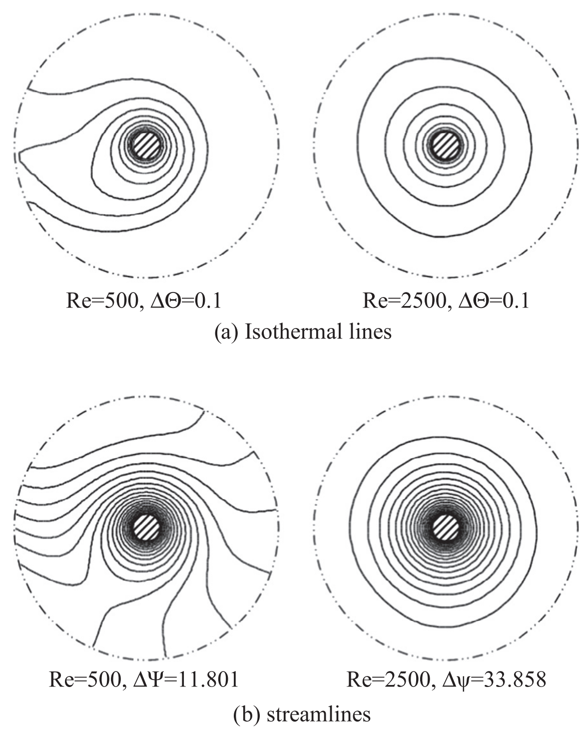

Fig. 6 Isotherm profiles and streamlines for a rotating cylinder (Re = 500 and 2500) and (Gr = 1000).

there remain considerable gradients outside the normal boundary-layer thickness. At higher rotative speeds the flow becomes turbulent; the free convection effect vanishes. It is also observed from Fig. 5 that on increasing the Re number isotherms shifts in the direction of rotation of the cylinder and the plume becomes almost horizontal at high values of the Re.

For higher values of the Re, Fig. 6, the plume disappears and the fluid immediately next to the surface of the spinning cylinder rotates with the cylinder in a laminar concentric circular stream.

4.2. Local Nusselt number

Fig. 7 shows the variation of the local Nu number on the surface of the circular cylinder for different Gr and Re. For a stationary cylinder (Re = 0) and for all values of Gr, Figs. 7(a–d), the variation of the local Nu number around the cylinder is found to be symmetrical at $\phi = 180°$. The figures show that the maximum value of the local Nu number occurs at the bottom stagnation point; whereas the least value occurs at the top stagnation point.

For a rotating circular cylinder, the maximum and minimum values of the local Nu number shifts in the direction of the rotation. The temperature distributions presented by way of isotherms in Fig. 5 can be used to interpret the variation in the local Nu number.

Fig. 7 shows also that for a rotating cylinder, the difference between maximum and minimum values of the local Nu number decreases with the increase of Re. For higher values of Re, this difference tends to vanish and local Nu number distribution on cylinder circumference tends to be straight line, i.e. uniform distribution of local Nu on cylinder circumference. The temperature distributions presented by way of isotherms in Fig. 6 can be used to interpret the variation in the local where the isotherms takes a circular form.

4.3. Average Nusselt number

The numerical results are given in Fig. 8, in which the average Nusselt number $\overline{Nu}$ is plotted against the Reynolds number Re, for different values of Gr number. In every case the same trend is observed, the Nusselt number being roughly independent of the Reynolds number up to critical value where $Gr/Re^2 = 1$. I.e. the Nusselt number is constant or slightly decreases with the increase of the Reynolds number up to this critical value, beyond which $\overline{Nu}$ increases with Re. For Rey-

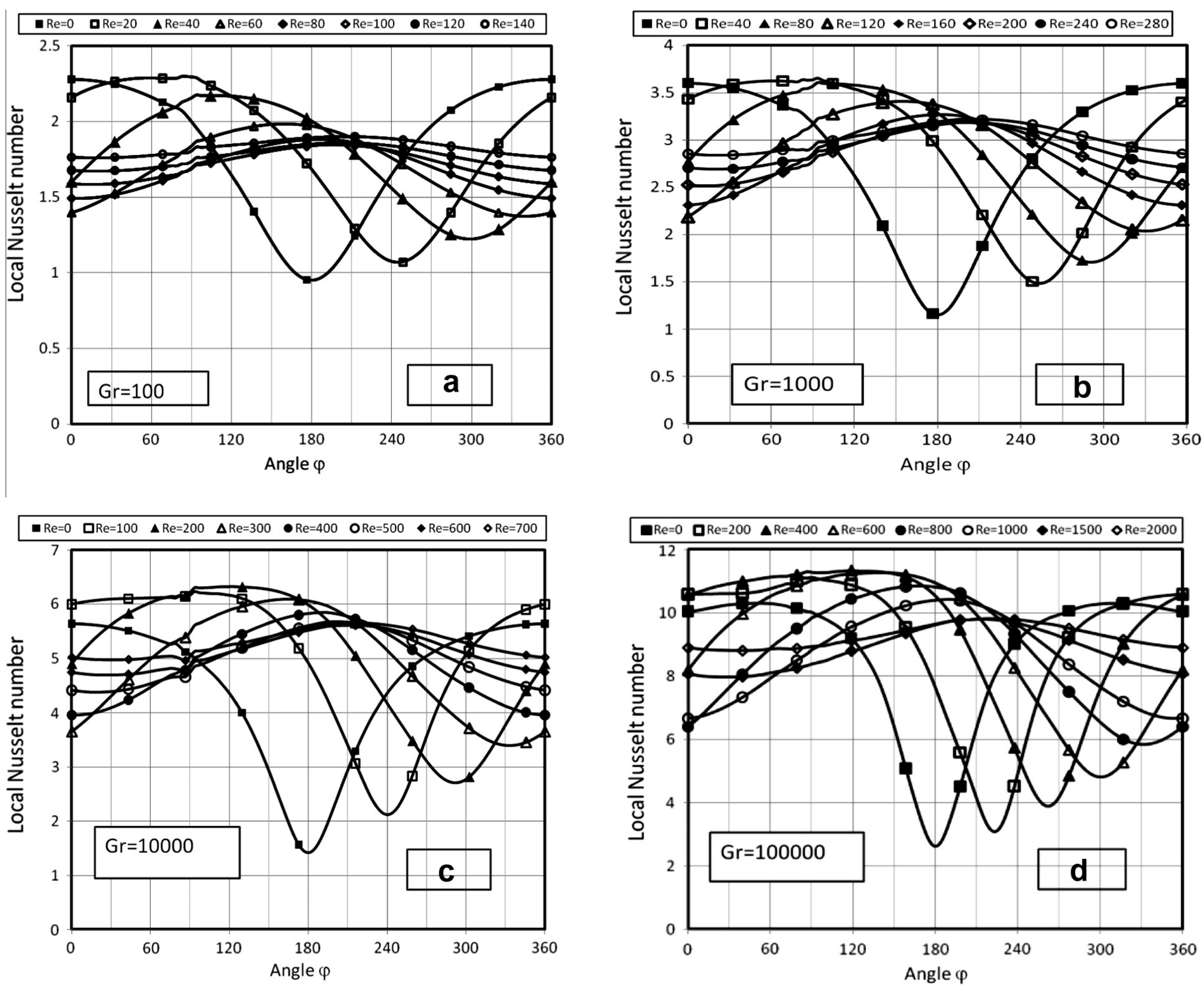

Fig. 7 Variation of the local Nusselt number on the surface of the circular cylinder for different Gr and Re.

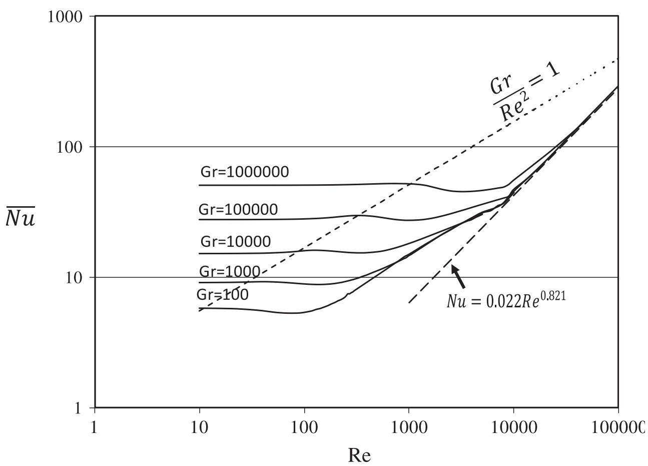

Fig. 8 Variation of the average Nusselt number with the Reynolds number Re, for different values of Gr. number.

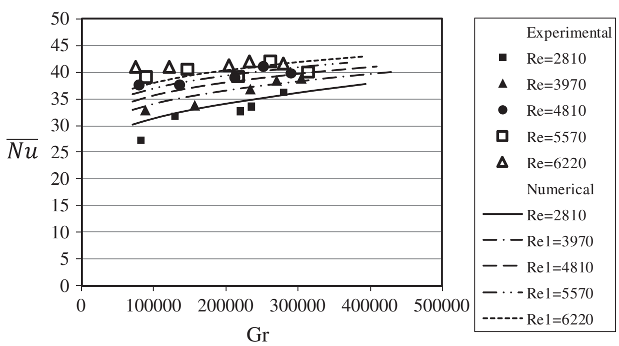

Fig. 9 Comparison of the present numerical with the present experimental results.

nolds numbers above 8000, the heat transfer rates are independent of the Grashof number (for Gr $\leqslant$ 100,000) and results for different values of Gr coincide and the results correlated as: Nu = 0.022Re$^{0.821}$. For Reynolds numbers below 500 the Nusselt numbers depended almost entirely on the Grashof numbers (for Gr > 100) and in the intermediate range between 500 and 8000 both the Grashof and the Reynolds numbers influenced the rate of heat transfer.

Isotherms plotted on Figs. 4–6 and local Nusselt number plotted in Fig. 7 show that the constant values of the average Nusselt number $\overline{Nu}$ were due to a decrease in local Nusselt number Nu on the descending side and an increase on the ascending side. The figures confirms the steepening of the temperature gradient at the upward side, and the flattening on the downward side, as compared with the corresponding values at Re = 0. For higher values of Re above the critical Re the temperature gradients on both sides have become much steeper than the values at Re = 0 and the temperature boundary layer becoming much thicker than for free convection.

In Fig. 9, the present numerical results are compared with the present experimental measurements. The agreement between the numerical solution and the measurements is rather good. It is shown from the figure that for the present experimental range of Grashof number, the dependence of Nusselt number on Grashof number decreases as the value of Reynolds number increases and for higher value of Reynolds number (above 6220) this dependence vanishes.

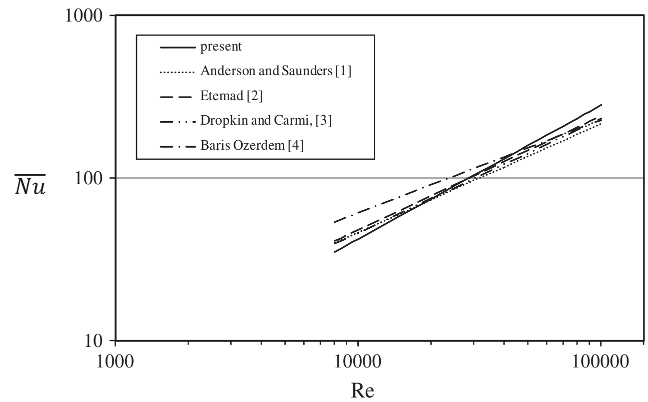

Fig. 10 Comparison of the present numerical with the experimental results.

The numerical correlation presented above predicts the effects of rotation on the convective heat transfer from an isothermal circular cylinder rotated in air at rest. Fig. 10 shows a comparison between the present numerical correlation with the experimental results of Anderson and Saunders [1], Etemad [2], Dropkin and Carmi [3], Ozerdem [4]. The figure shows a remarkable agreement with the present results.

5. Conclusions

(1) For a stationary cylinder (Re = 0) the maximum value of the local Nu number occurs at the bottom stagnation point; whereas the least value occurs at the top stagnation point. For a rotating circular cylinder, the maximum and minimum values of the local Nu number shifts in the direction of the rotation.
(2) For a rotating cylinder, the difference between maximum and minimum values of the local Nu number decreases with increase of Re. For high values of Re, this difference tends to vanish and local Nu number distribution on cylinder circumference becomes uniform.
(3) Isotherms and local Nusselt number distribution show that the constant values of the average Nusselt number at low Re up to critical value were due to a decrease in local Nusselt number on the descending side and an increase on the ascending side.
(4) For Reynolds numbers above 8000, the heat transfer rates were independent of the Grashof number (for Gr $\leqslant$ 100,000) and results for different values of Gr coincide and the results correlated as: Nu = 0.022Re$^{0.821}$. For Reynolds numbers below 500 the Nusselt numbers depended almost entirely on the Grashof numbers (for Gr > 100) and in the intermediate range between 500 and 8000 both the Grashof and the Reynolds numbers influenced the rate of heat transfer.
(5) The dependence of Nusselt number on Grashof number decreases as the value of Reynolds number increases and for higher value of Reynolds number this dependence vanishes.

(6) The comparison between the present correlation with the experimental results of Anderson and Saunders [1], Etemad [2], Dropkin and Carmi, [3], and Ozerdem [4] shows are remarkable agreement.

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