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Characteristics of the heat transfer from a horizontal rotating cylinder surface

Hongting Ma *, Zequn Ding, Yang Cao, Xinyu Lv, Wenqian Lu, Xiaopen Shen, Lihui Yin

School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, PR China
MOE Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Tianjin 300072, PR China

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ABSTRACT

In order to investigate the characteristics of the convective heat transfer from a large-diameter horizontal rotating isothermal cylinder at higher *Gr*-numbers (10^8), a specially designed micro-thermocouple is used to measure the temperature distribution around the cylinder at different rotational speeds *n*. The results indicate that the effect of rotation on the heat transfer on ascending side is different from that on the descending side. Rotation of the cylinder can lead to a nonuniform distribution of the local Nusselt number Nu_φ, especially in the region beyond the critical rotational Reynolds number $Re_{r,cri}$. There exists a critical Reynolds number $Re_{r,cri}$ when the mean Nusselt number *Nu* varies with the rotational Reynolds number Re_r, and *the* $Re_{r,cri}$ can be determined by $Re_r = 3.05Gr^{0.456}$. As $Re_r < Re_{r,cri}$, rotation has almost no effect on the *Nu* and the free convection dominates the heat transfer. As $Re_r \geqslant Re_{r,cri}$, *Nu* increases with rising Re_r, and the heat transfer characteristics are affected by both free and forced convection.

1. Introduction

Rotating cylinders have been widely applied in energy, metallurgy, light industry, spinning weaving industry and building material industry, etc. It is important to investigate the heat transfer characteristics of the rotating cylinders for designing and running these devices.

A large amount of research work has been done on natural convective heat transfer from a horizontal rotating cylinder. Mcadams [1] investigated the laminar free-convection characteristics from a horizontal isothermal cylinder, and proposed a heat transfer correlation that has been widely applied. By using laser technology and computer, the local convective heat transfer coefficient and velocity distribution around a horizontal static cylinder were studied, and a correlation $Re_r^2/Gr = 7.5$ was proposed to determine whether the impact of the free convection could be negligible [2,3]. Anderson et al. [4–6] investigated *Nu* from a horizontal rotating cylinder in three different flow patterns of natural, forced and mixed convection, and presented a correlation $Re_{r,cri} = 1.09Gr^{0.5}$ at lower *Gr*. Mahmoudi [7] has studied free convection heat transfer from an isothermal horizontal cylinder in the presence of DC positive corona discharge with a blade edge emitter electrode experimentally and numerically. The results reveal that corona discharge affects significantly on the average Nusselt number at lower Rayleigh numbers whereas it has smaller effect at higher Rayleigh numbers. Guillen [8] has experimentally investigated laminar opposing mixed convection to assess the thermal effects on the wake of an isothermal circular cylinder placed horizontally and confined inside a vertical closed-loop downward rectangular water channel by using particle image velocimetry (PIV) measurements. And strouhal number and vortex shedding modes are obtained as a function of the Richardson number to elucidate the effects of the lateral wall proximity effect and cylinder aspect ratio, separation angle, wake structure behind the cylinder, recirculation bubble length, time traces of velocity fluctuation.

Much intensive research on the pure forced convection from a flow-crossing cylinder with higher Re_r was conducted and the heat transfer correlation in consideration of rotation was proposed by Kays [9]. The literature reported effects of mixed convection parameter λ and *Pr* on the position of the separation point around the surface of the cylinder [10]. The results indicate that the decreasing λ would delay boundary layer separation, but the increasing λ would bring the separation point nearer to the lower stagnation point. And an increase in *Pr* would lead to a decrease of both the temperature and velocity profiles. Free-stream flow

* Corresponding author at: School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, PR China. Tel./fax: +86 022 27890131.
E-mail address: mht116@tju.edu.cn (H. Ma).

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Nomenclature

D	the outer diameter of the cylinder, mm
F	the cylinder surface area, m^2
Gr	Grashof number
h	the mean convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_φ	the local convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
n	the rotational speed of the cylinder, r. p. m
Nu	the mean Nusselt number
Nu_φ	the local Nusselt number at φ
Nu_{+90°	the local Nusselt number at +90°
Nu_{-90°	the local Nusselt number at −90°
$\Delta Nu_{\pm 90^\circ}$	the difference between Nu_{+90° and Nu_{-90°
$Nu_{\varphi_{max}}$	the maximal value of Nu_φ
$Nu_{\varphi_{min}}$	the minimal value of Nu_φ
Pr	Prandtl number
Q	the heat flux from the rotating cylinder surface to the ambient air, W
r_o	the radial of the cylinder, mm
Re_r	the rotational Reynolds number, $Re_r = uD/\nu$
$Re_{r,cri}$	the critical rotational Reynolds number
t	the temperature of the measuring point in the temperature boundary layer, °C
t_f	the temperature of the ambient air, °C
t_w	the temperature of the cylinder wall, °C
Δt	the difference between t_w and t_f, °C
y	the space from the measuring point to the cylinder wall, mm
Y	the dimensionless length, $Y = y/r_o$

Greek letters

Δ	difference
φ	the angle around the horizontal rotating cylinder, °
λ	the heat conductive coefficient of air, $W\,m^{-1}\,K^{-1}$
θ	the dimensionless temperature, $\theta = (t - t_f)/(t_w - t_f)$

Subscripts

cri	critical
f	the ambient air
w	the cylinder wall

and forced convection heat transfer across a rotating cylinder were investigated numerically at Re_r numbers of 20-160 and Pr numbers of 0.7. Nu was found to decrease with increasing rotational velocity and increase with increasing Re_r. A heat transfer correlation of Nu about Re_r was proposed in a 2D laminar flow regime under uniform heat flux and constant wall temperature boundary conditions [11].

Forced convective heat transfers to incompressible power-law fluids from a heated circular and elliptical cylinder in the steady, laminar cross-flow regime have been discussed numerically. The governing differential equations have been proposed to elucidate the influence of power law index, Pr, Reynolds number, and nondimensional rotational velocity on the detailed temperature field, and distribution of Nusselt number on the surface of the cylinder and Nu [12–15]. Zhang Ximin et al. [16,17] investigated the characteristics of the heat transfer from a horizontal rotating cylinder to ambient air at higher Gr and lower values of ratio Re_r^2/Gr, an equation correlating Nu with Gr and Pr was proposed, and finally both the first and second critical points were predicted in a uniform cross-flow using computational fluid dynamic simulation. Mohammed [18] presented an experimental investigation on mixed convection to study the local and average heat transfer for hydrodynamically fully developed, thermally developing and thermally fully developed laminar air flow in a horizontal circular cylinder subjected to a constant wall heat flux boundary condition. It was concluded that the free convection effects tended to decrease the heat transfer results at low Re while to increase the heat transfer results for high Re. The combined convection regime could be bounded by a suitable selection of Re number ranges and the heat flux ranges. Also, Mohammed [19] experimentally investigated the effect of different inlet geometries on laminar air flow combined convection heat transfer inside a horizontal circular pipe for Reynolds number range of 400–1600, and the Grashof number range from 3.12×10^5 to 1.72×10^6. An empirical correlation about the average heat transfer in terms of dependent parameters of Grashof, Prandtl and Reynolds numbers is proposed.

The heat transfer characteristics of an impinging jet-array issuing from the rotating inner cylinder in the concentric annulus with cooling applications to electric rotor machines were researched, and the isolated and interdependent influences of jet Reynolds number, Taylor number and Grashof number on both local and area-averaged Nusselt number were illustrated [20]. The heat transfer from a slot air jet impinging on a cylinder shaped food was investigated using computational fluid dynamics [21]. Equations correlating the local Nusselt numbers and mean Nusselt numbers with rotational speed, jet-to-surface distance, and nozzle geometry were given, and the heat and mass transfer coefficients distributions on the front edge, the rear, and the side of a circular and rectangular cylinder in an air jet impinging were studied experimentally, the results indicated that there are significant differences at various locations around the circumference of the cylinder [22,23]. Kendoush [24] investigated the convective heat transfer from a spinning cylinder in still air numerically, and obtained the analytical solution.

Ma Hongting et al. [25,26] investigated both the heat and mass transfer characteristics from a large diameter horizontal rotating cylinder with and without impingement. The local Sherwood number Sh_φ and the mean Sherwood number Sh varying with Re_r were studied experimentally. The first and second critical points were analyzed and validated. On the basis of experimental data, correlation equations of the mean convective mass transfer Sh and the critical Reynolds number Re_r were formulated respectively. Labraga and Berkah [27] measured the local mass transfer from a rotating cylinder in cross-flow by using the electrochemical method. Based on the experimental data, the equation correlating Sh with Re_r and free stream Reynolds number Re_∞ was obtained.

However, characteristics of the local and mean heat transfer from a larger diameter horizontal rotating cylinder at $Gr = 2.3 \times 10^8$ has not been reported so far. The present paper aims to conduct a deep investigation on the temperature distribution, the local and mean convective heat transfer coefficients, and the formula of $Re_{r,cri}$ at higher Gr.

2. Experimental apparatus and methods

2.1. Experimental apparatus

In order to investigate the characteristics of the convective heat transfer from a horizontal rotating cylinder with a larger diameter, a experimental equipment is designed and is shown in Fig. 1.