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Experimental investigation on the steady, external laminar mixed convection heat transfer characteristics around a large diameter horizontal rotating cylinder☆

Hongting Ma *, Wenjing Xia, Weiye Zhou, Wenwen Liu, Zhenyuan Guo, Chuanlong Zhang, Yufeng Zhang, Na Deng

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 steady, external laminar mixed convection, mainly the correlations about the heat transfer and the critical Reynolds number around a horizontal rotating isothermal cylinder, a particularly manufactured micro-thermocouple is employed to measure the temperature distribution in the thermal boundary layer around the cylinder surface at different rotational speeds, n. The results indicate that there exists a critical Reynolds number $Re_{r,cri}$ as the mean Nusselt number $\overline{Nu}$ varies with the rotational Reynolds number Re_r. The rotation of the cylinder can lead to a nonuniform distribution of local Nussel number Nu_φ, and the phenomenon becomes more obvious as Re_r exceeds $Re_{r,cri}$. $\overline{Nu}$ changes according to a certain rule with Re_r. As $Re_r < Re_{r,cri}$, the rotation has little impact on $\overline{Nu}$, and the free convection heat transfer plays a dominant role, but as $Re_r \geq Re_{r,cri}$, $\overline{Nu}$ increases with increasing Re_r, and the heat transfer characteristics are influenced by both the natural and the forced rotational convections simultaneously. Based on the experimental data, the correlations about the heat transfer can be expressed as $\overline{Nu} = 0.53\left[\left(0.0018Re_r^{2.66} + Gr\right)\cdot Pr\right]^{0.25}$, and the critical Reynolds number $Re_{r,cri}$ can be determined by $Re_{r,cri} = 3.05(Gr \cdot Pr)^{0.456}$.

1. Introduction

Rotating devices and machineries, such as cement rotary kiln, paper machine, roll of rolling mill, shaft of motor, rotary heat exchanger and heat pipe, are widely used in industries of energy, metallurgy, light industry, spinning and weaving industry, building material industry, etc. The rotating cylinder plays an important role in situations that need higher heat or mass transfer coefficient in practical engineering. The correlations of Nusselt number and critical Reynolds number could be used to predict the flow and heat transfer in rolling motion, and it is important for designing and running these devices and machineries to study the characteristics and correlations about the heat transfer.

Chhabra et al. [1,2] investigated a numerical free convective heat transfer from a horizontal cylinder immersed in quiescent power-law fluids in the laminar flow regime. As expected, the value of the local Nusselt number decreases from its maximum value at the front stagnation point along the surface of cylinder, as the flow remains attached to the surface of the cylinder over the range of conditions covered in this study and the surface-averaged Nusselt number shows positive dependence on both Grashof and Prandtl numbers. The governing differential equations have been solved numerically to elucidate the influence of power law index (n = 0.2, 0.6, and 1), Prandtl number ($1 \leq Pr \leq 100$), Reynolds number ($1 \leq Re \leq 40$), and nondimensional rotational velocity ($0 \leq \alpha \leq 6$) on the detailed temperature field, distribution of Nusselt number on the surface of the cylinder and on the mean Nusselt number when studying forced convection heat transfer from a heated cylinder rotating in streaming power-law fluids. Results showed that the mean Nusselt number shows positive dependence on both Reynolds and Prandtl numbers, which is obviously due to the gradual thinning of the boundary layer [3]. The qualitative and quantitative effects and differences between purely forced convective flow and purely free natural flow are concerned based on the rotating cylinder electrode configuration [4].

A large amount of researches have been done on the combined convective heat transfer in a laminar flow from the rotating horizontal cylinders in free stream. 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 and a numerical simulation based on the finite volume method of convection around a heated rotating cylinder are presented, which are in good agreement with experimental results for fluids of low Prandtl number and small

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

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Nomenclature

d	outer diameter of the cylinder (mm)
F	cylinder surface area (m^2)
Gr	Grashof number (–)
h	mean convective heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
h_{φ}	local convective heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
n	rotational speed of the cylinder (r.p.m)
$\overline{Nu}$	mean Nusselt number (–)
Nu'	arithmetic mean value of Nu_{φ} (–)
Nu_{φ}	local Nusselt number (–)
Pr	Prandtl number (–)
r_o	radius of test cylinder (mm)
Re_r	rotational Reynolds number (–)
β	ratio of Re_r^2 and Gr, $\beta = Re_r^2/Gr$ (–)
$Re_{r,cri}$	critical Reynolds number (–)
t_f	temperature of ambient air (°C)
t_q	qualitative temperature, ($t_q = (t_w + t_f)/2$) (°C)
t_w	temperature of cylinder wall (°C)
Δt	difference between t_w and t_f (°C)
y	space from measuring point to cylinder wall (mm)
Y	dimensionless length (–)

Greek letters

Δ	difference
φ	angle around a horizontal rotating cylinder (°)
λ	thermal conductivity of air ($Wm^{-1}\,K^{-1}$)
θ	dimensionless temperature (–)

Subscripts

cri	critical
f	ambient air
r	rotational
w	cylinder wall

values of the rotational speed [5,6]. Byoung et al. [7] numerically investigated the conjugate heat transfer around a circular cylinder in which the maximum temperature inside the cylinder decreases as Reynolds number increased lately. In this study the position of the maximum temperature inside the cylinder differs before $Re = 20$ and beyond $Re = 20$. A finite difference numerical method has been developed, validated, and used for the calculation of steady heat transfer and laminar flow around two rotating circular cylinders of the same diameter in a side-by-side arrangement, for the range of Reynolds number, $10 \le Re \le 40$, range of Prandtl number, $0.7 \le Pr \le 50$, range of absolute rotation, $|\alpha| \le 2.5$, and different gap spacing between cylinders. For the large gap spacing, the increase of $|\alpha|$ results in the decrease of the average Nusselt number and in decreasing variation of the local Nusselt number on the cylinder surfaces. The reason for this phenomenon is that as $|\alpha|$ increases, the size of the rotating fluid layers adjacent to the cylinder surfaces increases due to the no-slip requirement, which would decrease overall heat transfer rate [8]. Further numerical study has been researched for $20 \le Re \le 160$ and $Pr = 0.7$. The results also agree that cylinder rotation is an efficient Nusselt number reduction or cylinder-surface temperature enhancement technique for the reason explained above [9]. A numerical study of buoyancy-aided steady convection heat transfer from a horizontal cylinder placed in free stream was conducted and the results showed that the buoyancy force assists the forced convection flow significantly to improve the heat transfer characteristics from the heated cylinder [10]. Ozerdem [11] experimentally examined the convective heat transfer from a horizontal cylinder rotating in quiescent air, and measured the average convective heat transfer coefficients by using radiation pyrometer. The ambient air temperature was measured by means of four thermocouples placed equally around the rotating cylinder. The surface temperature of rotating cylinder was measured by a radiation pyrometer. It is found that the average Nusselt number increases with an increase in the rotating speed and a correlation in terms of the average Nusselt number and the rotating Reynolds number had been established. Cheng et al. [12] conducted the experiments to investigate the convective heat transfer on a radially rotating heated cylinder and indicated that the rotation-induced cross stream flow affects the heat transfer coefficient on the cylinder surface and the effect is more prominent for the cases with higher rotational speeds and lower Reynolds numbers.

Concerns are also paid to the heat transfer from the rotating horizontal cylinder in the cross-flow conditions. Shimada et al. [13] performed an experimental study of heat transfer on a horizontal rotating cylinder near a flat plate in a cross-flow and the results showed that when the space between the cylinder and plate is the same as the displacement thickness, the average Nusselt number from a cylinder with a plate is larger than without a plate and had a maximum value. Mohanty and Tawfek [14] analyzed the horizontal rotating cylinder surface heat transfer in the cross-flow conditions. The authors observed that for the same Reynolds numbers, the average heat transfer rate under pure rotation is about 30% higher than that for pure cross-flow and the Nusselt number could be adequately correlated against a Reynolds number based on the resultant velocity with in combined flow conditions.

There are some reports about the heat and mass transfers from a horizontal rotating cylinder. Ma Hongting et al. [15,16] studied the mass transfer on a large diameter rotating cylinder surface with and without a slot air jet flow. The effects of rotational Reynolds number Re_r, jet-exit Reynolds number Re_j, geometrical parameters of the nozzle and other factors on the heat and mass transfer were investigated, equations correlating the average Sherwood number Sh and the critical Reynolds number $Re_{r,cri}$ with the rotational Reynolds number Re_r, the Schmidt number Sc and the Grashof number Gr have been obtained, respectively.

However, characteristics of both the local and average heat transfers from a larger diameter horizontal rotating cylinder with the higher values of Grashof number Gr (10^8) and the lower values of ratio β ($\beta = Re_r^2/Gr$) have 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, correlations about the heat transfer and the determination of the critical Reynolds number $Re_{r,cri}$.

The following experimental range is covered in this paper: Rotating Reynolds number Re_r: 4×10^3–5×10^4, Grashof number Gr: 2.3×10^8–6.0×10^9. Cylinder surface temperature: 50–140 °C, rotational speed n: 6–180 r.p.m.

2. Experimental apparatus and methods

2.1. Experimental apparatus

The schematic diagram of the test apparatus is shown in Fig. 1. The rotating cylinder, 900 mm in length, 500 mm in outer diameter and 2 mm in thickness, is made of steel sheet covered with a thin layer of chromium.

The cylinder casing consists of two layers of which the distance is 18 mm in order to increase the strength of the cylinder, improve the uniformity of heat flow and make the cylinder surface isothermal. On the surface of the inside layer there are 20 rectangular holes for improving the air convection. The cylinder cavity is divided into three parts. The middle part, 500 mm long, in which the main electric heater is installed, is the experimental section. The both ends are 200 mm long, each fixed with a supplemental heater. The main and supplemental heaters are