International Communications in Heat and Mass Transfer 68 (2015) 283–290

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Influence mechanism of rotation on the convective heat transfer and fluid-flow characteristics from a large diameter rotating isothermal cylinder☆

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ARTICLE INFO

Available online 3 October 2015

Keywords:
Influence mechanism
Temperature distribution characteristics
Trailing vortex

ABSTRACT

A micro-thermocouple is specially designed and employed to measure the temperature distribution in the boundary layer around a cylinder surface, and the influence mechanism of rotation on the convective heat transfer characteristics from a large diameter rotating isothermal cylinder has been experimentally investigated. The effect of rotation on the trailing vortex is observed and analyzed by using a schlieren apparatus. The results show that rotation has an obvious effect on the air flow and temperature distribution characteristics around the cylinder surface. There exists a worst convective heat transfer region which does not coincide with the trailing vortex region as previously reported.

1. Introduction

Rotating devices and machineries are widely applied to the industries of energy, metallurgy, light industry, spinning weaving industry and building material industry, etc. It is important for designing and running these devices and machineries to study the heat transfer characteristics, analyze the influencing factors on the heat transfer, seek stronger or weaker heat transfer areas, and find effective measures to enhance or weaken the heat transfer.

A great number of investigations on the heat and mass transfer from rotating cylinders have been reported. Fénot et al. [1] investigated the convective heat transfer of a complex annular channel with an inner rotating wall. Local heat transfer on both cylinders (rotor and stator) was measured by using an infrared thermography device and PIV measurements were carried out in rotor slots. The results indicated a clear difference of heat transfer between slot sides and poles. Convective heat transfer from a rotating cylinder with inline and cross-flow oscillation was studied by a numerical investigation using a characteristic based split (CBS) method. It was found that vortex shedding was mainly suppressed beyond a critical rotating speed and as the rotational speed of the cylinder increased, both the Nusselt number and the drag coefficient decreased rapidly, but in the vortex lock-on region, the Nusselt number increased rapidly [2,3]. Latour et al. [4,5] evaluated the local convective heat transfer from a rotating finned cylinder to the surrounding air using an infrared thermographic experimental setup. The local heat transfer on the fin surface was analyzed to determine the influence of the rotational Reynolds number and the influence of the height and spacing of the fins. The relative influences of the rotational and airflow forced convections on the heat transfer were analyzed, and correlations of the mean Nusselt number on the fin, relative to both Reynolds numbers, were proposed by using an inverse method based on the mean squared error. Mohammed et al. [6] experimentally investigated the forced and free convective heat transfer for thermally developing and thermally fully developed laminar air flow inside horizontal concentric annuli in the thermal entrance length and indicated that the free convection effects tended to decrease the heat transfer at low *Re* number while to increase the heat transfer for high *Re* number. Jeng et al. [7] experimentally investigated the heat transfer characteristics of a rotating cylinder under lateral air impinging jet using an infrared thermo tracer. A prediction equation for critical L/W value that can generate maximum value was provided, and the equation could serve as reference for practical design of cooling system of related power machinery. Giordano et al. [8] experimentally studied the heat transfer on the base surface of a protruding cylinder in a cross flow by applying IR thermography and the heated thin foil heat flux sensor. The high heat transfer region downstream of the cylinder was found to correspond with the tip vortex impingement in the case of the short cylinder, and corresponded with the turbulent reattachment location in the case of the long cylinder. Nguyen and Harmand [9] studied the flow field and the heat transfer from a rotating cylinder with a spanwise disk attached and subjected to air crossflow using numerical simulation method. Reynolds Averaged Navier–Stokes (RANS) simulations using the realizable turbulence model were performed for various crossflow and rotational velocities. The heat transfer results from the RANS simulations were evaluated and were in good agreement to those obtained from previous heat transfer experiments.

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.09.006
0735-1933/

Nomenclature

D	outer diameter of cylinder (mm)
F	cylinder surface area (m^2)
Gr	Grashof number ($Gr = \frac{g\beta\Delta t D^3}{\nu^2}$)(−)
h	mean convective heat transfer coefficient (W m^{-2} K^{-1})
h_φ	local convective heat transfer coefficient (W m^{-2} K^{-1})
L	length of cylinder (mm)
n	rotational speed of cylinder (r.p.m.)
$\overline{Nu}$	mean Nusselt number (−)
Nu_φ	local Nusselt number at φ ($Nu_\varphi = \frac{h_\varphi D}{\lambda}$) (−)
$\overline{Nu'}$	arithmetic mean value of Nu_φ (−)
$Nu_{+90°}$	local Nusselt number at +90° ($Nu_{+90°} = \frac{h_{+90°}D}{\lambda}$) (−)
$Nu_{-90°}$	local Nusselt number at −90° ($Nu_{-90°} = \frac{h_{-90°}D}{\lambda}$) (−)
$\Delta Nu_{\pm 90°}$	difference between $Nu_{+90°}$ and $Nu_{-90°}$ (−)
Pr	Prandtl number ($\Pr = \frac{\nu}{a}$)(−)
Q	heat flow from rotating cylinder surface to ambient air (J)
r_o	radial of cylinder (mm)
R	dimensionless length (−)
Re_r	rotational Reynolds number ($Re_r = \frac{\pi D^2}{60\nu}n$)(−)
$Re_{r,cri}$	critical rotational Reynolds number ($Re_{r,cri} = \frac{\pi D^2}{60\nu}n$) (−)
T	temperature of the measuring point in temperature boundary layer (°C)
T_f	temperature of ambient air (°C)
T_w	temperature of cylinder wall (°C)
T_q	qualitative temperature, ($T_q = (T_w + T_f) / 2$) (°C)
ΔT	difference between T_w and T_f (°C)
y	space from the measuring point to cylinder wall (mm)

Greek letters

Δ	difference
φ	azimuth angle around horizontal rotating cylinder (°)
λ	thermal conductivity of air (W m^{-1} K^{-1})
θ	dimensionless temperature (−)
ω	deflection angle, (°)

Subscripts

cri	critical
f	ambient air
w	cylinder wall

Chatterjee et al. [10] performed a two-dimensional numerical simulation for the hydromagnetic mixed convective transport in a vertical lid-driven square enclosure filled with an electrically conducting fluid in the presence of a heat conducting and rotating solid circular cylinder, and observed that the heat transfer greatly depends on the rotational speed of the cylinder. Yoon Hyun Sik et al. [11] numerically investigated two-dimensional natural convection in a cooled square enclosure with two inner circular cylinders, which have different isothermal conditions for different Rayleigh numbers in the range of $10^3 \le Ra \le 10^5$. V.G. Kozlov et al. [12] experimentally investigated the thermal convection of fluid with internal heat sources in a rotating horizontal cylinder with isothermal boundary and adiabatic ends and found that the inertial waves which are generated near the ends of the cavity by tidal oscillations of non-isothermal liquid effect the convection. It is shown that the influence of inertial waves on heat transfer and structure of convective flows strongly depends on the cavity aspect ratio. Ma Hongting et al. [13–15] investigated both the heat and mass transfer characteristics and the analogy between the heat and mass transfer from a large-diameter horizontal rotating cylinder with and without impingement experimentally. The first and second critical points were analyzed and validated deeply and 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.

M. Sheikholeslami [16,17] has studied the ferrofluid flow and heat transfer in the presence of an external variable magnetic field, and nanofluid flow and heat transfer over a stretching porous cylinder, it was shown that the enhancement in heat transfer decreased with an increase in the Rayleigh number and magnetic number but it increased with an increase in the Hartmann number, and the Nusselt number was an increasing function of nanoparticle volume fraction, suction parameter and Reynolds number. The hydrothermal behavior of nanofluid fluid between two parallel plates has also been investigated, and found heat transfer enhancement has direct relationship with Reynolds number when power law index was equals to zero but opposite trend was observed for other values of power law index [18]. Mohsen Sheikholeslami et al. [19] has explored the effect of magnetic field on natural convection heat transfer of Al_2O_3–water nanofluid in a two-dimensional horizontal annulus with the lattice Boltzmann method, the results indicated that the Lattice Boltzmann method with double-population was a powerful approach for the simulation of natural convection heat transfer in nanofluids in regions with curved boundaries. Nanofluid flow and heat transfer characteristics between two horizontal parallel plates in a rotating system has been studied, and the Nusselt number increased with increase of nanoparticle volume fraction and Reynolds number but decreased with increase of magnetic and rotation parameters was found [20].

However, characteristics of heat transfer and air flow from a rotating cylinder surface has not been studied systematically. This work aims to investigate the temperature distribution, the local and mean convective heat transfer coefficients, and the air flow around the rotating cylinder, which is helpful to the thermal application of rotating circular devices, and the data are correlated empirically for use in predicting experimental data and thermal process design situation.

2. Experimental apparatus and methods

2.1. Experimental apparatus

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

The cylinder is made of steel sheet with an outer diameter of 315 mm, a length of 800 mm, a thickness of 3.5 mm and a taper of 6.34×10^{-4}, mounted horizontally. During fabrication, the cylinder was highly polished to adjust its un-roundness which was strictly controlled within 0.2 mm. To reinforce the strength of the cylinder and improve the uniformity of heat flux, the cylinder casing is composed of two layer with a distance of 18 mm. 20 rectangular holes are set on the surface of the inner layer for facilitating the air convection.

Before experiment, the cylindrical surface is covered with a layer of chromium by electroplating, as a result, the surface oxidation/deposition cannot occur in the experiment process, and the emissivity will not rapidly increase. The emissivity of the cylinder surface was carefully determined by AGA 780 Thermovision and normal emissivity meter, and found to be nearly steady and equals to 0.22.

In the experiment, all data were metered in steady state conditions so that two consecutive readings taken at half an hour intervals displayed almost the same values.

2.2. Experimental methods

2.2.1. Measurement of the cylinder surface temperature

The heating system of the cylinder consists of one main heater and two supplemental heaters. The AC power is supplied to heaters by a transformer and the power mains are introduced through the center of the shaft. The cylinder surface temperature is measured by five