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Measurement of the temperature and concentration boundary layers from a horizontal rotating cylinder surface

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ABSTRACT

In order to measure the temperature and concentration boundary layers from a large diameter horizontal rotating cylinder surface, a minitype thermocouple and a dry-wet bulb thermocouple have been used in the present study. The effect of rotation on the temperature and concentration distributions has been investigated experimentally. The results indicate that the influence of rotation on the ascending side is different from that on the descending side. With the increase of rotational Reynolds number Re_r, the temperature and concentration gradients increase consistently on the ascending side. But on the descending side, the temperature and concentration gradients decrease initially and reach a minimum, then begin to increase with the increase of Re_r. The temperature measurement error caused by radiation is less than 3%, while the concentration measurement error caused by radiation ranges from 3% to 8%, and it will get larger when approaching the cylinder surface.

1. Introduction

Rotating cylinder equipment is widely used in industrial processes, and plays an important role in occasions that need higher heat or mass transfer coefficient. A great number of investigations on the heat and mass transfer from rotating cylinders have been reported. Herráez and Belda [1] explored the free convection in air around horizontal cylinders of different diameters based on holographic interferometry, with the aim of defining the corresponding temperature fields, and the Nusselt numbers corresponding to each direction of measurement were calculated. Qzerden [2] experimentally analyzed the convective heat transfer from a horizontal cylinder rotating in quiescent air and measured the average convective heat transfer coefficients by using radiation pyrometer. It was found that the average Nusselt number increased with an increase in the rotating speed, and a correlation in terms of the average Nusselt number and rotating Reynolds number had been established. Fénot et al. [3] 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 using an infrared thermography device and PIV measurements were carried out in rotor slots. The results indicated a clear difference of heat transfer between slots 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 [4,5]. Ma et al. [6] investigated the correlations about the heat transfer and the critical Reynolds number around a horizontal rotating isothermal cylinder.

Latour et al. [7,8] evaluated the local convective heat transfer from a rotating finned cylinder to the surrounding air using an infrared thermographic experimental set up. A model of local convective heat transfer was developed to take lateral conduction and 2D geometry into account. 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. [9] 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

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Nomenclature

d	diameter of cylinder, mm
F	area of thermocouple surface, m^2
F_{s-w}	radiation heat transfer area between thermocouple and cylinder wall, m^2
Gr	Grashof number (–)
h_φ	local convective heat transfer coefficient, W/(m^2 K)
n	cylinder rotational speed, r/min
Nu_φ	local Nusselt number (–)
p_a	ambient pressure, p_a
p_{cri}	critical pressure of vapor, p_a
p_{sv}	saturation pressure, p_a
Pr	Prandtl number (–)
Q_c	convective heat between thermocouple and boundary layer medium, J
Q_c'	convective heat between wet bulb and boundary layer medium, J
Q_m	latent heat of vaporization from wet bulb surface, J
Q_r	radiation heat from thermocouple to ambient air, J
Q_r'	radiation heat from wet bulb to ambient air, J
Q_R	radiation heat from porous medium to thermocouple, J
Q_R'	radiation heat from porous medium to wet bulb, J
r_0	radius of porous medium cylinder, mm
r	distance between measured point and cylinder wall, mm
r^+	dimensionless distance, r/r_0
Re_r	rotational Reynolds number, $\pi nd^2/(60\nu)$
$Re_{r,cri}$	critical Reynolds number (–)
Sh_φ	local Sherwood number (–)
$\overline{Sh}$	mean Sherwood number (–)
t	temperature of the measuring point in temperature boundary layer, °C
t_d	dry-bulb temperature, °C
t_f	ambient temperature, °C
t_m	wet-bulb temperature, °C
t_s	temperature of thermocouple surface, °C
t_w	temperature of cylinder wall, °C
Δt	difference between t_w and t_f, °C
T	temperature of boundary layer media, K
T_f	absolute temperatures of ambient air, K
T_s	absolute temperature of thermocouple surface, K
T_w	absolute temperature of cylinder wall, K

Greek letters

ε_s	emissivity of thermocouple surface
ε_w	emissivity of cylinder surface
ε_f	emissivity of environment
ε_s'	emissivity of wet bulb surface
ε_w'	emissivity of porous medium surface
σ	radiant emissivity of black body, W/(m^2 K^4)
Ψ_{s-w}	radiative angle factor from thermocouple to cylinder wall
Ψ_{s-f}	radiative angle factor from thermocouple to environment
α	convective heat transfer coefficient between thermocouple and ambient air W/(m^2 °C)
ν	kinematic viscosity, m^2/s
ρ	water vapor density in concentration boundary layer, kg/m^3
ρ_{sv}	saturated density, kg/m^3
ρ_w	water vapor density at surface of cylinder, kg/m^3
ρ_f	water vapor density in ambient air, kg/m^3
ρ^+	dimensionless density, $(\rho - \rho_f)/(\rho_w - \rho_f)$
φ	angle around a horizontal rotating cylinder, °
ϕ	relative humidity, %
λ	heat conductive coefficient of air, W/(m K)
θ	dimensionless temperature, $(t - t_f)/(t_w - t_f)$

Subscripts

r	rotational
w	cylinder wall
cri	critical
sv	saturation

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. Paramane and Sharma [10,11] numerically investigated the free-stream flow and forced convection heat transfer across a rotating cylinder. The average Nusselt number was found to decrease with increasing rotational velocity and increase with increasing *Re*, and at higher rotational velocity, the Nusselt number was almost independent of Reynolds number and thermal boundary conditions as the heat transfer near cylinder surface was limited to conduction only. Juncu [12] analyzed the unsteady conjugate heat/mass transfer between a circular cylinder and a surrounding fluid flow. The heat/mass balance equations were solved numerically in cylindrical coordinates by the ADI finite difference method.

Jeng et al. [13] 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 *Nu* value was provided, and the equation could serve as reference for practical design of cooling system of related power machinery. Giordano et al. [14] 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 [15] 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 κ–ξ 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. Yan and Zu [16] studied the heat transfer of a rotating isothermal cylinder and simulated that numerically by the lattice Boltzmann method (LBM). The numerical strategy and method were validated by comparing the numerical results of flow without heat transfer with those of available previous theoretical, experimental and numerical studies, showing good agreements.

Labraga and Berkah [17] investigated the local mass transfer from a rotating cylinder in a crossflow by using the electrochemical method. Based on the experimental data, the upstream moving surface of the rotating cylinder contributed the most to the mass transfer enhancement and equation correlating the mean Sherwood number $\overline{Sh}$ with the rotational Reynolds number Re_r and free stream Reynolds number Re_∞ was obtained. Ma et al. [18,19] experimentally investigated 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 determined,