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Experimental research on natural convective heat transfer of water near its density maximum in a horizontal annulus

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ABSTRACT

In this paper, the heat transfer characteristics of the natural convection of water near its density maximum in a horizontal annulus had been experimentally investigated. The annulus was formed with two copper cylindrical walls, which were concentric or eccentric. The temperature of the outer cylinder was kept at around 0 °C and that of the inner cylinder was ranged from 0 to 12 °C. In order to enhance heat transfer, three-dimensional external fins were applied on the inner wall. The effects of the gap width and the eccentricity of annulus and the fin geometric parameters on heat transfer were studied. The results show that the two turning points of the average Nusselt number on the inner wall appear at the temperature differences close to 4 °C and 8 °C, respectively. With the increase of temperature difference, the average Nusselt number firstly increases, and then decreases, finally increases again. The minimum value of the average Nusselt number locates near the temperature difference 8 °C. Additionally, it increases with the increase of the gap width of annulus and the eccentricity. Furthermore, when three-dimensional external fins were applied, the average Nusselt number increases with the increase of the fin axial pitch, whereas it decreases with the increase of the fin width. In the range of experimental values, the influences of the fin height and circular pitch are slight. Finally, the experimental empirical correlations of heat transfer on the inner wall are obtained.

1. Introduction

Natural convective heat transfer between two concentric or eccentric horizontal cylindrical walls are encountered in some important process in engineering, such as the cooling of electronic equipments, solar collector spaces, the ice forming and melting in the cool-thermal energy storage system, and crystal growth. Kuhen and Goldstein [1,2] conducted an comprehensive experimental investigation on the natural convective heat transfer of air in concentric and eccentric horizontal annuli for the Rayleigh (*Ra*) numbers from 2.2×10^2 to 7.7×10^7. It was reported that the eccentricity substantially altered the local heat transfer ability on both cylinders, but the overall heat transfer coefficient was changed by less than 10%. Later, some experimental and numerical investigations had been carried out for natural convection in a horizontal annulus with different inclination angle measured from the horizontal level, by Takata et al. [3], Hamad et al. [4,5] and Nada [6]. In these works, it was concluded that the influences of the annulus gap and the Rayleigh number on natural convection heat transfer were more significant than that of the inclination angle. The heat transfer rate increased with the increase of the annulus gap width and the Rayleigh number and the decrease of the inclination angle of the annulus. Furthermore, many numerical simulations and linear stability analysis had been also performed for natural convective heat transfer in concentric and eccentric horizontal annulus. In previous works, the density of the fluid was considered as a linear function of temperature, and the influences of the geometry parameters [7–9] and the Rayleigh number, the Prandtl number [10–12], eccentricity [13,14] were studied, and the transition and multiplicity of flows [15–18] were also exhibited.

Up to now, various numerical simulations on the natural convection of cold water near its density maximum in concentric and eccentric horizontal annuli had been performed. Nguyen et al. [19], Vasseur et al. [20], Raghavarao and Sanyasiraju [21] obtained the heat transfer characteristics, the velocity profiles, the local and average Nusselt (*Nu*) numbers of the steady natural convection of cold water between two horizontal concentric cylinders with constant surface temperatures for different Rayleigh number, radius ratio and density inversion parameter. It was also found that the flow pattern was greatly influenced by the density inversion parameter of water. The work of Raghavarao and Sanyasiraju [22] on the steady-state natural convection of water in an eccentric annulus showed that the flow was symmetric about vertical axis for vertical eccentricity. The heat transfer rate depended on the position of the maximum density point in the

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Nomenclature

A	heat transfer surface area, m^2
B	fin width, m
c_p	specific heat at constant pressure, J/(kg K)
d	eccentric distance between the center of inner cylinder and outer cylinder, m
D	cylindrical wall diameter, m
e	eccentricity, $e = 2d/(D_o - D_i)$
g	acceleration of gravity, m/s^2
h	average heat transfer coefficient, $W/(m^2 K)$
H	fin height, m
l	the gap width of annulus, $l = (D_o - D_i)/2$, m
Nu	average Nusselt number, –
P	pitch of fin, m
Pr	Prandtl number, $Pr = \nu/\alpha$, –
q	exponent in density-temperature Eq. (1)
q_m	mass rate of circulating fluid, kg/s
Q	heat transfer rate, W
Ra	Rayleigh number based on the gap width, $g\gamma\Delta T^q l^3/(\nu\alpha)$
T	temperatures, °C

Greek symbols

α	thermal diffusivity, m^2/s
γ	coefficient in density-temperature Eq. (1), $(°C)^{-q}$
μ	dynamic viscous, kg/(m s)
Θ_m	density inversion parameter, $\Theta_m = (T_m - T_o)/(T_i - T_o)$
ρ	density, kg/m^3
λ	thermal conductivity, W/(m K)

Subscripts

a	axial
c	circular
i	inner wall
o	outer wall
m	density inversion point
in	inlet
out	outlet
f	the circulating fluid in the inner tube
ave	average

annulus. Li and Yuan et al. [23,24] revealed the complicated flow patterns and the heat transfer characteristics of the natural convection of water near its density maximum from steady-state to oscillatory flow between horizontal cylinders with different radius ratio, density inversion parameter and eccentricity by numerical simulation. On the other hand, Seki et al. [25] experimentally investigated the effect of density inversion on the steady natural convective heat transfer of cold water between two horizontal concentric cylinders with radius ratio in the range of 1.18–6.39. It was concluded that the effect of density inversion was unexpectedly large and the average Nusselt number was different from those of common liquids. Funawatashi et al. [26] experimentally observed the flow structure on natural convection of water near its density maximum in a horizontal annulus by trace method. However, there are a few experimental investigations on the heat transfer characteristics of natural convection of water near its density maximum in the concentric and eccentric horizontal annuli.

In this paper, a comprehensive experimental investigation on the natural convective heat transfer of cold water in concentric and eccentric horizontal annuli is performed at different gap width of the annulus and eccentricity. At the same time, general heat transfer correlations are obtained, which can be used as the design guidance in a wide range of engineering applications.

2. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. The horizontal annulus is constructed by an inner copper tube with 14 mm outer diameter and an outer copper tube with three different inner diameters 26 mm, 38 mm and 50 mm, respectively. As pointed out by Seki et al. [25], the natural convection begins to dominate the heat transfer in the horizontal annulus when the radius ratio of outer to inner cylindrical walls exceeds 1.6. Therefore, the minimum gap width is set up at 6 mm in this experiment. The length of the annulus is 400 mm. In order to reduce heat losses, two end walls of the annulus are sealed by two circular rubber sheets with low thermal conductivity. The temperature of the inner cylinder is kept at a high temperature by circulating fluid in the inner tube. The annulus is placed in ice-storage tank to maintain the surface temperature of the outer cylinder close to 0 °C. The different eccentricity is obtained by adjusting the position of the inner tube. In this work, only the case in which the center of the inner tube is below the center of the outer tube is considered. To enhance the convective heat transfer, three-dimensional external fins are applied on the outer wall of the inner tube, as shown in Fig. 2. The detailed geometrical sizes of the three-dimensional external fins are listed in Table 1.

The inner tube is connected with a constant temperature bath with a temperature sensitivity of ±0.05 °C to control the temperature of the inner cylinder from 0 to 12 °C. The temperature distributions of the inner and outer walls of the annulus are measured by eight thermocouples (type T), respectively. The thermocouples are riveted on the outer wall of the inner tube and the inner wall of outer tube to reduce the measuring error, and arranged in this way in which two adjacent thermocouples are spaced by 90° along the circumferential direction and equally spaced in the axial direction. The inlet and outlet temperatures of the circulating fluid in the inner tube are measured by three thermocouples (type T) spaced evenly apart, respectively. All the temperature signals are acquired with a HP data acquisition instrument and sent into a PC for data recording. As the mass flow rate of the circulating fluid is a very little quantity, an electronic weighing scale is used for its measurement. The mass flow rate of the circulating fluid is an important parameter in controlling the temperature variation on the inner cylindrical wall of the annulus. In this experiment, the

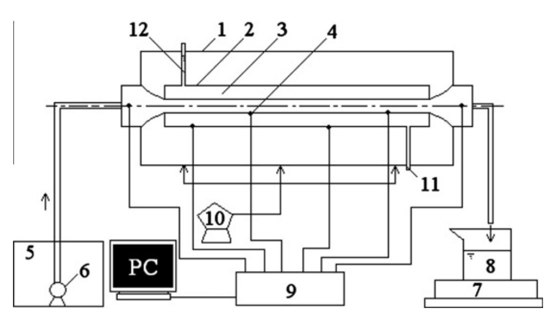

Fig. 1. The schematic diagram of the experimental setup. 1 – Ice-storage tank; 2 – concentric tubes; 3 – horizontal annulus; 4 – thermocouple; 5 – constant temperature bath; 6 – submersible pump; 7 – electronic weighing scale; 8 – measuring cup; 9 – HP data acquisition instrument; 10 – blender; 11 – intake pipe; 12 – balance pipe.