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Heat transfer in rotating cylindrical cells with partitions

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ABSTRACT

A numerical analysis and an experimental study of heat transfer rate in rotating cylindrical cells with partitions are performed. The work is done mainly in the Ekman suction regime, where the Coriolis force dominates over centrifugal buoyancy. It is shown that the heat transfer rate increases substantially by placing partitions in the cell. The partitions suppress the Coriolis force so that convection induced by the centrifugal buoyancy becomes important. It is found that the Nusselt number correlates with the parameter $\mathrm{Pr}\beta\Delta\mathrm{TEk}^{-1/2}$ with the partitions. The partitions have no effect on the heat transfer in the centrifugal buoyancy convection regime.

1. Introduction

Advanced life support systems and waste treatment systems will become increasingly important in future long-duration space missions (Committee on Microgravity Research, 2000). A significant problem in the development of life support systems in microgravity is insufficient knowledge concerning fluid motion. One effective way to induce fluid flow in the presence of density gradients (for increased heat or mass transfer) is to use rotation (centrifugal acceleration). Also, the performance of rotating electrochemical cells in microgravity has been extensively investigated by our group (e.g. Weng et al., 1998). Flows in rotating systems with heat or mass transfer are also of scientific interest because of complex interactions among centrifugal and gravitational buoyancy, Coriolis and viscous forces. Heat transfer in rotating cylindrical cells with their axes aligned with gravity has been studied by several investigators in the past, theoretically (Barcilon and Pedlosky, 1967; Homsy and Hudson, 1969), experimentally (Hudson et al., 1978), numerically (Chew, 1985; Guo and Zhang, 1992; Brummell et al., 2000), among many others. Those studies were performed under negligible gravity or the heat-from-above configuration. Mass transfer in rotating shallow electrochemical cells was investigated experimentally (Weng et al., 1998) and numerically (Weng et al., 2000). Weng et al. (1998) also performed a scaling analysis of heat and mass transfer in rotating cells to determine the flow and boundary layer characteristics. They delineated two convection mechanisms for the boundary layer regime: one is centrifugal buoyancy dominated convection and the other is called Ekman suction convection. In the Ekman suction regime, the Coriolis force suppresses centrifugal buoyancy, inhibiting the heat transfer rate. In some applications it is desirable to increase the heat or mass transfer rate (e.g. electrochemical applications in microgravity). Since the Coriolis force is associated with the azimuthal flow, the heat transfer rate can be increased by placing partitions in the cell in order to suppress the azimuthal flow and thus the Coriolis force. For this reason the effect of partitions on the flow and heat transfer in rotating cylindrical cells is investigated mainly numerically in this work. Experimental work is also performed to validate some of the numerical results. The work is done mainly under the condition that gravitational buoyancy is negligible.

2. Mathematical formulation and important dimensionless parameters

The flow and heat transfer in rotating cells are investigated mainly numerically in this work. Fig. 1 is a schematic of rotating cylinder with partitions. The (r, θ, z) coordinate system, defined in Fig. 1, is attached to the rotating container. The flow is assumed to be steady and laminar. The modified Boussinesq approximation is employed, namely the fluid density is variable only in the centrifugal and gravitational terms, which gives rise to centrifugal buoyancy and gravitational buoyancy, respectively. The coordinates r and z are non-dimensionalized by R and H, respectively. The velocities (u, v, w) are made dimensionless by $R\Omega\beta\Delta T$, $R\Omega\beta\Delta T$, and $R\Omega\beta\Delta T$ Ar, respectively, based on the scaling analysis by Weng et al. (1998). The pressure p is modified from the original pressure p^* as $p = p^* + \rho g z - \rho\Omega^2 r^2/2$. The modified pressure p is non-dimen-

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Nomenclature

Symbols

Ac	ratio of gravitational to centrifugal acceleration, g/Ω^2R
Ar	aspect ratio, H/R
Ek	Ekman number, $\nu/\Omega H^2$
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 °C)
H	height of test cell (m)
K	thermal conductivity (W/m °C)
NP	number of partitions
Nu	Nusselt number, hH/k
P	modified pressure, $p = p^* + \rho gz - \rho\Omega^2\mathbf{r}^2/2$ (Pa)
p^*	pressure (Pa)
Pr	Prandtl number, ν/α
r	radial coordinate (m)
R	radius of test cell (m)
Ro_T	thermal Rossby number, $\beta\Delta T$
T	temperature (°C)
T_C	cold wall temperature (°C)
T_H	hot wall temperature (°C)
(u,v,w)	velocity components (m/s)
U	radial reference velocity (m/s)
Z	axial coordinate (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric expansion coefficient (1/°C)
δ_T	thermal boundary layer thickness (m)
δ_V	velocity boundary layer thickness (m)
ΔT	temperature difference, $T_H - T_C$ (°C)
θ	azimuthal angle (rad)
θ_0	sector opening angle (rad)
ν	kinematic viscosity (m^2/s)
Ω	rotation rate (rad/s)
ρ	density (kg/m^3)

sionalized by $\mu\Omega\beta\Delta T$. The temperature is non-dimensionalized as $(T - T_C)/\Delta T$. The following dimensionless equations are solved.

Continuity equation:

$$\frac{\partial}{\partial r}(ru) + \frac{\partial}{\partial \theta}(rv) + \frac{\partial}{\partial z}(rw) = 0 \quad (1)$$

Momentum equations:

$$\beta\Delta T\left(u\frac{\partial u}{\partial r} + \frac{1}{r}v\frac{\partial u}{\partial \theta} + w\frac{\partial u}{\partial z} - \frac{v^2}{r}\right) = 2v - rT - Ar^2Ek\frac{\partial p}{\partial r} + Ek\left(\nabla^2 u - \frac{u}{r^2} - \frac{2}{r^2}\frac{\partial v}{\partial \theta}\right) \quad (2)$$

$$\beta\Delta T\left(u\frac{\partial v}{\partial r} + \frac{1}{r}v\frac{\partial v}{\partial \theta} + w\frac{\partial v}{\partial z} + \frac{uv}{r}\right) = -2u + Ek\left(\nabla^2 v - \frac{v}{r^2} + \frac{2}{r^2}\frac{\partial u}{\partial \theta}\right) \quad (3)$$

$$\beta\Delta T\left(u\frac{\partial w}{\partial r} + \frac{1}{r}v\frac{\partial w}{\partial \theta} + w\frac{\partial w}{\partial z}\right) = \frac{Ac}{Ar}T - Ek\frac{\partial p}{\partial z} + Ek\nabla^2 w \quad (4)$$

where $\nabla^2 = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}$.

Energy equation:

$$\beta\Delta T\left(u\frac{\partial T}{\partial r} + \frac{1}{r}v\frac{\partial T}{\partial \theta} + w\frac{\partial T}{\partial z}\right) = \frac{Ek}{\text{Pr}}\nabla^2 T \quad (5)$$

As for the boundary conditions, all the velocities vanish on the walls (top, bottom, outer and partition walls). The top and bottom walls are maintained at uniform temperatures (T_H or T_C). The outer and partition walls are thermally insulated. The partitions are equally spaced in the azimuthal direction.

Several important parameters appear in the above equations: Ek (Ekman number) = $\nu/\Omega H^2$, Ro_T (thermal Rossby number) = $\beta\Delta T$, Pr (Prandtl number) = ν/α, Ar (container aspect ratio) = H/R, and Ac (gravitational to centrifugal acceleration ratio) = $g/\Omega^2 R$. From the above equations one sees that Ek represents the ratio of viscous to Coriolis forces, and $\beta\Delta T$ represents the ratio of inertia to Coriolis forces. The ratio of gravitational to centrifugal buoyancy forces scales as Ac/Ar. The overall heat transfer coefficient (h) is computed from the total heat transfer rate through the liquid and the imposed temperature difference, which is then non-dimensionalized as the average Nusselt number (Nu = hH/k).

This work covers the following parametric ranges: $0.7 \leqslant \text{Pr} \leqslant 3000$ (mainly Pr = 7), $0.002 \leqslant \beta\Delta T \leqslant 0.2$, $0.3 \leqslant \text{Ar} \leqslant 1.4$, and $2 \times 10^{-5} \leqslant \text{Ek} \leqslant 10^{-2}$. Ac = 0, except when the numerical results are compared with experimental data. This work is directly applicable to the corresponding mass transfer problem if we replace ΔT by ΔC (C, concentration), Pr by Schmidt number, and Nu by Sherwood number (Weng et al., 1998). The above range of Pr is selected because the Schmidt number can be as large as 3000 in electrochemical applications (Weng et al., 1998).

The flow structure is well known for axisymmetric flow in rotating cylinders. According to the scaling analysis by Weng et al. (1998), the flow structure is fundamentally different depending on the range of combined parameter $\text{PrRo}_T = \text{Pr}\beta\Delta T$. When the

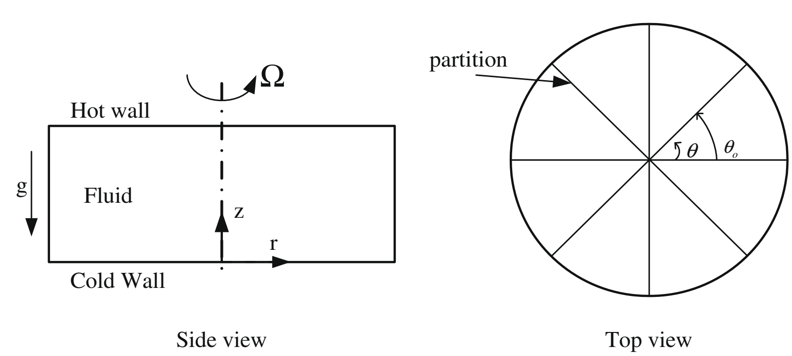

Fig. 1. Schematic of rotating cylinder with partitions.