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Thermal convection in a rotating fluid annulus blocked by a conducting barrier

Q G RAYER BSc, ARCS, DPhil, CPhys, MInstP
Nuclear Electric plc, Berkeley, UK

SYNOPSIS

An investigation has been made using a thermally conducting radial barrier in a differentially heated rotating fluid annulus. Previous experiments have shown that the radial fluid heat transport, H, in an annulus blocked by an insulating barrier is largely independent of rotation rate, linking H to a fluid temperature difference across the barrier, ΔT_B. In the current experiments, the annulus configuration was unchanged except that the barrier was replaced with a thermal conductor, in the expectation that this might effect ΔT_B and hence H. However despite using a conducting barrier $\Delta T_B \neq 0$, and H was little changed.

NOTATION

a,b	Radii of inner and outer cylinders of annular convection chamber
C_P	Specific heat capacity of fluid
d	Depth of convection chamber
H, H_A	Total fluid heat transport and heat transport by advection only
k	Thermal conductivity of fluid
T	Fluid temperature
α	Expansion coefficient of fluid
$\Delta T, \Delta T_B$	Applied temperature difference and temperature difference across barrier
ν, ρ	Fluid kinematic viscosity and density
Ω	Uniform angular velocity of annular convection chamber

1 INTRODUCTION

The study of heat transfer in rotating fluids can contribute to the understanding of fluid motions in geophysical systems (e.g. atmospheres and oceans). The differentially heated rotating fluid annulus (Figure 1a) is an idealised representation of such systems, allowing basic fluid processes to be elucidated, as well as being a system of considerable interest in its own right. The total fluid heat transport, H through a differentially heated annulus of

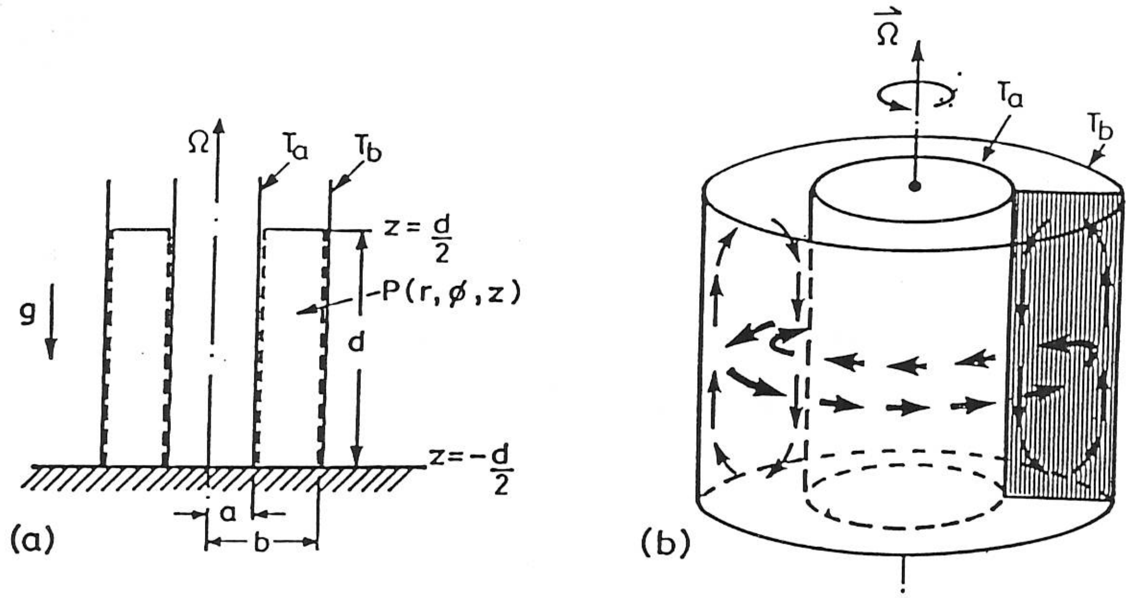


Fig 1 (a) Diagram of fluid annulus. (r,ϕ,z) are cylindrical polar coordinates of a general point P, fixed in a frame moving with the annulus which rotates uniformly with Ω rad.sec^{-1}. The upper surface is in contact with a rigid lid (4). $\Delta T \equiv T_b - T_a$ = 4 or 10°C. a=2.5cm, b=8.0cm, d=14.0cm.
(b) Diagram illustrating the two main circulations seen when the annulus is fully blocked by a thin thermally conducting radial barrier. The side-walls are at constant temperatures T_a and T_b, with $T_b > T_a$.

liquid rotating with uniform angular velocity Ω is, in general, strongly dependent upon Ω, as well as the imposed temperature difference ΔT, the convection chamber geometry and fluid properties. For an annulus with no barrier $H(\Omega)$ decreases from $H(\Omega=0)$ with increasing Ω (1). Further work (2,3) showed that the introduction of a thin, rigid, thermally insulating radial barrier into the convection chamber caused H to become largely independent of Ω. Rayer (3) showed that a fluid temperature difference observed across the insulating barrier, ΔT_B was associated with fluid heat advection, H_A, by a process known as azimuthal geostrophic balance. For the range of Ω over which azimuthal geostrophic balance is the only significant process effecting fluid heat advection, it requires that ΔT_B increase with Ω in order that the total fluid heat advection, H_A should remain constant with Ω. Thus the hypothesis could be made that replacement of the insulating barrier by a conductor might effect ΔT_B, leading to a change in H_A and thus in H. This paper reports the results of measurements of H, fluid temperatures and velocities in the system using the conducting radial barrier described above.

2 APPARATUS DESCRIPTION

The annular convection chamber was formed by trapping fluid between two co-axial cylinders and a thermally insulating lid (at z=d/2) and base (at z=-d/2). Differential heating was provided by maintaining the cylinders at two different constant temperatures, T_a and T_b, (see Figure 1a) with the outer cylinder warmer than the inner cylinder, so that $T_b > T_a$. The chamber was placed upon a turntable so that its central axis of symmetry coincided with the axis of rotation of the turntable, and could be rotated over a range of uniform angular velocities, Ω. The dimensions of the annulus, fluid properties and the ranges of certain other experimental parameters are given in Table 1.

Measurements of H were made by calorimetry. Temperature measurements, taken as a temporal mean, were made using a ring of thermocouples equally spaced around the azimuth, at mid-depth and mid-radius. Fluid motions were visualized by using neutrally buoyant tracer particles of diameter 600-700 μm, and used to infer fluid velocities and the three-dimensional structure of the flow.

Table 1 Range of experimental parameters

Parameter	Symbol	Value
Radii of inner & outer cylinders	a,b	2.5 & 8.0 cm
Depth of chamber	d	14.0 cm
Angular velocity	Ω	0.0-5.0 rad.sec^{-1}
Mean fluid temperature	T_0	20 °C
Applied temperature difference	ΔT	4 or 10 °C
Kinematic viscosity of fluid	ν	1.8 cm^2.sec^{-1}
Specific heat capacity of fluid	C_P	3.84-3.85 J.g^{-1}.°C^{-1}
Mean density of fluid	ρ_0	1.045-1.088 g.cm^{-3}
Expansion coefficient of fluid	α	3.03×10^{-4} °C^{-1}
Thermal conductivity of fluid	k	5.2×10^{-3} W.cm^{-1}.°C^{-1}

3 EXPERIMENTAL RESULTS

3.1 Velocity Measurements

A schematic representation of the typical flow in the convection chamber is given in Figure 1(b). Fluid rises by the hot outer cylinder, moves radially across the chamber at the top, before sinking by the cool inner cylinder and returning to the outer cylinder at the bottom of the chamber. As Ω increases there is a horizontal circulation, with the same sense as the background rotation which is superimposed upon the radial over-turning cell. At higher Ω time-dependent eddies were observed. These flows were generally similar to those observed with an insulating barrier (3,4).

3.2 Heat transport and temperature measurements

Plots of ΔT_B at mid-height and mid-radius are given in Figure 2(a). The replacement of the insulating barrier by a thermal conductor has not inhibited the formation of ΔT_B which initially increases linearly with Ω, and even reaches a slightly larger value than when the barrier was an insulator (3). The results of heat transport measurements as a function of Ω are given in Figure 2(b), H remains largely independent of Ω, despite the barrier being a good thermal conductor.

4 DISCUSSION

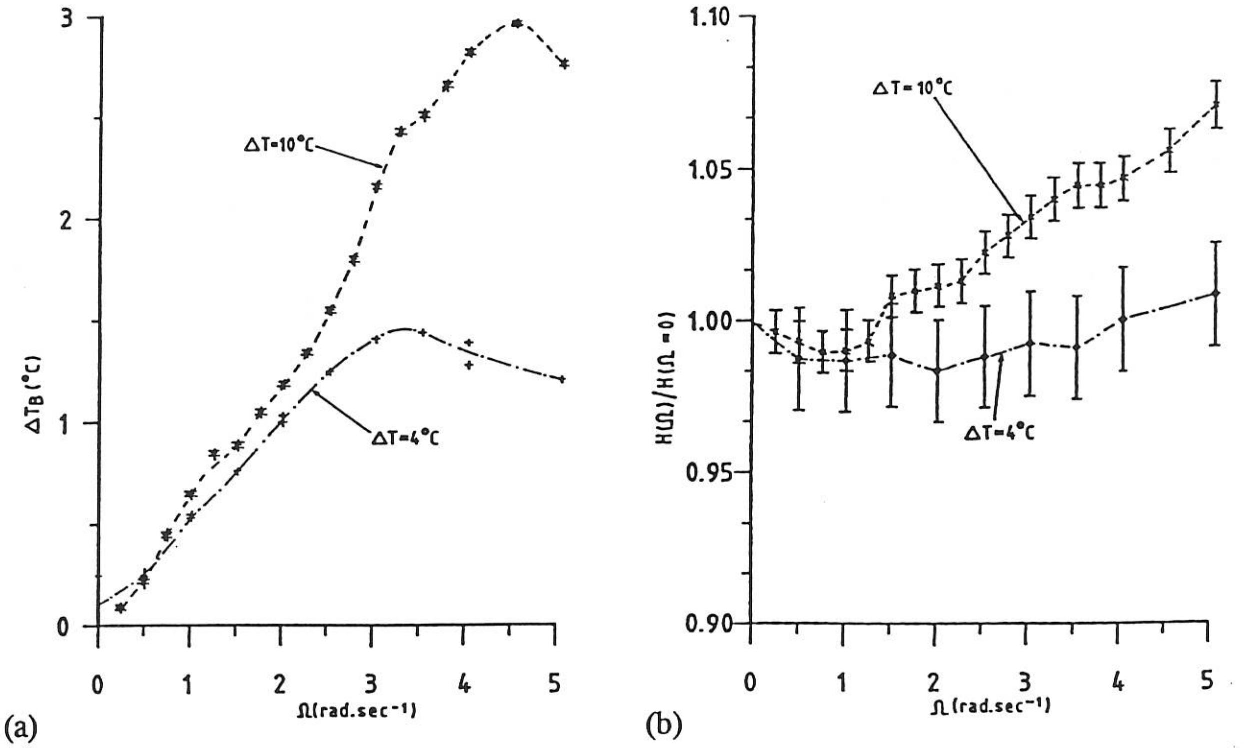
The appearance of a temperature difference across the thermally conducting barrier is initially rather surprising. The fact that there is a temperature gradient in the vicinity of the barrier, suggests that a significant boundary layer must be present. Having established that $\Delta T_B \neq 0$ for the conducting barrier, with an accompanying azimuthal temperature gradient in the fluid, then by comparison with the results of experiments with an insulating barrier (3) it is perhaps not surprising that H should be largely independent of Ω. Rayer (3) considered the heat advection through a cylindrical surface at mid-radius due to azimuthal geostrophic balance, which relates the local shear in the radial component of the fluid velocity, $\partial u/\partial z$ to the local azimuthal temperature gradient. By assuming $\partial u/\partial z$ and $\partial T/\partial \phi$ to be linear H_A was related to ΔT_B. At higher Ω a correction was required, which was dependent on the quantity R_D (see below). Thus H_A could be correlated with ΔT_B to give

$$H_A = \left(\frac{\rho_0 C_P g \alpha \Delta T d^2}{24\,\Omega \mathrm{Min}(1, R_D/R)} \right) \cdot \frac{\Delta T_B}{A},$$

where A=1.27 and the function 'Min(x,y)' is defined as the smaller of the two quantities x and y, and

$$R_D = \sqrt{\frac{g\alpha \Delta T d}{2\Omega}}.$$

In the experiments, R=0.78cm when ΔT=4°C, and 0.75cm when ΔT=10°C.



(a) (b)

Fig 2 (a) Measurements of ΔT_B against Ω. (b) Normalized total fluid heat transport measurements plotted against Ω. H was normalized by dividing H(Ω) by the value of H when there was no rotation, H(Ω=0).

The region in Figure 2(a) where ΔT_B increases linearly with Ω corresponds to the fluid heat advection being dominated by a geostrophic radial overturning cell, where H_A is independent of Ω and $R_D \geq R$. The points in Figure 2(a) at which ΔT_B stops increasing with Ω ($\sim$3.5rad.sec^{-1} when $\Delta T = 4°C$ and $\sim$4.5 rad.sec^{-1} when $\Delta T = 10°C$) indicate the values of Ω above which azimuthal geostrophic balance ceases to be the sole significant mechanism for heat advection in the system. The additional fluid heat transport mechanism when $R_D < R$ is not fully understood, but may possibly be associated with the time-dependent eddies observed in the system.

5 CONCLUSIONS

Total fluid heat transport measurements have been made for a differentially heated rotating fluid annulus which was blocked by a thermally conducting radial barrier. Despite the barrier being a thermal conductor, a temperature difference was observed across it. This temperature difference has been linked to the fluid heat advection through the annular convection chamber. The total fluid heat transport was largely independent of rotation rate over the range of the measurements (see Table 1). The fluid flow, temperature and heat transport results are broadly similar to those when an insulating barrier is used.

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