2 Laboratory experiment: Fluid annulus

An ice bucket placed in the center of a rotating tank of water readily induces a radial temperature gradient analogous to that created on earth by differential heating which warms the equator and cools the pole. If the turntable is rotated very slowly an axisymmetric Hadley circulation is set up.

2.1 Hadley Cell: Experimental procedure

It is straightforward to obtain a steady, axially-symmetric circulation driven by radial temperature gradients in our laboratory tank, a useful analogue of the Hadley Circulation. Ice placed in a metal bucket at the center of a rotating tank will induce a radial temperature gradient, and in the case of slow rotation, an azimuthal current and an associated overturning circulation in the radial plane. We place a circular tank dead center on a white board on the turntable. We fill it with water to a depth of 10 cm or so. At the center of the tank we place an open can of 10cm diameter weighted down to prevent it from floating away. The turntable is then set in to rotation at a speed of 1-2rpm (even less if possible) and left for 10 minutes or so until it has come in to solid body rotation.

The can is then filled with ice and topped up with water to flush out all air pockets and ensure good thermal conduction between the ice and the sides of the can. In this manner, water adjacent to the can is cooled, inducing a substantial radial temperature gradient.

The tank is then left for a few minutes for the circulation to develop before the experiment proper begins.

2.2 Measurements

We will take the following measurements:

- vertical and radial temperature gradients via thermistors attached to data loggers which are placed in the fluid — three arranged vertically up the side of the central can and two radially outward along the bottom, is a good combination.

- tracking of black paper dots floating on the surface to reveal surface flow.

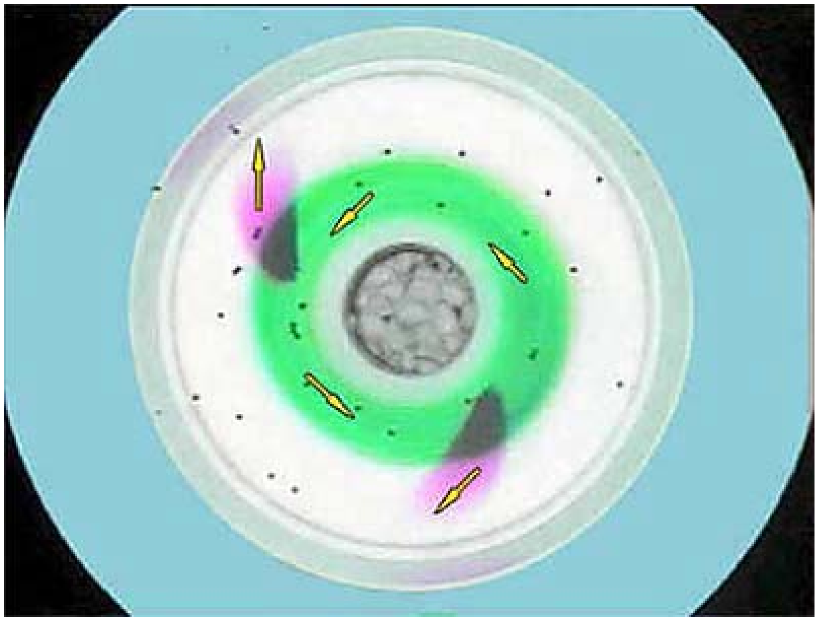

Figure 6: The Hadley circulation regime visualised using paper dots to reveal surface flow, dye to map out the interior flow and potassium permanganate to reveal flow at the bottom.

- measurment of bottom flow by dropping in a few permanganate crystals roughly halfway from the center, which streak the vertical column and settle on the bottom.

- injection of colored dye at various points (but be sparing with the dye!) to aid visualization of the flow.

The photograph in Fig.6 is a top view of the tank in the Hadley regime (i) pink permanganate streaks reveal the flow at the bottom, (ii) green dye maps out the interior flow and (iii) black paper dots map the surface flow.

A more detailed description of how to carry out the experiment can be found here: http://weathertank.mit.edu/links/projects/general-circulation-an-introduction/general-circulation-tank-hadley

2.3 Calculating the radial heat flux in the Hadley Cell experiment

The melting of ice in the can at the center of the tank extracts energy from the water, because on moving from solid to liquid, latent heat of fusion is required. Thus there is an energy sink at the center of the tank. The overturning circulation in the Hadley Circulation experiment — sinking of cold water at the edge of the ice bucket, flow outwards at the bottom and return of warmer water inwards above — transports heat radially inwards towards the ice can, offsetting cooling induced by the melting of ice. The equilibrium condition, assuming that no heat is lost to the laboratory through the upper surface or the sides (perhaps not a good assumption!), can be written thus:

$$\rho c_p \int \oint vT dz = L \frac{\Delta m}{\Delta t} \tag{1}$$

where L is the latent heat of fusion for ice, Δm is the mass of ice that melts in a time Δt, ρ and c_p are the density and specific heats of water, respectively, vT is the radial temperature flux and the double integral is the flux integrated first vertically and then around the tank at a chosen radius.

We can estimate the central cooling rate, $L\Delta m/\Delta t$ (units of Joules/second or Watts), by measuring the mass of ice that melts in a given time. The question we want to answer is whether this can by balanced by the radial flux of heat achieved by the vertical overturning circulation, as assumed in Eq.(1)? We can estimate the magnitude of the lateral by measuring typical velocity and temperature fluctuations.

We infer radial velocities at the surface (v_t) by tracking paper dots and radial velocities at the bottom (v_b) by measuring the rate of radial spread of dissolving potassium permanganate crystals at the bottom. The temperature distribution is measured through the use of thermistors taped to the side and bottom of the tank. The state of affairs is as drawn in Fig.7 and caption.

To carry out our estimates we adopt a two layer model in which the water column is separated in to an upper layer of thickness H_t and temperature T_t and the lower layer of thickness H_b and temperature T_b as indicated in the figure, with

$$H_t + H_b = H \tag{2}$$

where H is the total depth of the fluid.

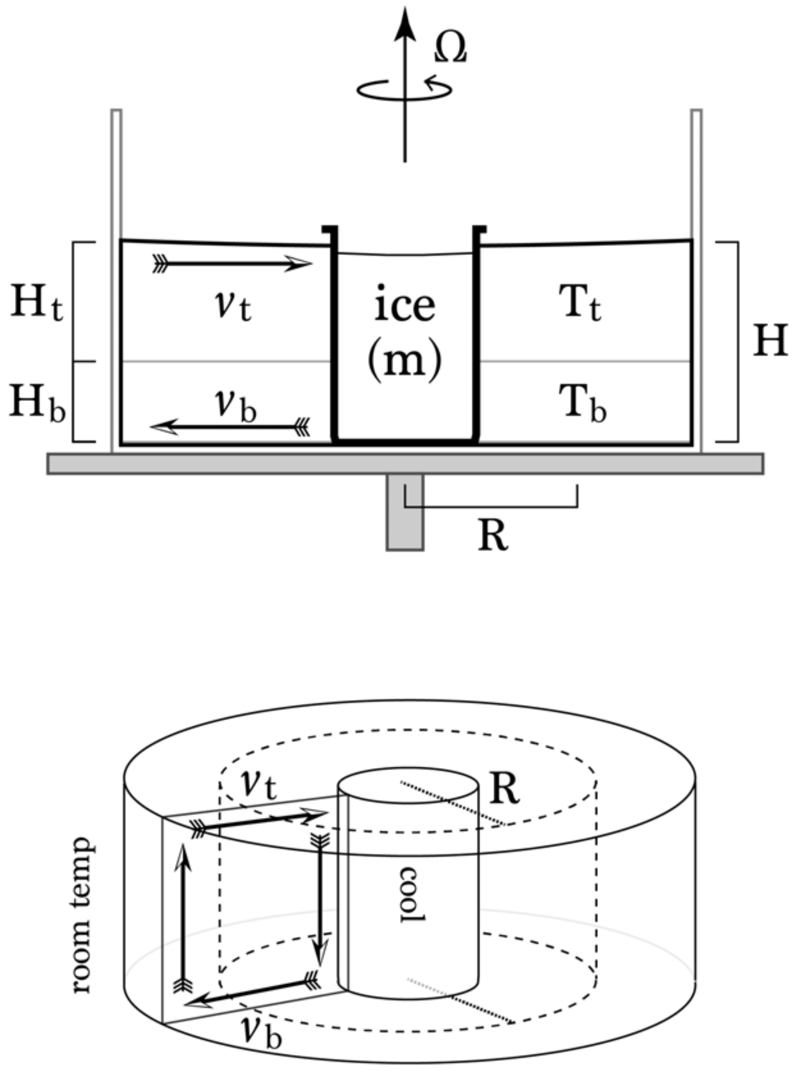

Figure 7: Schematic of the rotating annulus experiment in the Hadley Cell experiment. The configuration of the two level model is also indicated, on which our estimates of radial heat flux are based.

The radial temperature flux of Eq.(1) may now be written, approximately as:

$$\int \oint vTdz \simeq 2\pi R \left(H_t v_t T_t + H_b v_b T_b\right)$$

where R is the radius of the control surface through which the heat flux is to be estimated. From Eq.(1) we may now write:

$$\rho c_p 2\pi R \left(H_t v_t T_t + H_b v_b T_b\right) = L\frac{\Delta m}{\Delta t}. \tag{3}$$

We must also state that volume is conserved and write:

$$H_t v_t + H_b v_b = 0 \tag{4}$$

We will assume that v is positive when directed radially inwards in to the pole (ice can) and negative when directed outwards.

Rearranging Eq.(4), the ratio $\gamma = \frac{H_b}{H}$ may be expressed in terms of the ratio of upper and lower layer velocities as:

$$\gamma = \frac{-\frac{v_t}{v_b}}{\left(1 - \frac{v_t}{v_b}\right)}.$$

Eq.(3) may now be rearranged and expressed thus:

$$\rho c_p 2\pi R H \gamma v_b \left(T_t - T_b\right) = \ L\frac{\Delta m}{\Delta t}. \tag{5}$$

So, we must measure $v_b, v_t, T_t, T_t, R,\ H$ and $\frac{\Delta m}{\Delta t}$, and explore whether the two sides can balance one-another.