

# Radial Inflow Experiment:GFD III

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## Abstract

We rotate a cylinder about its vertical axis: the cylinder has a circular drain hole in the center of its bottom. Water enters at a constant rate through a diffuser on its outer wall and exits through the drain; a steady state is set up in which the flow down the central drain exactly balances the inflow from the outer edge. The water flows inwards from the diffuser conserving angular momentum and, in so doing, acquires a swirling motion which exhibits a number of important principles of rotating fluid dynamics - conservation of angular momentum, geostrophic (and cyclostrophic) balance.

## 1 Introduction

We are all familiar with the swirl and gurgling sound of water flowing down a drain. Here we set up a laboratory illustration of this phenomenon and study it in rotating and non-rotating conditions.

We rotate a cylinder about its vertical axis: the cylinder has a circular drain hole in the center of its bottom - see Fig.1. Water enters at a constant rate through a diffuser on its outer wall and exits through the drain; a steady state is set up in which the flow down the central drain exactly balances the inflow from the outer edge. The water flows inwards from the diffuser conserving angular momentum and, in so doing, acquires a swirling motion, as sketched in Fig.2. The swirling motion can become very vigorous if the cylinder is rotated even at only moderate speeds, because the angular momentum of the cylinder is concentrated by inward flowing rings of fluid.

The swirling flow exhibits a number of important principles of rotating fluid dynamics - conservation of angular momentum, geostrophic (and cyclostrophic) balance, all of which will be studied in detail in this chapter and made use of in our subsequent discussions. The experiment also gives us an opportunity to think about frames of reference.

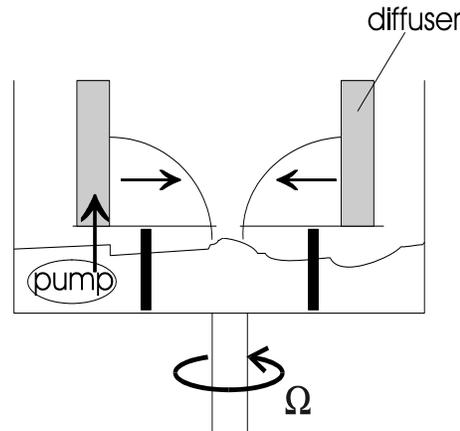


Figure 1: Sketch of radial inflow apparatus. A diffuser with a 30 cm inside diameter is constructed of wire screen (and filled with stones approximately 1cm in size), is placed in a larger tank. Water is then fed evenly in to the bottom of the diffuser. The diffuser is effective at producing an axially-symmetric, inward flow at the screen. Below the tank there is a large catch basin, partially filled with water and containing a submersible pump whose purpose is to return the water to the diffuser in the upper tank. The whole apparatus is then placed on a turntable.

The experiment described here was designed by Jack Whitehead of the Woods Hole Oceanographic Institution. For more details refer to Whitehead, J.A and Potter, D.L (1977) Axisymmetric critical withdrawal of a rotating fluid. Dynamics of Atmospheres and Oceans, 2, 1-18.

## 2 The apparatus and observed flow patterns

We take a cylindrical tank with a drain hole in the center of the bottom - see Fig.1. A diffuser is effective at producing a symmetrical inflow toward the drain. The entire apparatus is mounted on a turntable and viewed from the laboratory frame and, using a camera mounted above co-rotating with the apparatus, from the rotating frame. The table is turned in an anticlockwise direction (in the same direction as the spinning Earth). The path of fluid parcels is tracked by dropping paper dots on the free surface.

When the apparatus is not rotating, water flows radially inward from the diffuser to the drain in the middle, as sketched in Fig.2 (lhs). The free surface is observed to be rather flat. When the apparatus is rotated, however, the water acquires a swirling motion: fluid parcels *spiral* inward as sketched in Fig.2 (rhs). Even at modest rotation rates of  $\Omega = 1$  radian per second (corresponding to a rotation period of around 6 seconds)<sup>1</sup>, the effect of rotation is

<sup>1</sup>Note that if  $\Omega$  is the rate of rotation of the tank in radians per second, then the period of rotation is

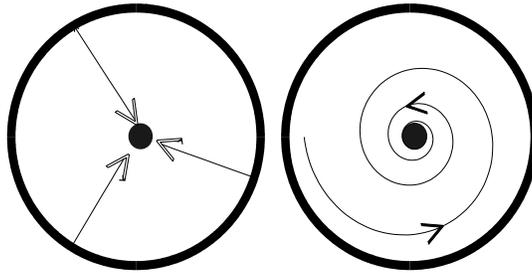


Figure 2: Flow patterns (left) in the absence of rotation and (right) when the apparatus is rotating in an anticlockwise direction.



Figure 3: The free surface of the radial inflow experiment viewed in the laboratory frame, in the case when the apparatus is rapidly rotating. The curved surface provides a pressure gradient force directed inwards that is balanced by an outward centrifugal force due to the anticlockwise circulation of the spiraling flow.

marked and parcels complete many circuits before finally exiting through the drain hole. In the presence of rotation the free surface becomes markedly curved, high at the periphery and plunging downwards toward the hole in the center, as shown in the photograph - see the photograph in Fig.3.

### 3 Experiments and measurements

The main object of our experiment is to measure, and interpret in terms of angular momentum principles, the velocity field,  $v_\theta(r)$ , and its connection to the pressure field given by the height of the free surface  $H(r)$ .

Set the tank rotating at a rate of  $\sim 10$  rpm (revolutions per minute), turn on the pump and record the flow rate,  $Q$ . The task is then to measure the surface flow and free surface

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$$\tau_{\text{tank}} = \frac{2\pi}{\Omega}. \text{ Thus if } \tau_{\text{tank}} = 2\pi s, \text{ then } \Omega = 1.$$

profiles and compare them with predictions based on the theory in Section 4. Try various rotation rates and flow rates.

1. **Velocity.** Measure the velocity of particles (black paper dots) moving with the flow in the free surface of the fluid. This can be done by recording a sequence of images using the overhead camera and making use of the particle tracking software on the laboratory computers. This will return the coordinates of individual particles as a function of time (frame number). Compute both the azimuthal and radial velocity.

Check whether the azimuthal speed of the dots,  $v_\theta(r)$ , is consistent with angular momentum conservation, Eq.(11) below.

Compute the Rossby number given by Eq.(8). How does it compare to the theoretical prediction, Eq.(12)?

2. **The height field.** Measure the depth,  $H$ , of the water at the radius  $r_1$  and estimate  $H$  at other radii. Use your measurements of radial velocity,  $v_r$ , and radial volume flux,  $Q$ , to infer  $H(r)$  using Eq.(13).

Are the gradients of the free surface sufficient to balance the centrifugal acceleration in Eq.(3)?

## 4 Theory

### 4.1 Dynamical balances

In the limit in which the tank is rotated rapidly, parcels of fluid circulate around many times before falling out through the drain hole; the pressure gradient force directed radially inwards (set up by the free surface tilt) is balanced by a centrifugal force directed radially outwards.

If  $V_\theta$  is the azimuthal velocity in the absolute frame (the frame of the laboratory) and  $v_\theta$  is the azimuthal speed *relative* to the tank (measured using the camera co-rotating with the apparatus) then (see Fig. 4):

$$V_\theta = v_\theta + \Omega r \tag{1}$$

where  $\Omega$  is the rate of rotation of the tank in radians per second. Note that  $\Omega r$  is the azimuthal speed of a particle fixed to the tank at radius  $r$  from the axis of rotation.

We now consider the balance of forces in the vertical and radial directions, expressed first in terms of the absolute velocity  $V_\theta$  and then in terms of the relative velocity  $v_\theta$ .

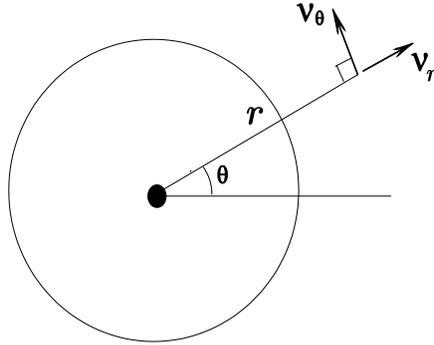


Figure 4: The velocity of a fluid parcel viewed in the rotating frame of reference:  $v_{rot} = (v_\theta, v_r)$ .

#### 4.1.1 Vertical force balance

We suppose that hydrostatic balance pertains in the vertical:  $\frac{\partial p}{\partial z} + \rho g = 0$  where  $\rho$  is the density,  $g$  is the acceleration due to gravity and  $z$  is a vertical coordinate. Integrating in the vertical and supposing that the pressure vanishes at the free surface (actually  $p =$  atmospheric pressure at the surface, which here can be taken as zero), we find that ( $\rho$  and  $g$  are constant):

$$p = \rho g (H - z) \quad (2)$$

where  $H(r)$  is the height of the free surface and we suppose that  $z = 0$  (increasing upwards) on the base of the tank.

#### 4.1.2 Radial force balance in the non-rotating frame

If the pitch of the spiral traced out by fluid particles is tight (*i.e.* in the limit that  $\frac{v_r}{v_\theta} \ll 1$ , appropriate when  $\Omega$  is sufficiently large<sup>2</sup>) then the centrifugal force directed radially outwards acting on a particle of fluid is balanced by the pressure gradient force directed inwards associated with the tilt of the free surface. This radial force balance can be written in the non-rotating frame thus:

$$\frac{V_\theta^2}{r} = \frac{1}{\rho} \frac{\partial p}{\partial r}.$$

Using Eq.(2), the radial pressure gradient force in the above can be directly related to the gradient of the free surface enabling the force balance to be written:

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<sup>2</sup>Note that this assumption is relaxed in the appendix.

$$\frac{V_\theta^2}{r} = g \frac{\partial H}{\partial r} \quad (3)$$

### 4.1.3 Radial force balance in the rotating frame

Using Eq.(1), we can express the centrifugal acceleration in Eq.(3) in terms of velocities in the rotating frame thus:

$$\frac{V_\theta^2}{r} = \frac{(v_\theta + \Omega r)^2}{r} = \frac{v_\theta^2}{r} + 2\Omega v_\theta + \Omega^2 r \quad (4)$$

Hence

$$\frac{v_\theta^2}{r} + 2\Omega v_\theta + \Omega^2 r = g \frac{\partial H}{\partial r} \quad (5)$$

The above can be simplified by writing  $\Omega^2 r = \frac{\partial}{\partial r} \left( \frac{\Omega^2 r^2}{2} \right)$  and defining a quantity  $h$ :

$$h = H - \frac{\Omega^2 r^2}{2g}, \quad (6)$$

the height of the free surface measured relative to that of the reference parabolic surface  $\frac{\Omega^2 r^2}{2g}$  (see notes on ‘parabolic surface’). Then Eq.(5) can be written in term of  $h$  thus:

$$\frac{v_\theta^2}{r} = g \frac{\partial h}{\partial r} - 2\Omega v_\theta: \quad \text{Gradient wind} \quad (7)$$

Eq.(3) and Eq.(7) are completely equivalent statements of the balance of forces. The distinction between them is that the former is expressed in terms of  $V_\theta$ , the latter in terms of  $v_\theta$ . Note that Eq.(7) has the same form as Eq.(3) except an extra term,  $-2\Omega v_\theta$ , appears on the rhs of Eq.(7) - this is called the ‘Coriolis acceleration’. It has appeared because we have chosen to express our force balance in terms of *relative*, rather than absolute velocities.

Let us compare the magnitude of the  $\frac{v_\theta^2}{r}$  and  $2\Omega v_\theta$  terms in Eq.(7). Their ratio is the ‘Rossby number’:

$$R_o = \frac{|v_\theta|}{2\Omega r} \quad (8)$$

If  $R_o \ll 1$ , the  $\frac{v_\theta^2}{r}$  term can be neglected in (7). In this limit, Coriolis and pressure gradient terms balance one another.

$$2\Omega v_\theta = g \frac{\partial h}{\partial r}: \quad \text{geostrophic balance} \quad (9)$$

Equation (9) is a simple form of the ‘geostrophic equation’ relating velocities in the rotating frame to the horizontal pressure gradient in the limit of small  $R_o$ . So, how large

is  $R_o$  in our experiment? We can estimate its size by computing  $v_\theta$  based on angular momentum conservation.

## 4.2 Angular momentum

Fluid entering the tank at the outer wall will have angular momentum because the apparatus is rotating. As parcels of fluid flow inwards they will conserve this angular momentum (provided that they are not rubbing against the bottom or the side). Conservation of angular momentum states that:

$$V_\theta r = \text{constant} = \Omega r_1^2 \quad (10)$$

Here  $r_1$  is the inner radius of the diffuser in Fig.(1) and  $V_\theta$  is the azimuthal velocity in the laboratory (inertial) frame given by Eq.(1). Combining Eqs.(10) and (1) we find:

$$v_\theta = \Omega \frac{(r_1^2 - r^2)}{r} \quad (11)$$

and hence, from our definition of  $R_o$ , Eq.(8):

$$R_o = \frac{1}{2} \left( \frac{r_1}{r} \right)^2 - 1. \quad (12)$$

Thus  $R_o = 1$  at  $r = \frac{r_1}{\sqrt{3}}$ ;  $R_o < 1$  if  $r > \frac{r_1}{\sqrt{3}}$  (the region of geostrophic balance) and  $R_o > 1$  if  $r < \frac{r_1}{\sqrt{3}}$  (the region of cyclostrophic balance - a tornado region!). We see that in the outer regions of the flow the inward radial pressure gradient is balanced by outward Coriolis forces (small  $R_o$ ): the flow is in geostrophic balance here. But as parcels spiral in to the drain they pass through a region where  $R_o$  becomes increasingly large and  $\frac{v_\theta^2}{r}$  in Eq.(7) becomes a dominant term. Cyclostrophic balance is the one in which the centrifugal term dominates the Coriolis term in Eq.(7):

$$\frac{v_\theta^2}{r} = g \frac{\partial h}{\partial r}: \text{cyclostrophic balance}$$

## 4.3 The mass balance

If the volume source coming radially inwards through the diffuser has strength  $Q$ , then conservation of volume tells us that:

$$2\pi r H V_r = Q \quad (13)$$

where  $V_r(r)$  is the radial velocity at radius  $r$ .

## 5 Appendix

Eq.(3) is an approximate statement of radial force balance in the limit that the pitch of the spiral traced out by fluid particles is tight (*i.e.* in the limit that  $\frac{v_r}{v_\theta} \ll 1$ ). If this is not true then we must include radial accelerations and use the following more accurate statement of radial momentum equation:

$$V_r \frac{\partial V_r}{\partial r} - \frac{V_\theta^2}{r} = -g \frac{\partial H}{\partial r} \quad (14)$$

radial acc<sup>n</sup>
centrifugal acc<sup>n</sup>
pressure gradient

Here  $V_r$  is the radial component of velocity.

### 5.0.1 Solutions

Using Eqs.(10) and (13), Eq.(14) can be written:

$$\frac{\partial}{\partial r} \left( \frac{Q^2}{8\pi^2 r^2 H^2} \right) - \frac{\Omega^2 r_1^4}{r^3} = -g \frac{\partial H}{\partial r}$$

which, on integration, can be written:

$$gH + \frac{Q^2}{8\pi^2 r^2 H^2} + \frac{\Omega^2 r_1^4}{2r^2} = \text{constant} \quad (15)$$

where  $H_1$  is the depth of the water at radius  $r_1$ . Eq.(15) is a cubic for  $H$  which can be solved.

Use your velocity measurements to estimate how large is the term  $V_r \frac{\partial V_r}{\partial r}$  relative to  $\frac{V_\theta^2}{r}$  in Eq.(14) in your experiment.

Use (13) to show that if

$$\frac{Q}{2\pi H \Omega r_1^2} \ll 1 \quad (16)$$

then the force balance Eq.(14) reduces to Eq.(3). Can you see that Eq.(16) is just the condition that  $\frac{v_r}{v_\theta} \ll 1$ ?