The thermally-driven rotating annulus: horizontal velocities in regular and weakly chaotic flow regimes

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This readme contains general information about the AOPP rotating annulus datafiles expf1, expf2, expf5, and expf6. You should read this readme along with the readme for the specific datafile you are using.

1 Overview

The data are from the AOPP 'small annulus' used by Hignett et al. (1985), QJRMS, 111, 467, and others. The measurements were taken in 1998. The apparatus consists of two concentric right circular cylinders at radii of $a = 2.5\,\mathrm{cm}$ and $b = 8.0\,\mathrm{cm}$, each $d = 14.0\,\mathrm{cm}$ high. The space between the cylinders is filled with 17% glycerol / 83% water by volume, which has the following properties at $20\,\mathrm{°C}$ [all from Hignett et al. (1985)]:

Density:	$\rho = 1.044\,\mathrm{g\,cm^{-3}}$
Kinematic viscosity:	$\nu = 0.0166\,\mathrm{cm^2\,s^{-1}}$
Thermal diffusivity:	$\kappa = 0.001\,27\,\mathrm{cm^2\,s^{-1}}$
Volume expansion coefficient:	$\alpha = 0.000\,286\,\mathrm{K^{-1}}$

The inner and outer cylinders are at temperatures T_a and T_b respectively, and the apparatus is rotated about the coincident axis of the two cylinders with rotation rate Ω (right).

Each datafile contains about $10\,000\,\mathrm{s}$ of horizontal velocity data. The data are grouped into datasets every $5\,\mathrm{s}$. The temperature of the two cylinders and the rotation rate are also measured every $5\,\mathrm{s}$. Up to five vertical levels are available, depending on the particular datafile, at 12.4, 9.7, 7.0, 4.3 and 1.6 cm above the bottom of the tank. Only one vertical level is available at any particular time; the observations cycle through the available levels moving down every $5\,\mathrm{s}$.
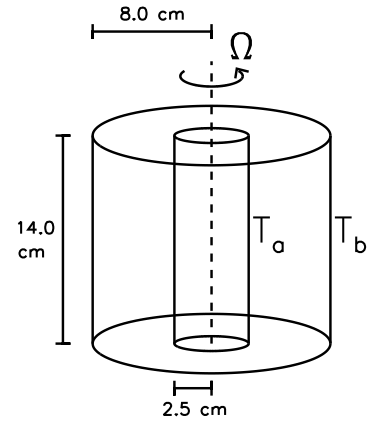
2 Data acquisition

The method for taking observations is Particle Image Velocimetry. A horizontal plane of light $3\,\mathrm{mm}$ thick is shone into the tank at a single vertical level, which reflects off neutrally buoyant particles into a video camera $1\,\mathrm{m}$ directly above the fluid, rotating in the same coordinate frame and about the same vertical axis. The particles (500–1000 per frame) are tracked over one second, producing a set of images from which particle positions and velocities are calculated using the software package 'DigImage' [Dalziel, 1995, http://www.damtp.cam.ac.uk/lab/digimage/index.htm].

The light is shone into the tank at each level for $5\,\mathrm{s}$. During that $5\,\mathrm{s}$ two or more sequences of images are taken, each one containing about five frames taken over $1\,\mathrm{s}$. The result is that each dataset contains two or more independent subsets of data valid at different times within the $5\,\mathrm{s}$ window. The subsets are about a second apart (precise figures are given in the individual readme files).

This method of data acquisition means there are fewer particle tracks at the lower vertical levels than at the higher levels. This is not because there are more particles higher in the tank, but more particle tracks are rejected by the data collection software at the lower levels. The light reflecting off the particles and into the camera has to pass through more liquid the lower in the tank the light sheet is, so more particle tracks at lower levels will be obscured by particles higher in the tank.

3   Datafile contents

Each datafile contains the following files (substitute <file> for the name of the datafile):

- **data/**

  The main data files.

<file>-rot.dat:	Processed rotation and cylinder temperature data.
<file>-vel.dat:	Processed velocity data.

- **etc/**

  Miscellaneous files.

<file>-missing.list:	List of missing datasets and data subsets.
<file>-parameters.ps:	Plots of the forcing parameters (T_a, T_b, Ω, $T_b - T_a$, Taylor number, thermal Rossby number, observations vertical level) as a function of time.
<file>-rot.log:	List of changes made during processing of the rotation/temperature data.
<file>-vel.log:	List of velocity observations removed during data processing.

  The Taylor number is the ratio between inertial forces due to rotation, and viscous forces. It measures the ability of a fluid to resist shear stresses. It is defined by

  $$\text{Ta} = \frac{4\Omega^2(b-a)^5}{\nu^2 d}$$

  The thermal Rossby number is the ratio between buoyancy/inertial forces and Coriolis forces. It is defined by

  $$\text{Ro}_T = \frac{g\alpha(T_b - T_a)d}{\Omega^2(b-a)^2}$$

- **raw/**

  This folder contains the raw data, before any processing. You are strongly advised only to use the processed data, but these files are provided for information and completeness. The files ending .tgz are raw velocity data files at each vertical level (1 is the top, 5 is the bottom). The files with 'par' in the name contain raw temperature / rotation data.

  If you wish to re-process these files you will need to look through the processing scripts in src/ yourself to work out the format of the files and how they have been processed previously.

- **src/**

<file>-preproc.sh:	Commands performed on the raw data files before they were processed. These commands are specific to each datafile because the raw data in each was slightly different in format and content.
obs-proc.pro:	Processes the raw data (both velocity data and temperature/rotation data) to procduce the processed files in data/.
plot-datasets.pro:	Produces horizontal velocity vector fields at each observation time from the processed velocity data. The output from this routine is not included in this distribution as the output data is several hundred MB in size. Run this yourself (recommended) if you want to see what the velocity fields look like.
plot-params.pro:	Produces the file etc/<file>-parameters.ps from the processed temperature/rotation data.

For both plot-datasets.pro and plot-params.pro you will need the IDL packages TeXtoIDL and SYM installed. These can be obtained from http://physweb.mnstate.edu/mcraig/textoidl/ and http://www.astro.washington.edu/docs/idl/cgi-bin/getpro/library08.html?SYM (and elsewhere) respectively.

4 Data format

The processed data files in data/ are plaintext ASCII. They are in the following format (formats listed as standard Fortran format codes):

<file>-rot.dat:

[Column]	[Format]	[Contents]
1	I8	Time (s)
2	F15.8	Temperature T_b (outer cylinder at $R = b$) (°C)
3	F15.8	Temperature T_a (inner cylinder at $R = a$) (°C)
4	F15.8	Rotation rate ($\mathrm{rad\,s^{-1}}$)
5	I4	Vertical level (counting from the top). See individual datafile readme for the height each level corresponds to.

<file>-vel.dat:

Positions and velocities are in Cartesian coordinates.

[Column]	[Format]	[Contents]
1	I1	Data subset. See individual datafile readme for the time within the 5 s window this subset corresponds to.
2	I7	Time (s)
3	F13.6	X position (cm)
4	F13.6	Y position (cm)
5	F9.2	Z position (cm)
6	F13.6	Velocity in X direction ($\mathrm{cm\,s^{-1}}$)
7	F13.6	Velocity in Y direction ($\mathrm{cm\,s^{-1}}$)

Some individual velocity datasets or subsets of datasets are missing from each datafile. These are listed in src/<file>-missing.list.

5 Observational errors

This section estimates the error in each observed position and velocity. In reality the observational error is more complicated than presented here, but for the sake of a little extra accuracy the more complicated analysis is not worth the effort. The error derived here is expected to be within a factor of 2 or 3 of the true error.

The observations are recorded by DigImage as images over a N_X times N_Y pixel grid. $N_X = N_Y = 512$ for these data. Within the grid, a single observation has its position defined as the centre of the pixel. Assuming a uniform distribution of particles, the position of a single observation is uniformly distributed within a range $2b/N_X$ in each direction, where b is the outer cylinder radius, so the error in the position of a single observation has mean zero and standard deviation $S_X = b/(N_X\sqrt{3})$. This error is the same for each observation and the error is isotropic, so the position error expressed in polar coordinates is also the same.

Each observation position in the data is a mean over N_S snapshots ($N_S = 5$). By combining N_S observations each with error S_X to get the mean, the positional error in both coordinates is $E_X = b/(N_X\sqrt{3N_S})$.

Each component of the velocity is given by the distance the particle has moved over the observation period divided by that period. The observation period is denoted T_0 ($T_0 = 1\,\mathrm{s}$) and is assumed to be exact. The speed in each direction is given by the difference in position between the start and end of the particle track, divided by T_0. The velocity is averaged over about N_S particle pairs in the track. Combining these errors gives the error in the velocity as $E_V = b\sqrt{2/(3N_S)}/(N_X T_0)$. Using $N_X = 512$, $T_0 = 1\,\mathrm{s}$, $b = 8.0\,\mathrm{cm}$, and $N_S = 5$, This gives $E_X \approx 0.0040\,\mathrm{cm}$ and $E_V \approx 0.0057\,\mathrm{cm\,s^{-1}}$ as the errors in position and velocity of each observation.

6 Data processing

The observations have already been processed. The scripts used to process the data are provided in src/ for information. The horizontal velocity data and parameter data were processed and converted from raw data for each sequence of observations to a single combined datafile, using a filter designed to remove spurious velocity and parameter values.

First the forcing parameters were processed. Every 5 s two measurements of the rotation rate and the two temperatures are available. The filter used the mean of the two measurements as the processed value unless (1) they differed by more than 2% or (2) the mean differed from the mean of the previous processed value by more than 2%. In either of these cases the user was prompted to either accept the mean value, overwrite the value, or to use the processed value from the previous dataset. This filter could not be automated because when the rotation rate is stepped up or down condition (2) will be triggered but the changed value should be accepted.

Second, the velocity observations were processed, examining each dataset in turn. For each dataset, the filter first removed any observations outside the horizontal boundaries. It then looped over each observation and identified the 15 nearest neighbours. The mean and standard deviation of the 15 neighbours' velocities were calculated, and if the observation of interest fell outside five of these standard deviations in either horizontal velocity component then it was removed. If the velocity was small and within 5% of the radius of either boundary, however, then it was not removed, as all the values are small near the boundaries and observational error has a larger percentage effect on the spread of velocity values. This step was automated, meaning about 400–500 observations are removed erroneously from each datafile during the process. This is only about one observation every five datasets (one point in $\sim$2700), an acceptable loss of good data if all the bad data is removed as well.

Once the filter was run, a further step was required to clean up the processed data. In each datafile the raw sequences of parameter data and the velocity datasets were different lengths, meaning that the two started at different times. This was resolved manually by identifying the Ω transitions in the velocity data (there is a sudden increase in the azimuthal velocity at the transition) and matching up these transitions with the parameter data. Some velocity datasets were then found not to have any corresponding parameter data, so these were discarded.