Complementary numerical and experimental study in the baroclinic annulus for the microgravity experiment AtmoFlow

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Introduction

The experimental investigation of large-scale flows on atmospheric circulation and climate such as Earth, Mars or even distant exoplanets are of great interest in geophysics. The investigation of the fundamental knowledge or the origin of planetary waves or global cell formation is mainly gained by experiments in spherical shells or annuli. We here utilise a thermally forced baroclinic annulus to record evolving temperature fields by an infrared (IR) camera together with a Wollaston shearing interferometry (WSI). Both techniques are used to produce a benchmark solution by comparing recorded IR images with interferograms for the upcoming AtmoFlow experiment, a spherical gap experiment, designed to work under microgravity conditions planned after 2022 on the International Space Station (ISS). Without losing the overall focus of complex planetary atmospheres, the AtmoFlow experiment is able to model the intake and outtake of energy (e.g. radiation), the rotational forcing and a central force field by using the thermo electrohydrodynamic effect [1-4]. The experiments in the baroclinic wave tank will enable us to develop a post processing algorithm and the knowledge to interpret the recorded interferograms of the AtmoFlow experiment on the ISS.

Geometry

R_1	30 mm
R_2	70 mm
L	40 mm
d	50 mm
ΔT	0-20 °C
Ω	0-20 rpm
Ta	$\leq 3.5 \times 10^7$
Ro_T	≥ 0.015

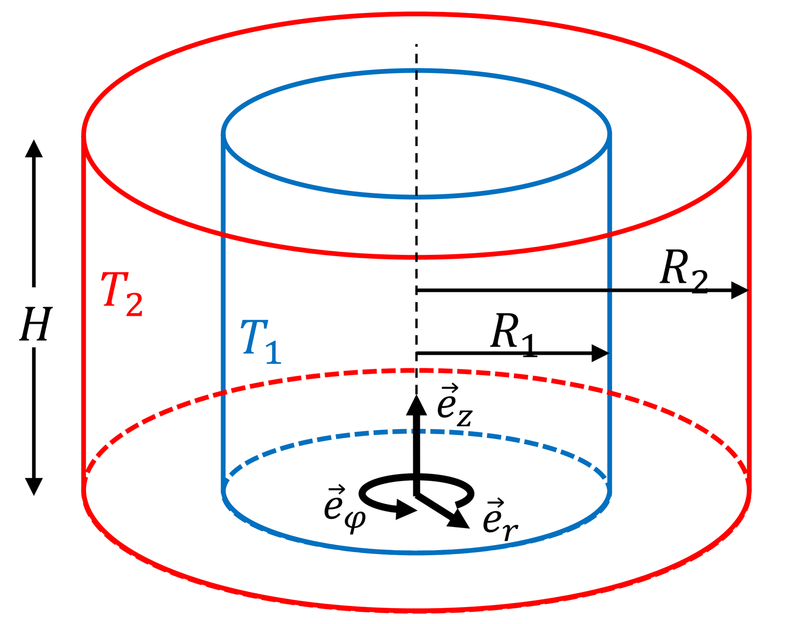

Figure 1: Thermally heated baroclinic annulus

Theoretical formulation

Continuity: $\nabla \cdot \boldsymbol{u} = 0$ with $\boldsymbol{u} = (u, v, w)$

Momentum: $\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla\mathbf{u} = -\nabla p + \nu\nabla^2\mathbf{u} - \beta\Delta T\mathbf{g}$

Heat conduction: $\frac{\partial\theta}{\partial t} + \boldsymbol{u} \cdot \nabla T = \kappa\nabla^2 T$

Boundary Conditions:

$u = 0$; $v = 0$; $w = 0$; $T_1 = T_0$; at $r = R_1$

$u = 0$; $v = 0$; $w = 0$; $T_2 = T_1 + \Delta T$; at $r = R_2$

Non-dimensionless quantities

Use of the scale $L = R_2 - R_1$ of length, L^2/ν of time, $\Delta T = T_1 - T_2$ of temperature

Radius ratio: $\eta = R_1/R_2$

Prandtl number: $Pr = \nu/\kappa$

Taylor number: $Ta = \frac{4\Omega^2 L^5}{\nu^2 H}$

Thermal Rossby number: $Ro_T = \frac{gH\alpha\Delta T}{\Omega^2(r_2 - r_1)^2}$

Experimental setup

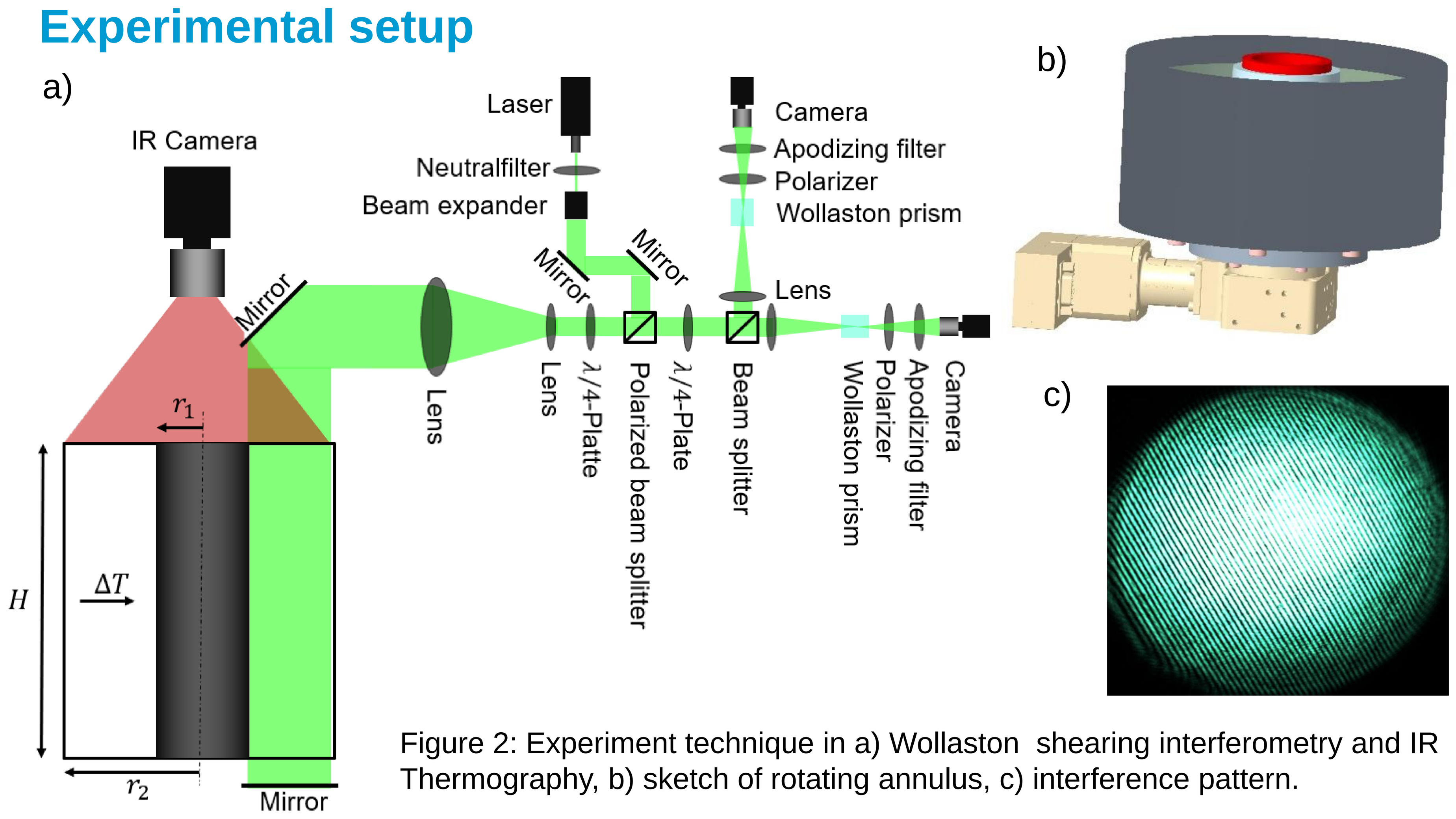

Figure 2: Experiment technique in a) Wollaston shearing interferometry and IR Thermography, b) sketch of rotating annulus, c) interference pattern.

A laser emits a gaussian beam that is reduced in intensity by a neutral filter and expanded via a beam expander. Two mirrors direct the beam into a polarized beam splitter where the polarized beam is reflected at a 90° angle and passed through a quarter wave plate at a 45° angle to change the polarization state to circular polarized light. The beam is expanded via two lenses into the test section of the baroclinic wave tank. A mirror reflects the beam which is passed back to the quarter wave plate where the polarization state is change again to linear but now shifted by 90° of the original state of the laser beam such that the beam can pass the polarized beam splitter into another quarter wave plate to convert the linear polarised light into circular. A beam splitter splits the beam into two where each beam is focussed via a lens on a Wollaston prism.

The Wollaston prism will split the two components of the circularly polarised beam by deflecting and expanding one of the polarizing states along one coordinate axis. After passing through a linear polarizer at 45° these two beams will interfere on a camera. Variations in the optical path length (e.g. due to refractive index changes in the water tank) will then be visible over the area the two beams overlap and are displaced. Therefore, each prism will only measure the refractive index changes in the coordinate direction it has split the beams. Each camera provides the images that represents the information only in one gradient direction [6].

Experiments and numerical simulations

Here, we present numerical simulations of the formation of the convective wave patterns in the thermally heated annulus seen in Figure 3. The results of the temperature field show a wave number 4 in Figure 3a, a temperature field that an IR-camera would record is shown in Figure 3b and the projection onto a hemisphere in Figure 3c. The computational model was solved with a commercial solver using the finite element technique [7].

Figure 4a and c present experimentally recorded temperature fields by an IR camera that are post processed to generate numerical interferograms as seen in Figure b and d, respectively. Equivalent to the experiment, numerical simulations present a corresponding temperature fields here with a wave number 4 in Figure 4e and the numerical interferogram in Figure 4f.

The results show that a small temperature difference such as is Figure 4a can lead to a difficult interpretation of the wave structure and wave number. While the refractive index of the fluid is depending on the fluid's density as is the temperature difference, a higher temperature gradient may reveal the wave patterns. Hence, an appropriate selection of Taylor and Rossby number are essential for the success of the experiment. The numerical simulations will be compared to the experimental recorded interferograms to find a technique to post process with an efficient algorithm the recorded WSI interferograms of the AtmoFlow space experiment.

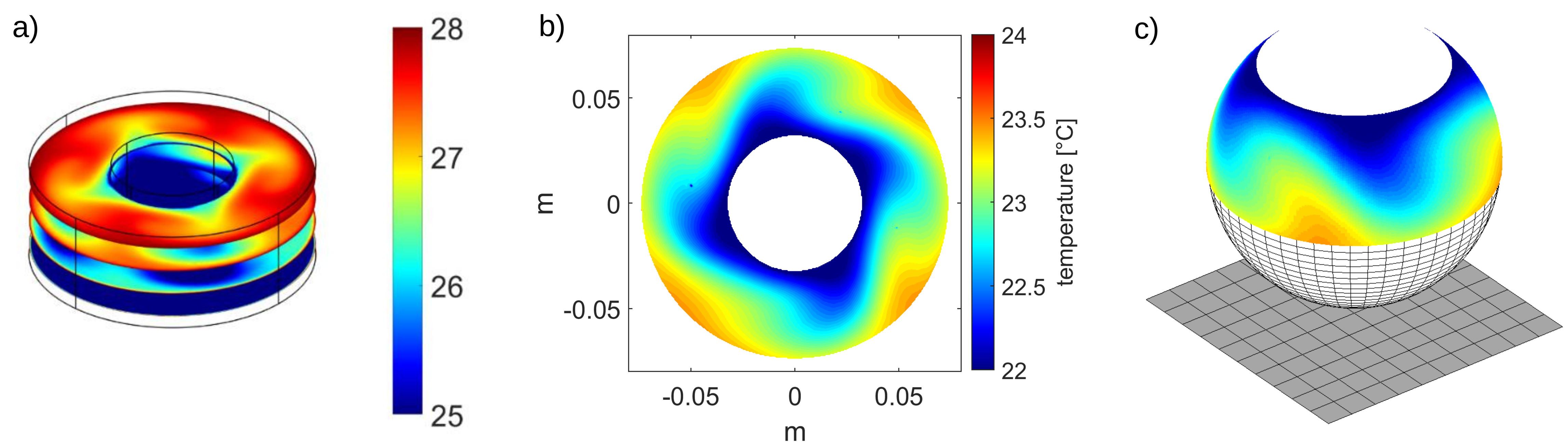

Figure 3: Numerical simulation a) Temperature field in baroclinic annulus, b) Temperature field of top plane to visualise what the IR camera records, c) projection of the 2D temperature field onto a hemisphere.

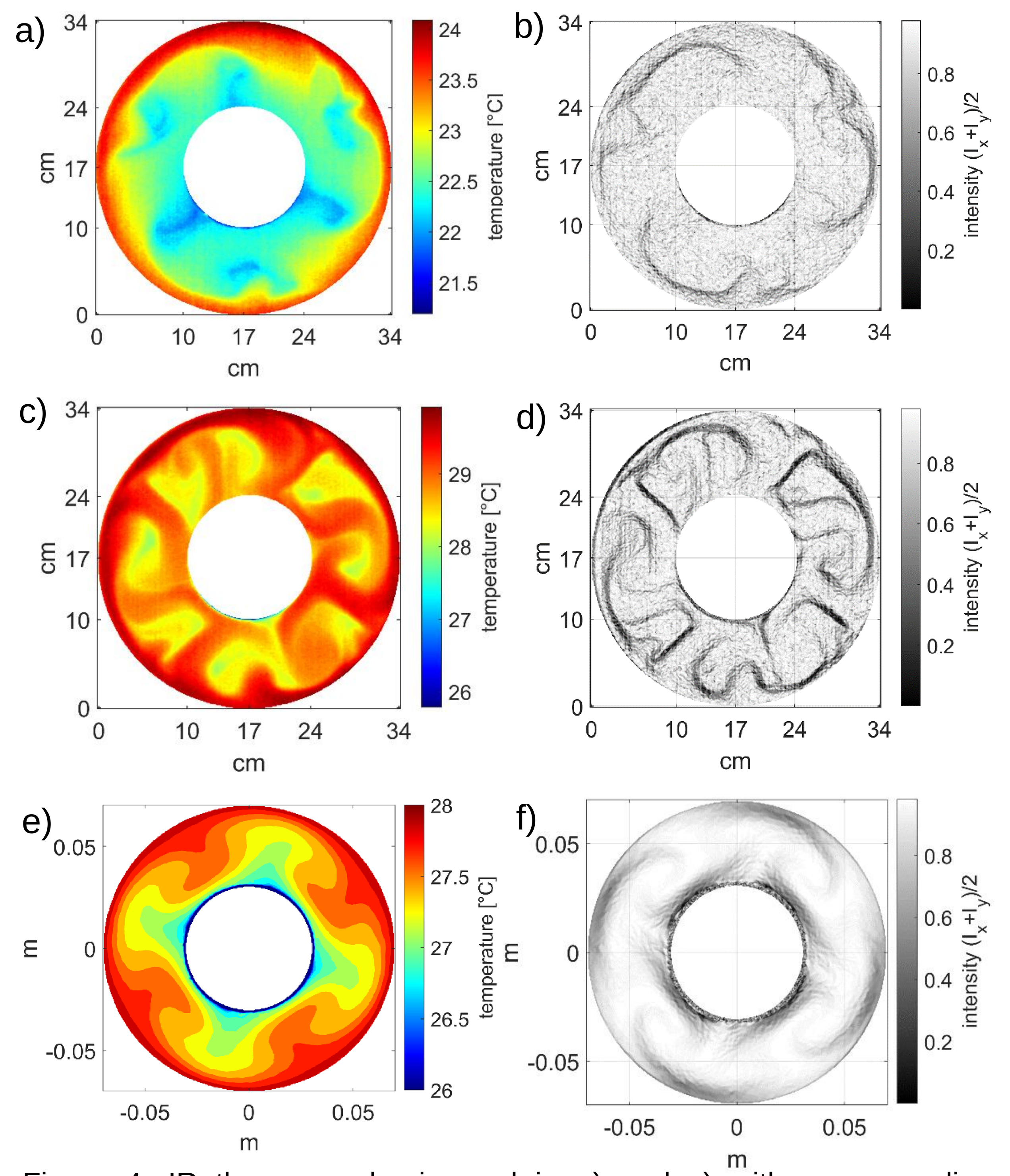

Figure 4: IR thermography imaged in a) and c) with corresponding artificial interferograms in b) and d). Numerical simulations of temperature profile in e) and corresponding artificial interferogram in f)

Outlook

- Design and manufacture of the thermally heated annulus
- Benchmark of WSI system to measure baroclinic instability
- Provide a regime diagram of analysed parameter range
- Develop postprocessing algorithm for the AtmoFlow space experiment

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