PIV- and LDV- measurements of baroclinic wave interactions in a thermally driven rotating annulus

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BTU

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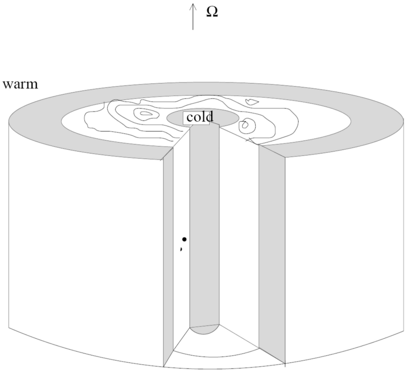
Content

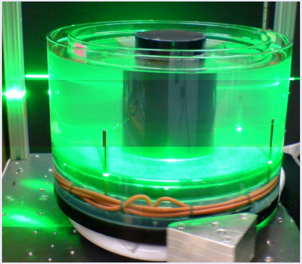
Sketch of thermally driven rotating annulus



Früh and Read, 1997

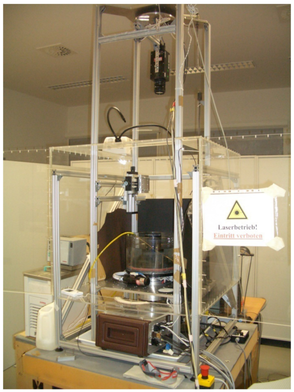
The thermally driven rotating annulus at BTU Cottbus

Annulus



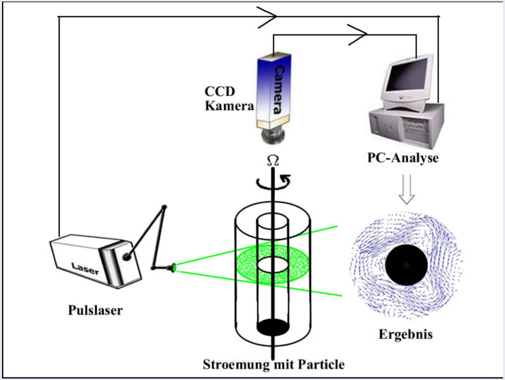
$$r_{out} = 12.5\text{cm}$$
$$r_{in} = 4.5\text{cm}$$
$$\Delta T = 7.5\text{K}$$
$$3 \text{ cpm} < \Omega < 12 \text{ cpm}$$

Experimental setup



Experimental setup for PIV observations

Data mining



Wang, BTU Cottbus 2008

Model

Non-dimensional equations

$$\frac{d\mathbf{v}}{dt} = -\nabla p + \nabla^2 \mathbf{v} - Ra\,\theta \mathbf{k} - Ta^{1/2} \mathbf{k} \times \mathbf{v}$$

$$\frac{d\theta}{dt} = \frac{1}{Pr} \nabla^2 \theta$$

$$\nabla \cdot \mathbf{v} = 0$$

Boundary conditions

$$w = 0 \quad \text{and} \quad \frac{\partial \theta}{\partial z} = 0 \quad \text{at} \quad \text{top and bottom}$$

$$v_r = 0 \quad \text{and} \quad \theta = \theta_i \quad \text{at} \quad r = r_i$$

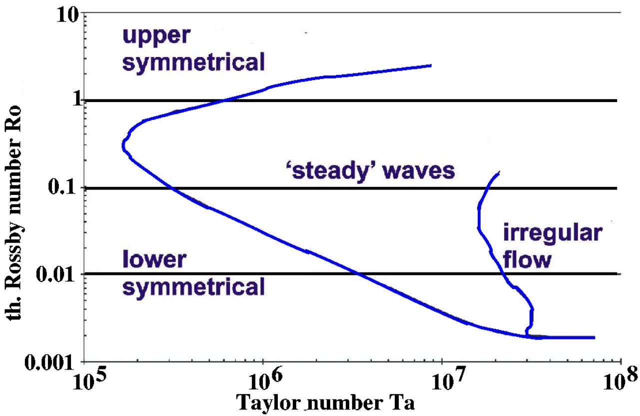
$$v_r = 0 \quad \text{and} \quad \theta = \theta_o \quad \text{at} \quad r = r_o$$

Important numbers

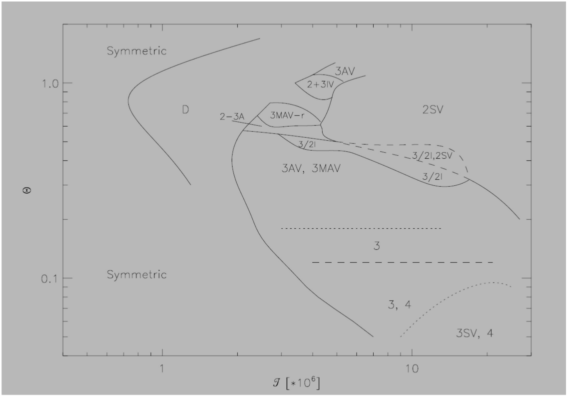
Non-dimensional numbers determine the flow regime

$$
\begin{aligned}
\text{Taylor number} \quad Ta &= \frac{4 \cdot \Omega^2 \cdot (b-a)^5}{\nu^2 \cdot d} \\
\text{Rayleigh number} \quad Ra &= \frac{g\alpha\Delta T(b-a)^3}{\nu\kappa} \\
\text{Prandtl number} \quad Pr &= \frac{\nu}{\kappa} \\
\text{Rossby number} \quad Ro &= \frac{4Ra}{PrTa} = \frac{g \cdot d \cdot \alpha\Delta T}{\Omega^2 \cdot (b-a)^2}
\end{aligned}
$$

Fowlis and Hide (1965)

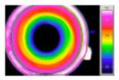


Früh and Read (1997)

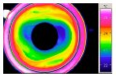


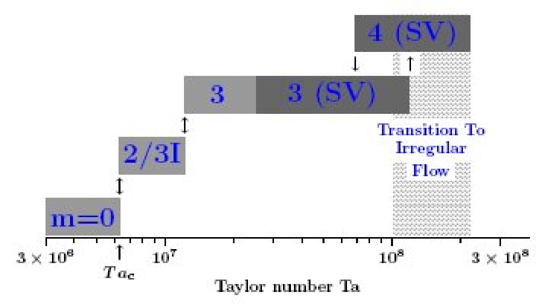
Regime transitions

$m = 0$

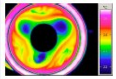


$m = 2$

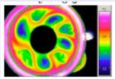




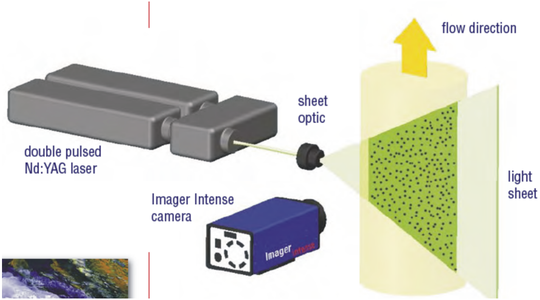
$m = 3$



$m \approx 4$

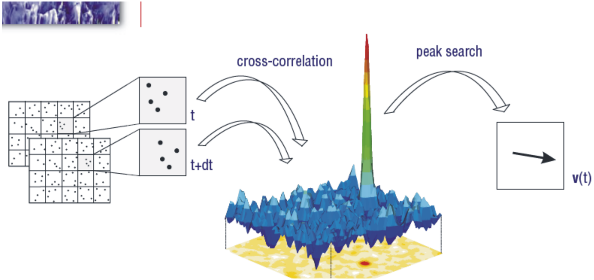


PIV principle



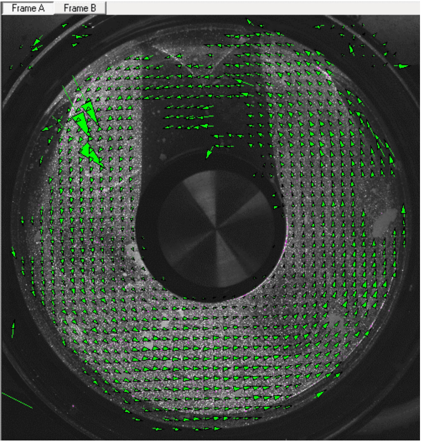
Source LaVision (2008)

PIV principle



Source LaVision (2008)

PIV observation in the inertial frame



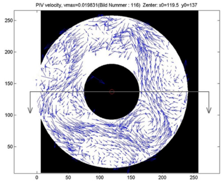
Problems

How to switch to co-rotating frame?

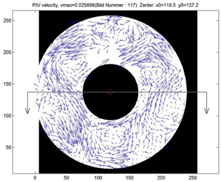
$$\vec{v}_c = \vec{v}_i - \vec{\Omega} \times \vec{r}$$

How to get rid of the shadow?

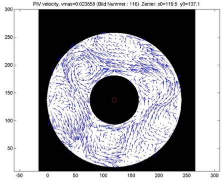
Avoiding the shadow zone



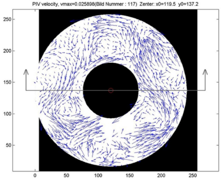
Erste Aufnahme



Zweite Aufnahme in halb Umdrehung



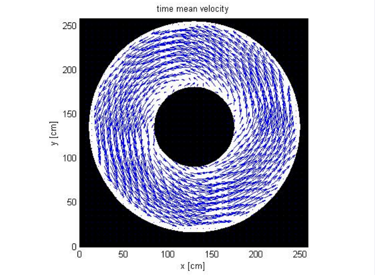
Geklebte Ergebnis



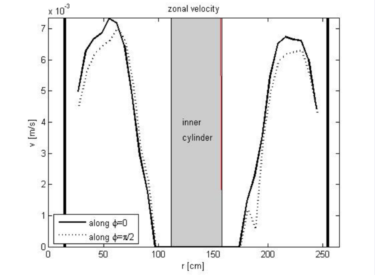
Zweite Aufnahme wird in 180 Grad gedreht

Results: mean flow

Time mean flow



Time and zonal mean flow



Harlander, Wang, Egbers (2008), proceedings Laser conference, Lisbon

Proper Orthogonal Decomposition (POD)

Different names for the same thing: POD, EOF, PCA, Factor Analysis, Karhunen-Loéwe-Expansion, $\cdots$

Data matrix

$$\mathbf{F} = \begin{pmatrix} u'_{11} & u'_{12} & \cdots & u'_{1p} \\ u'_{21} & \cdots & & \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ u'_{n1} & \cdots & & u'_{np} \end{pmatrix}$$

Covariance matrix

$$\mathbf{R} = \mathbf{F}^{\mathbf{T}}\mathbf{F}$$

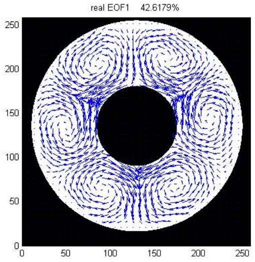
$$\mathbf{F} = \sum_{j=1}^{p} \mathbf{a_j}(t)\,\mathbf{v_j}(x,y)$$

$$\mathbf{a_j} = \mathbf{F}\mathbf{v_j}$$

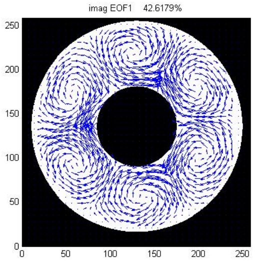
Explained variance γ of $\mathbf{v_j}$ is defined as $\gamma := \frac{\lambda_j}{\sum_{i=1}^{p}\lambda_i}$

Results: variability

EOF1 real

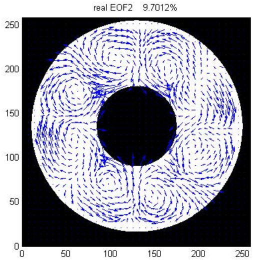


EOF1 imag

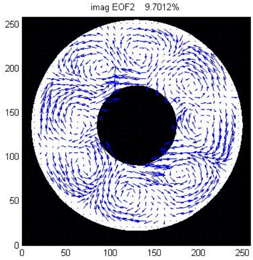


Results: variability

EOF2 real

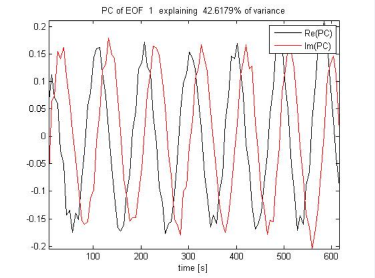


EOF2 imag

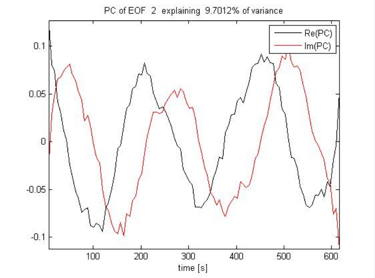


Results: variability

PC1



PC2



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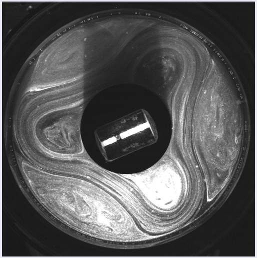
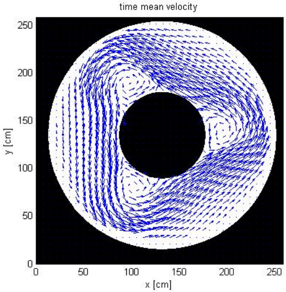
Results: mean flow

Laser slice



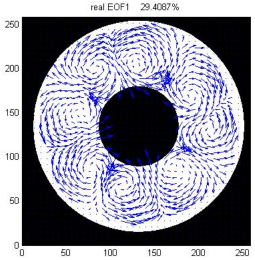
PIV: time mean flow



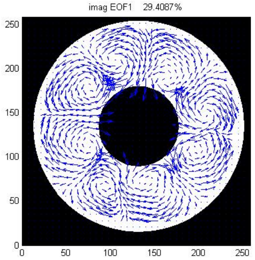
Harlander & Wang, BTU Cottbus 2008

Results: variability

EOF1 real

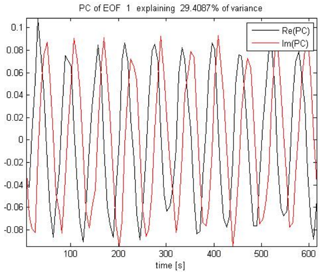


EOF1 complex

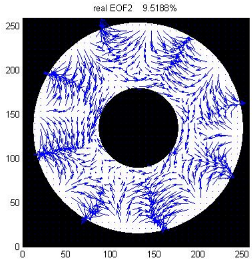


Results: variability

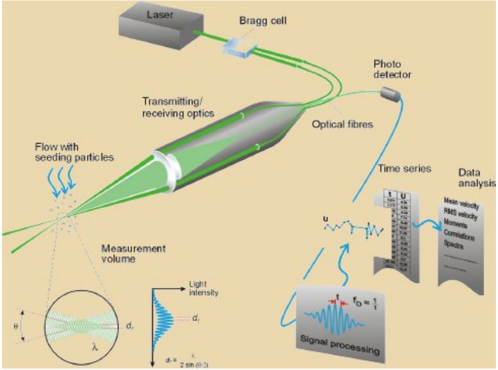
PC1



EOF2 real

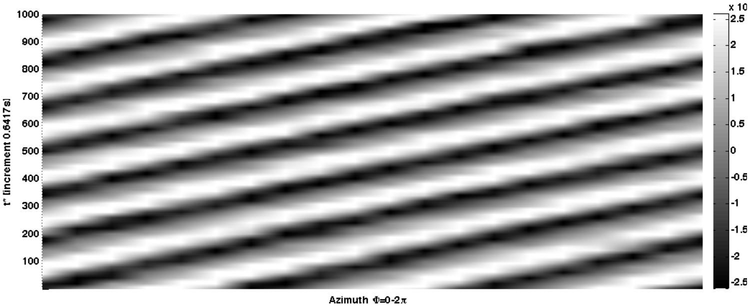


LDA principle



Source http://laum-vld.univ-lemans.fr

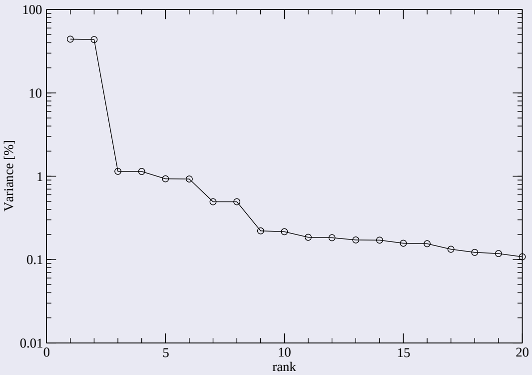
LDA data



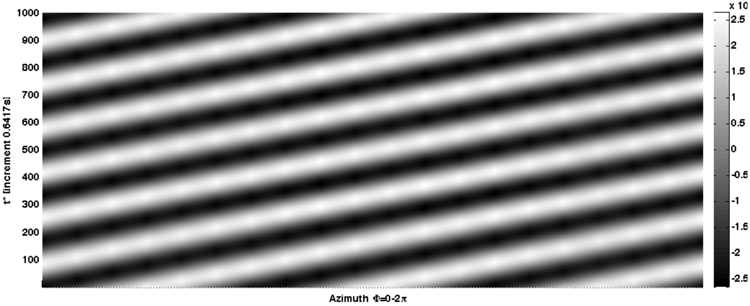
Harlander, v. Larcher, Wang, and Egbers (2008)

LDA data

PC1



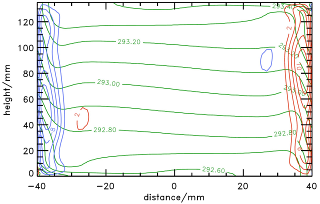
LDA data


t* [increment 0.6417s]
1000
900
800
700
600
500
400
300
200
100
Azimuth Φ=0-2π
x 10
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5

Differentially heated periodic channel (Simulation by Andreas Dörnbrack)

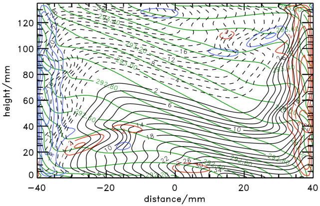
Parameters

heating/cooling
± 0.2K/s
time 100s
no rotation



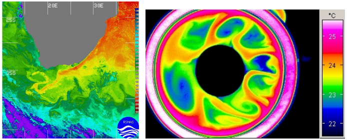
Parameters

heating/cooling
± 0.2K/s
time $100 + 50$s
rotation 7.6cpm



Future activities

- Combining PIV and thermography: can we estimate velocity from temperature?



- Breaking azimuthal symmetry of the annulus: still regular flows?
- Irregular regime: is the wave breaking symmetric?

Acknowledgement

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