# NON-OBERBECK-BOUSSINESQ EFFECTS IN A TURBULENT TALL WATER-FILLED DIFFERENTIALLY HEATED CAVITY

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# OUTLINE

1. INTRODUCTION AND MOTIVATION
2. MATHEMATICAL FORMULATION AND NUMERICAL METHODS
3. NUMERICAL RESULTS AND DISCUSSION FOR NOB EFFECTS
4. CONCLUSIONS AND FUTURE WORK

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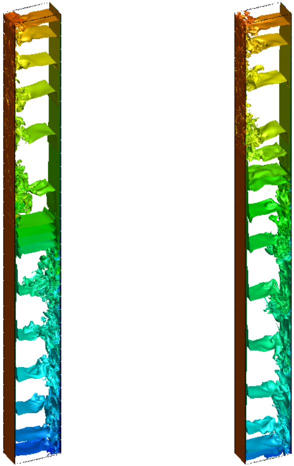
# INTRODUCTION

## NATURAL CONVECTION WITHIN ENCLOSURES

- Cooling of electronic devices
- Air flow in buildings
- Heat transfer in solar collectors

## FLOW CONFIGURATION

- Rayleigh-Bénard
- Differentially Heated Cavity (DHC)



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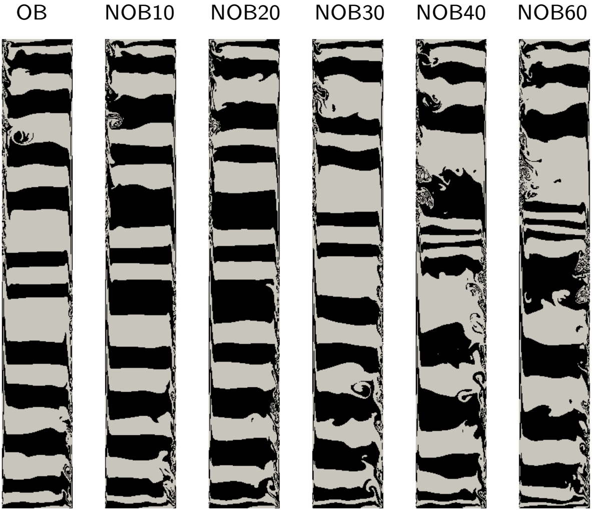
# 2D WATER-FILLED DHC, INITIAL INVESTIGATION



## CASE DEFINITION

- 2D
- $\Gamma \approx 7$
- $Ra = 2.12 \times 10^{11}$
- $Pr = 3.27$
- $\Delta T$ up to 60 °C

## MAIN CONCLUSIONS

- $\Delta T \leq 30$ °C heat transfer is unaffected, flow parameters only slightly affected
- $\Delta T > 30$ °C substantially different flow configuration observed, heat transfer enhanced by aprox. 10 %, highly stratified zone appears

D. Kizildag, I. Rodríguez, A. Oliva, O. Lehmkuhl, Limits of the Oberbeck-Boussinesq approximation in a tall differentially heated cavity filled with water, *International Journal of Heat and Mass Transfer* 68 (2014) 489-499.

# OBJECTIVES

- Identify the **non-Oberbeck-Boussinesq** (NOB) effects by means of 3D DNS
- Check the validity of the conclusions obtained for **2D NOB effects**
- Shed light on the physics of the complex phenomena like **transition**, **turbulent mixing**, **relaminarization zones**, **core stratification**
- Contribute data on the less studied water-filled cavities

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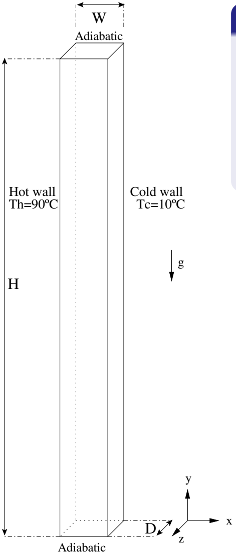
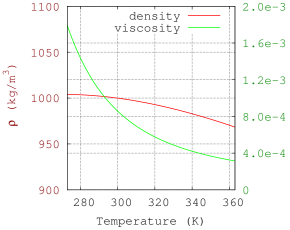
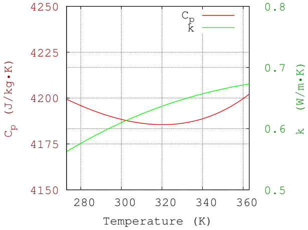
# DEFINITION OF THE PROBLEM



## CASE DEFINITION

- Rayleigh number $Ra = 3 \times 10^{11}$ $(Ra = g\beta(T_h - T_c)H^3 Pr/\nu^2)$
- Prandtl number $Pr = 3.41$ $(Pr = \nu/\alpha)$
- $T_h = 90$ °C and $T_c = 10$ °C ($T_m = 50$ °C)
- Aspect ratio $\Gamma = 10$ $(\Gamma = H/W)$





- viscosity changes more than 4 times, thermal conductivity aprox. 20 %*
- changes in density and specific heat can be ignored

* D. Gray, A. Giorgini, The validity of the Boussinesq approximation for liquids and gases, *International Journal of Heat and Mass Transfer* 19 (1976) 545-551.

# MATHEMATICAL FORMULATION AND NOB APPROACH

Governing equations using **Oberbeck-Boussinesq (OB)** approximation:

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0, \\ \partial_t \mathbf{u} + \mathcal{C}(\mathbf{u}, \mathbf{u}) &= \nu_m \Delta \mathbf{u} - \nabla p - \beta_m (T - T_m) \mathbf{g}, \\ \partial_t T + \mathcal{C}(\mathbf{u}, T) &= \alpha_m \Delta T, \end{aligned}$$

Governing equations considering **non-Oberbeck-Boussinesq (NOB)** effects:

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0, \\ \partial_t \mathbf{u} + \mathcal{C}(\mathbf{u}, \mathbf{u}) &= 2\rho_m^{-1} \nabla \cdot (\mu S(\mathbf{u})) - \nabla p + (1 - \rho/\rho_m) \mathbf{g}, \\ \partial_t T + \mathcal{C}(\mathbf{u}, T) &= (\rho_m C_{p,m})^{-1} \nabla \cdot (k \nabla T), \end{aligned}$$

## NOB APPROACH

- Incompressible flow
- Constant specific heat calculated at mean temperature
- Constant density except for the buoyancy term where temperature dependany applied
- Temperature dependent viscosity and thermal conductivity
- Same approach used in recent works on RB convection of water, like Sugiyama et al. (2009)

The diffusive term for NOB is discretized as in:
F.X. Trias, A. Gorobets and A. Oliva. "A simple approach to discretize the viscous term with spatially varying (eddy-)viscosity", Journal of Computational Physics, 253 (1): 405-417, 2013.

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# NUMERICAL MODEL

- Symmetry-preserving discretization in differential operators
- Finite volume fully conservative fourth-order scheme
- Second-order explicit scheme in time integration
- Fractional step method in pressure-velocity linkage
- Direct-Schur complement-based domain decomposition method in conjunction with a FFT for the system periodic in z-direction.

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# Mesh definition

$\delta_{vis} \sim Pr^{1/2}\delta_T$ (thinner thermal bounday layer for Pr $>$1)*

*J. Patterson, J. Imberger, Unsteady natural convection in a rectangular cavity, *Journal of Fluid Mechanics* 100 (1980) 65-86.

| | $N_x$ | $N_y$ | $N_z$ | $NBL^*$ | $D/H$ | $\gamma_x$ | $(\Delta x)_{\min}/H$ | $(\Delta x)_{\max}/H$ | $(\Delta x)_{\max}/\eta$ |
|---|---|---|---|---|---|---|---|---|---|
| DNS | 194 | 782 | 196 | 14($OB$)<br>12/19($NOB$) | 0.075 | 1.8 | $1.03 \times 10^{-4}$ | $9.80 \times 10^{-4}$ | $\approx 0.2(OB)$<br>$\approx 0.4(NOB)$ |

* NBL: Number of CVs in the inner viscous boundary layer

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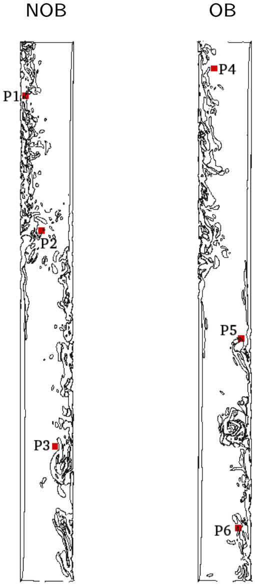
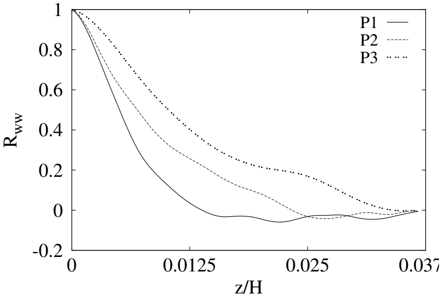
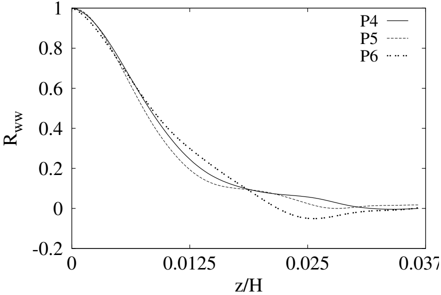
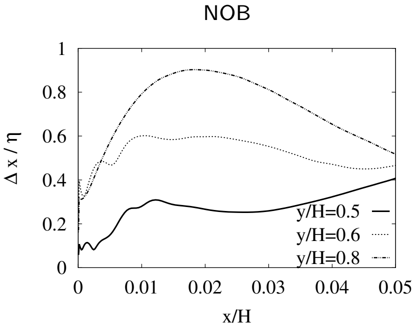
# VERIFICATION OF DNS: TWO-POINT CORRELATIONS

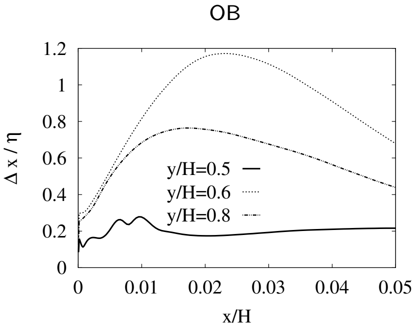


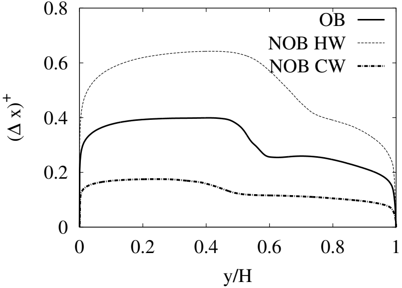




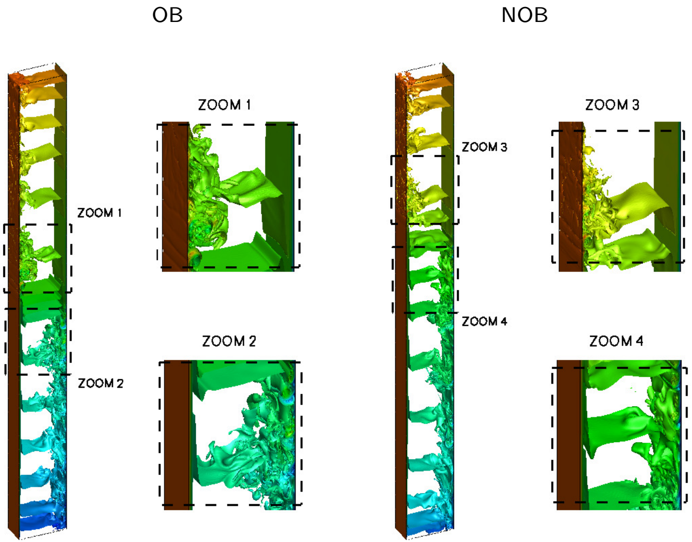
# Verification of DNS







# INSTANTANEOUS FLOW, ISOSURFACES



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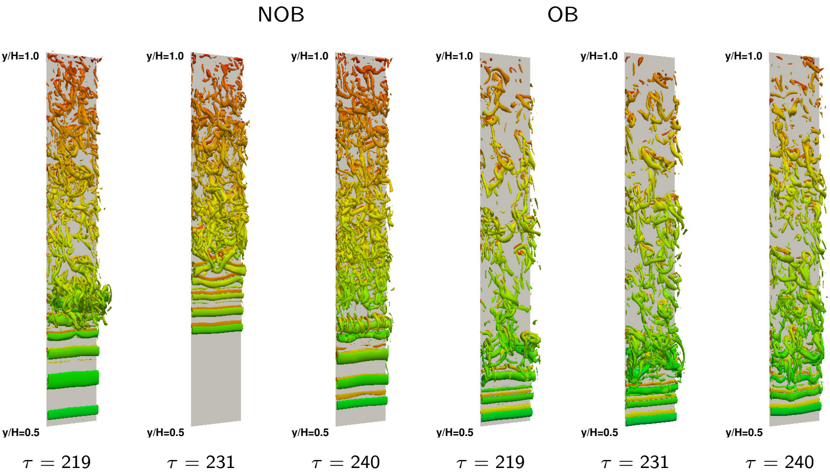
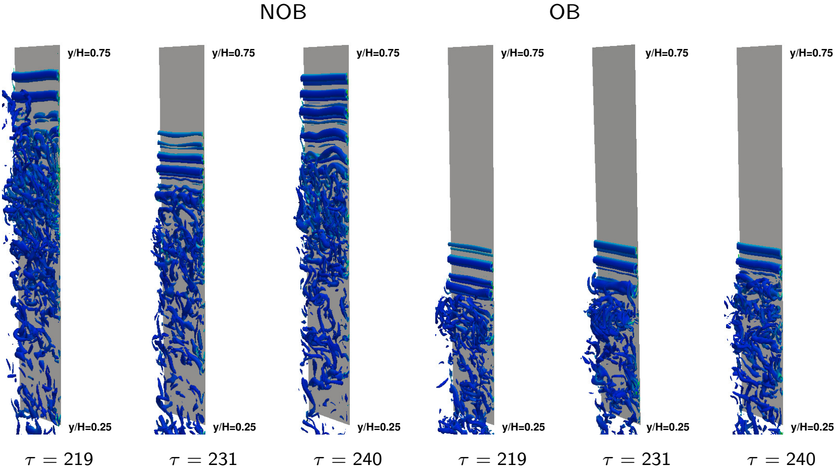
# INSTANTANEOUS FLOW, COHERENT STRUCTURES (HOT WALL)



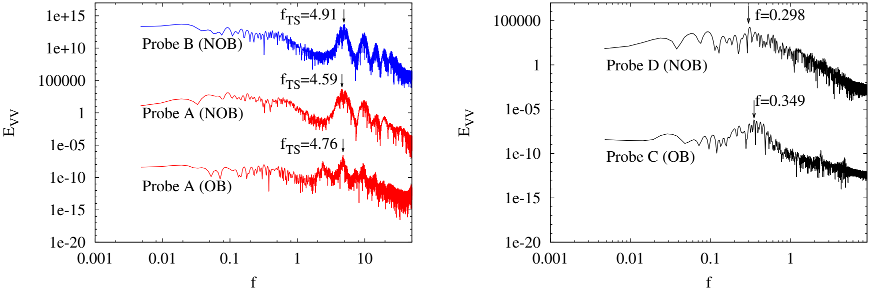
- transition to turbulence:
  $y_{tr,NOB,h}/H$=0.68 (NOB); $y_{tr,OB,h}/H$=0.58 (OB)

# INSTANTANEOUS FLOW, COHERENT STRUCTURES (COLD WALL)



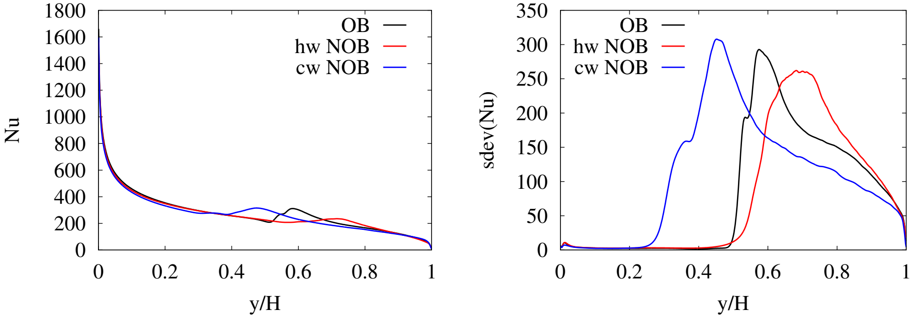
- transition to turbulence:
  $y_{tr,NOB,c}/H$=0.45 (NOB); $y_{tr,OB,c}/H$=0.58 (OB)

# ENERGY SPECTRA



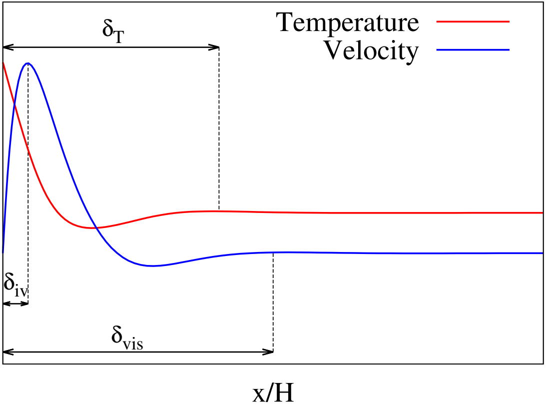
$ProbeA \equiv (0.0016, 0.54)$; $ProbeB \equiv (0.0977, 0.7)$; $ProbeC \equiv (0.05, 0.5)$; $ProbeD \equiv (0.05, 0.6)$.

# Heat transfer



- TRANSITION TO TURBULENCE:
  hot wall : $y_{tr,NOB,h}/H$=0.68 (NOB); $y_{tr,OB,h}/H$=0.58 (OB)
  cold wall: $y_{tr,NOB,c}/H$=0.45 (NOB); $y_{tr,OB,c}/H$=0.58 (OB)
- $Nu_{OB} = 283.0$ $Nu_{OB} = 274.5$
- This predicts with previous 2D findings, where $Nu_{NOB}$>$Nu_{OB}$.

# BOUNDARY LAYER DEFINITION



- inner viscous boundary layer, $\delta_{iv}$, defined as the location where streamwise velocity peaks
- viscous boundary layer, $\delta_{vis}$, defined as the location where streamwise velocity tends to zero
- thermal boundary layer, $\delta_T$, defined as the location where the temperature tends to the core value

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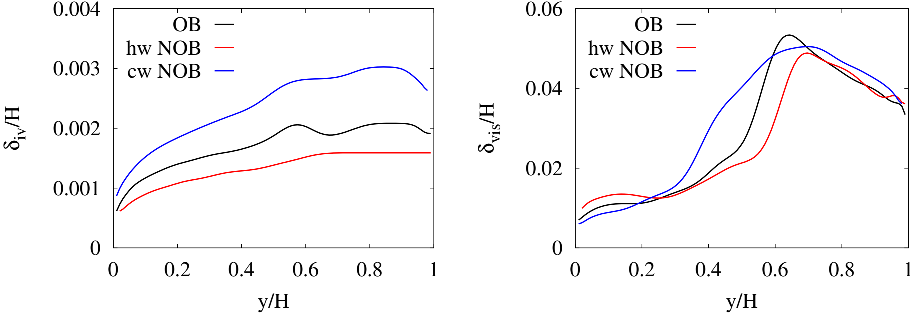
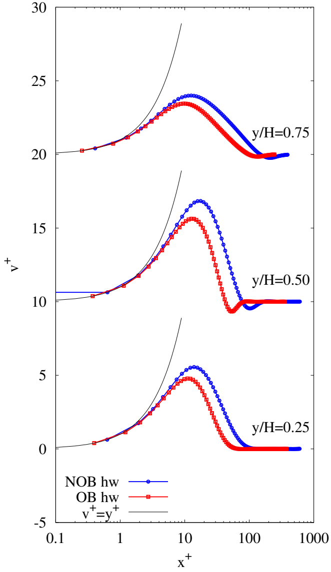
# BOUNDARY LAYER ANALYSIS, VISCOUS BOUNDARY LAYER

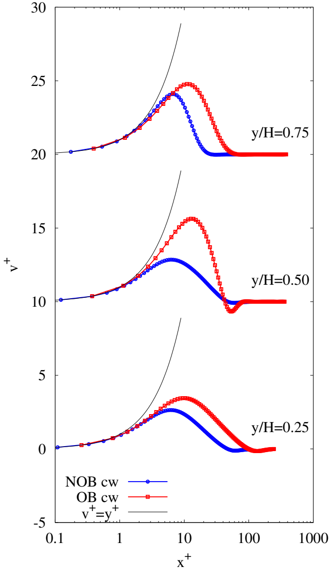


# VELOCITY PROFILES

HOT WALL

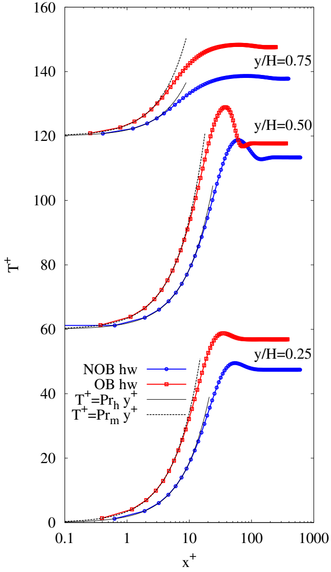


COLD WALL

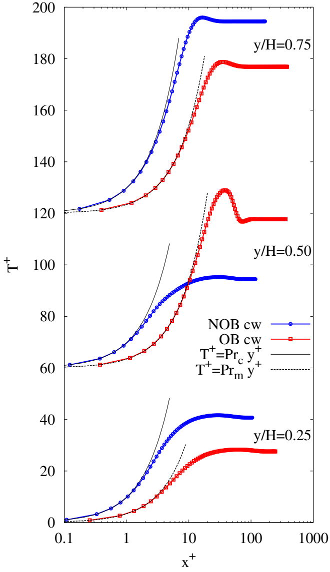


# TEMPERATURE PROFILES

HOT WALL

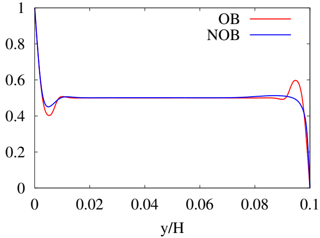


COLD WALL

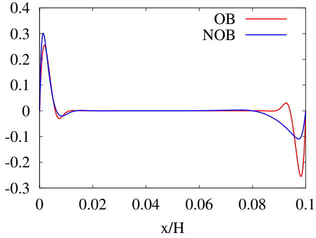


# Topology of the flow, first order statistics

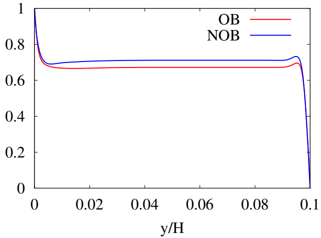
$<\Phi>$at $y/H = 0.5$



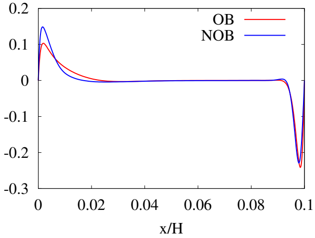
$<V>$ at $y/H = 0.5$



$<\Phi>$at $y/H = 0.7$

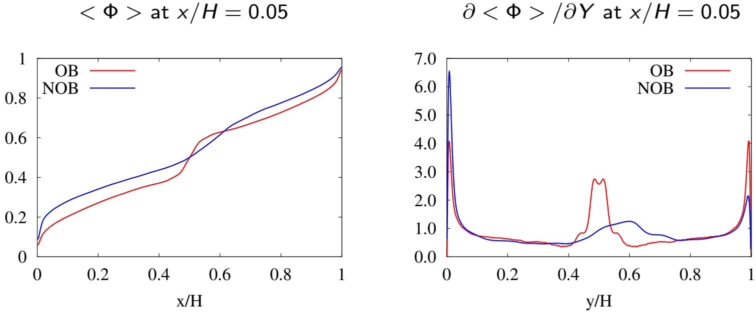


$<V>$ at $y/H = 0.7$

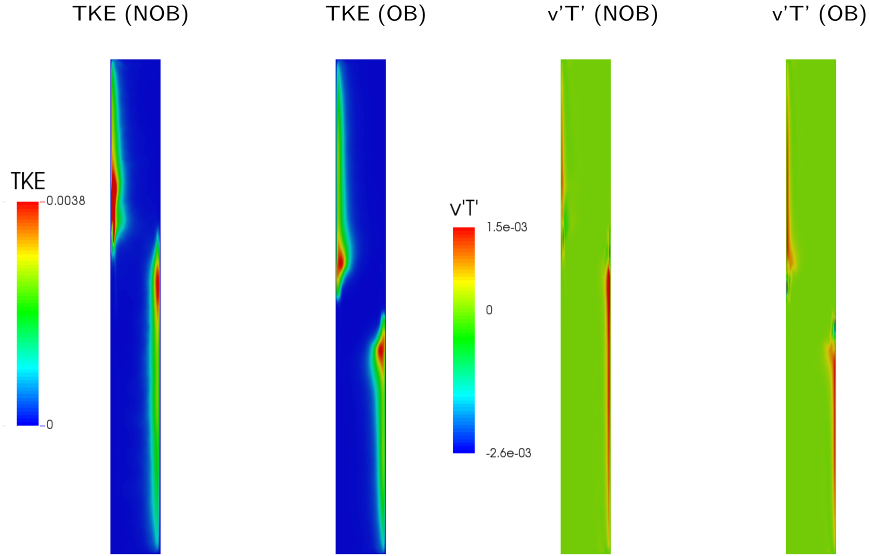


- Hot wall 20 % higher velocity peak, cold wall 50 % lower velocity peak in midheight

# STRATIFICATION



# Topology of the flow, second order statistics



# CONCLUSIONS

- NOB effects are observed to play a role in transition to turbulence location, transition occurs downstream in the hot wall, and upstream in the cold wall, breaking the symmetry of the flow.
- Mechanism of transition, formation and sizes of coherent structures do not present fundamental differences as the physics of the flow concerned.
- The stratification region shifts upwards as NOB effects are considered, however the interaction of the boundary layer seems to degrade the stratification in this zone.

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Thank you for your attention!

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