Direct and Large Eddy Simulations of Non-Oberbeck-Boussinesq Effects in a Turbulent Tall Water-Filled Differentially Heated Cavity

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WCCM-ECCM-ECFD 2014 Congress
Barcelona, 24 July 2014

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Outline

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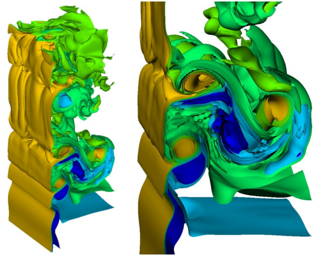
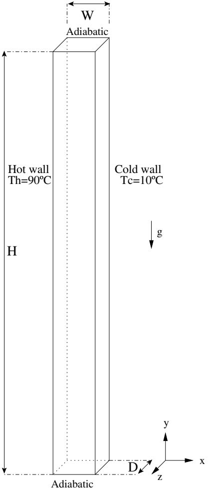
Natural convection within enclosures:

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

Flow configuration:

- Rayleigh-Bénard
- Differentially Heated Cavity (DHC)





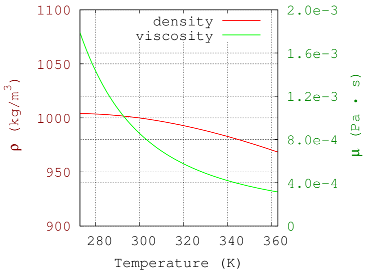
DHC flow features

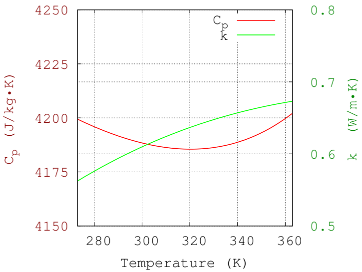
- air-filled cavities
- simple geometry, complex flow
- transition phenomenon
- relaminarization zones
- core stratification

Case definition

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

VARIABLE THERMOPHYSICAL PROPERTIES

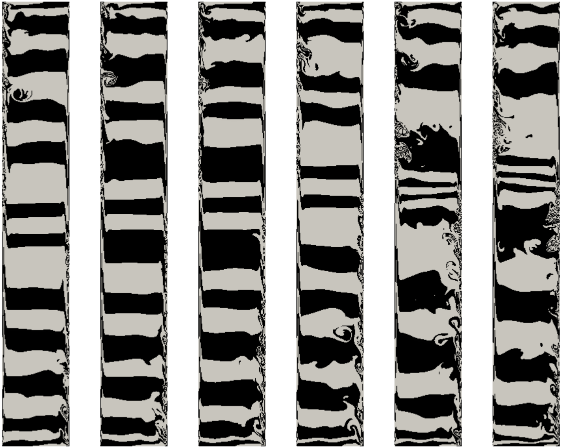




- viscosity changes more than 4 times!
- thermal conductivity changes approx. 20 %
- Gray and Giorgini anticipate important NOB effects! *
- $\delta_v \sim Pr^{1/2}\delta_T$ **

* 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.

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



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

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.

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

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0, \\ \partial_t \mathbf{u} + \mathcal{C}(\mathbf{u},\mathbf{u}) &= \nu_m \Delta \mathbf{u} - \nabla p - \beta_m (T - T_m)\mathbf{g}, \\ \partial_t T + \mathcal{C}(\mathbf{u}, T) &= \alpha_m \Delta T, \end{aligned} \tag{1}$$

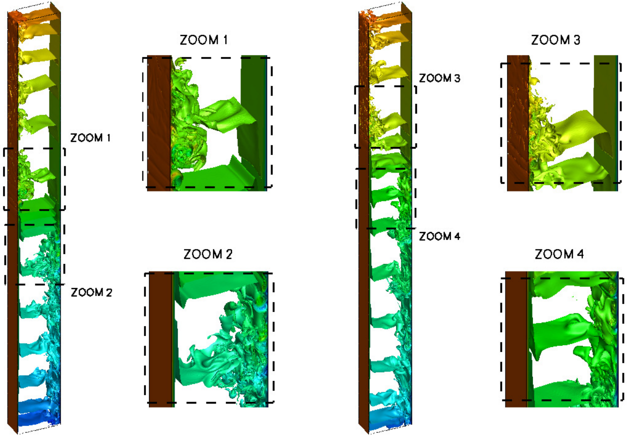
Governing equations considering **non-Oberbeck-Boussinesq (NOB)** effects:

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

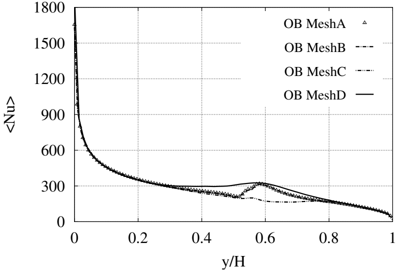
The diffusive term for NOB is discretized as in:
F.X. Trias, A. Gorobets and A. Oliva. "A simple approach to discretize the viscous term with spatially varying (eddy-)viscosity", Journal of Computational Physics, 253 (1): 405-417, 2013.

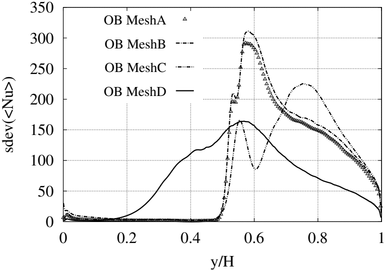
Table: Mesh parameters for DNS. N_x, N_y, and N_z are the number of CVs in $x-$, $y-$, and $z-$directions, respectively. N_{total} is the number of total CVs in millions. Δx_{min} is the smallest non-dimensional wall-normal distance.

Mesh	N_x	N_y	N_z	N_{total}	$\Delta x_{min}/H$
MeshA	194	782	128	19.42	1.03×10^{-4}
MeshB	174	702	96	11.73	1.15×10^{-4}
MeshC	140	560	64	5.02	1.44×10^{-4}
MeshD	55	511	16	0.45	4.80×10^{-4}


ZOOM 1
ZOOM 2
ZOOM 1
ZOOM 2
ZOOM 3
ZOOM 4
ZOOM 3
ZOOM 4

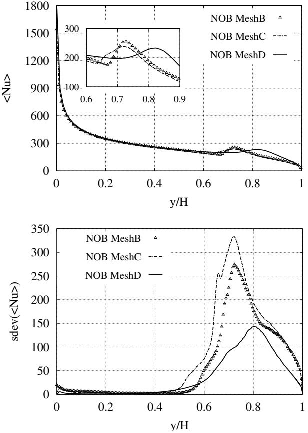
Local average Nusselt (<Nu>) for OB



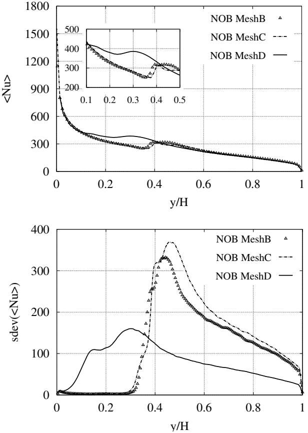


- symmetric behavior in hot & cold walls
- Mesh A is the **OB DNS** solution!

LOCAL AVERAGE NUSSELT (<Nu>) FOR NOB



- downstream transition
- Mesh B is the **NOB DNS**



- upstream transition
- no symmetry!

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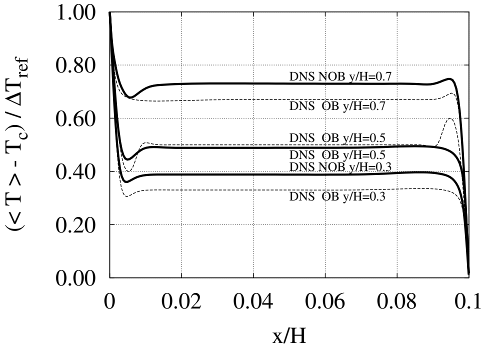
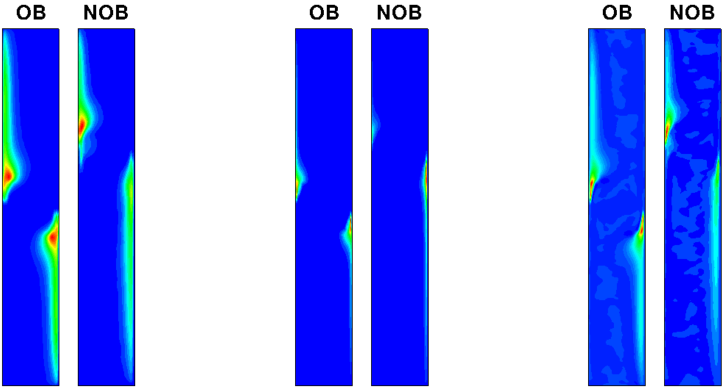


Case	$\overline{Nu}$	x_{tr-HOT}	$x_{tr-COLD}$
NOB	273	0.51	0.29
OB	283	0.48	0.48

- A qualitative glance at the second order statistics
- Large zones of laminar regime



$< k' >$ $< T'T' >$ $< u'v' >$

CASE DEFINITION

- $Ra = 3 \times 10^{11}$
- $Pr = 4.31$
- $\Gamma = 5$

LES MODELS

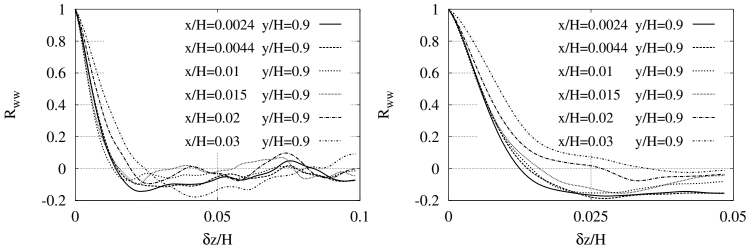
- WALE (Nicoud & Ducros, 1999)
- VMS-WALE (Hughes et. al., 2000)
- QR (Verstappen, 2011)
- No Model

D. Kizildag, F. X. Trias, I. Rodríguez, A. Oliva, Large eddy and direct numerical simulations of a turbulent water-filled cavity of aspect ratio 5, *International Journal of Heat and Mass Transfer* 77 (2014) 1084-1094.

DNS PARAMETERS

Case	N_x	N_y	N_z	$N_{tot} \times 10^{-6}$	D/H	γ_x	$(\Delta x)_{\min}/H$	$\Delta t/t_{ref}$
Mesh A	240	648	128	19.91	0.1	2.0	6.20×10^{-5}	2.71×10^{-4}
Mesh B1	160	432	128	8.85	0.1	2.0	9.38×10^{-5}	8.06×10^{-4}
Mesh B2	160	432	256	17.69	0.2	2.0	9.38×10^{-5}	8.06×10^{-4}

- Two-point correlations drop off to zero for narrower spanwidth, $D/H = 0.1$.



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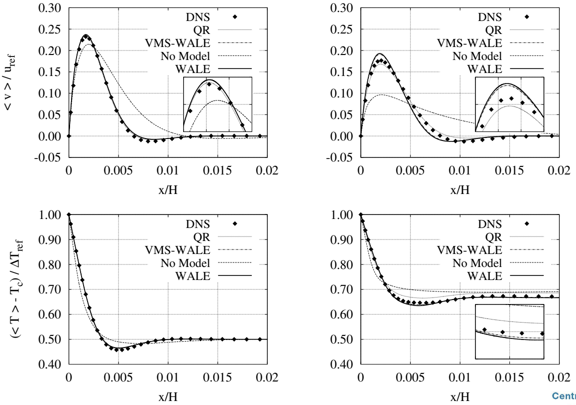
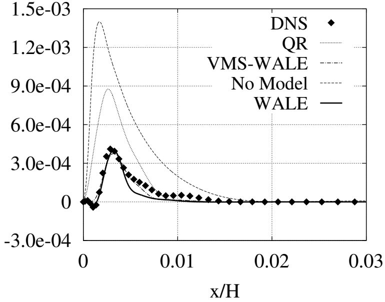
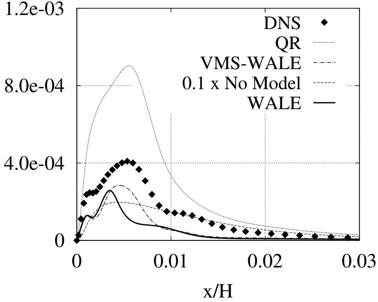
Mesh	N_x	N_y	N_z	$N_{tot} \times 10^{-6}$	γ_x	$(\Delta x)_{min}/H$
Mesh C	55	491	16	0.43	1.97	6.0×10^{-4}
Mesh D	33	319	8	0.08	2.15	8.0×10^{-4}
Mesh E	55	113	16	0.10	1.97	6.0×10^{-4}





$< v'T' >$ at $y/H = 0.75$



$< v'v' >$ at $y/H = 0.75$

- WALE and VMS-WALE predict transition correctly
- No model cannot even predict 1st order stats
- Streamwise resolution critical!

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Conclusions:

- NOB effects play a role in transition to turbulence, transition occurs downstream in the hot wall, and upstream in the cold wall
- Symmetry of the flow is broken
- Highly stratified core shifts upward as NOB effects are considered, like in 2D case.
- In this flow configuration, only moderate reduction in streamwise direction is possible in LES

Future work:

- Using the experience in $\Gamma = 5$ case using OB, the started LES will be concluded for both OB and NOB.

Thank you for your attention!

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