Centre Tecnològic de Transferència de Calor
Laboratori de Termotècnia i Energètica
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Numerical Simulation of the Thermal and Fluid-dynamic behaviour of fuel-oil in sunk ships

C.D.Pérez-Segarra, A.Oliva, F.X.Trias, O.Lehmkuhl, R.Capdevila,
Heat and Mass Transfer Technological Center (CTTC)
Technical University of Catalonia (UPC)
www.cttc.upc.edu

Membre de:
XARXA DE CENTRES DE SUPORT A LA INNOVACIÓ TECNOLÒGICA

Edifici TR4, ETSEIAT
C/ Colom, 11
08222 Terrassa (Barcelona)
Tel. 93 739 81 92 Fax 93 739 81 01
segarra@cttc.upc.edu
http://www.cttc.upc.edu

Presentation:

1. *Project objectives and work performed*

2. *Numerical studies using structured multiblock meshes.*
   a. *RANS modelling.*
   b. *Parallelization techniques.*

3. *Advanced turbulence modelling (DNS & LES models)*
   a. *Current DNS research at MareNostrum supercomputer.*
   b. *Conservative Regularization Modelling (CRM) for LES. An overview of the method.*
   c. *Results for a differentially heated cavity at Ra=10^{10} and Pr=0,71.*
   d. *Results for a tank cooling problem at very high Pr-number*

4. *Conclusions and Future research*

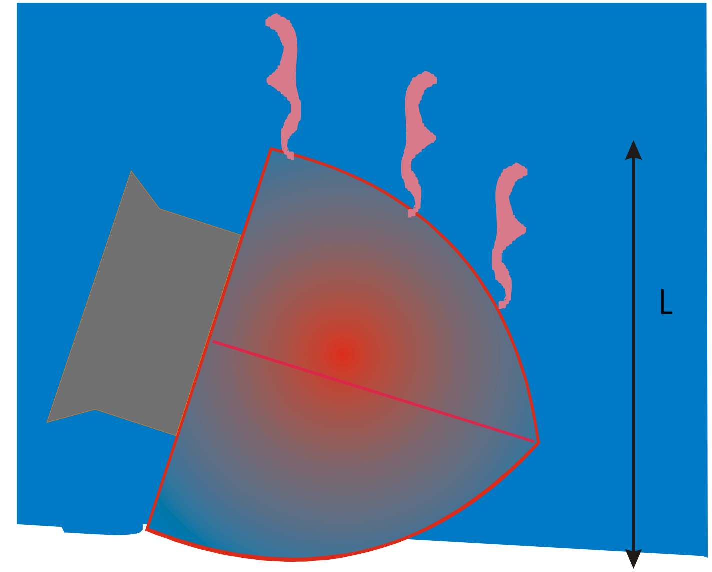
1. Project objectives and scope of this presentation

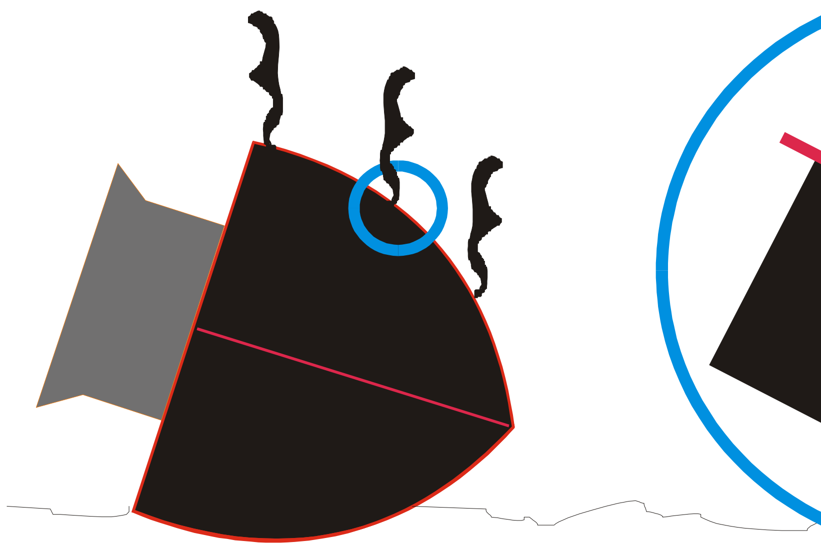
Basic objective: *Development of a code for the numerical simulation of the thermal and fluid-dynamic behaviour of the fuel-oil contained in sunk ships (VEM2003-20046).*

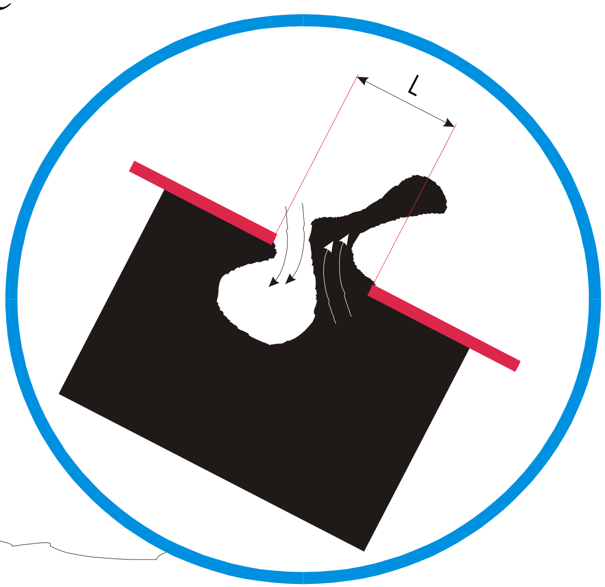
Work performed*:*

1. Main code based on fully-implicit structured multiblock techniques. Turbulence by means of RANS two equation models. Newtonian and non-Newtonian fluids,…

2. Development of a new advanced turbulence model.



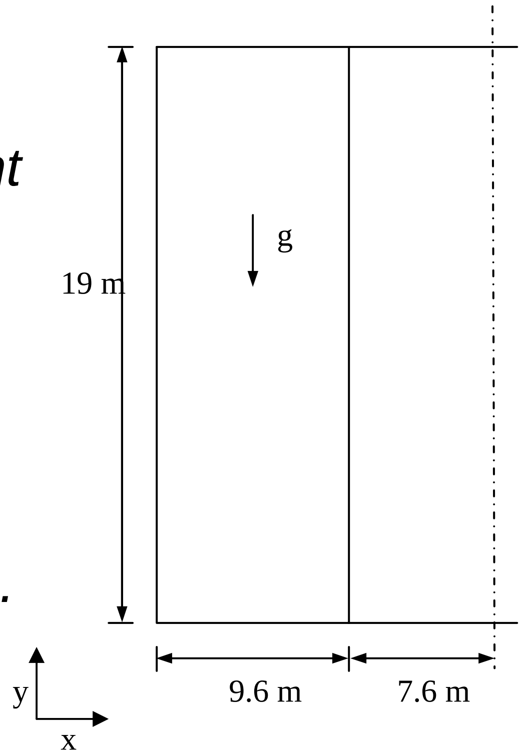


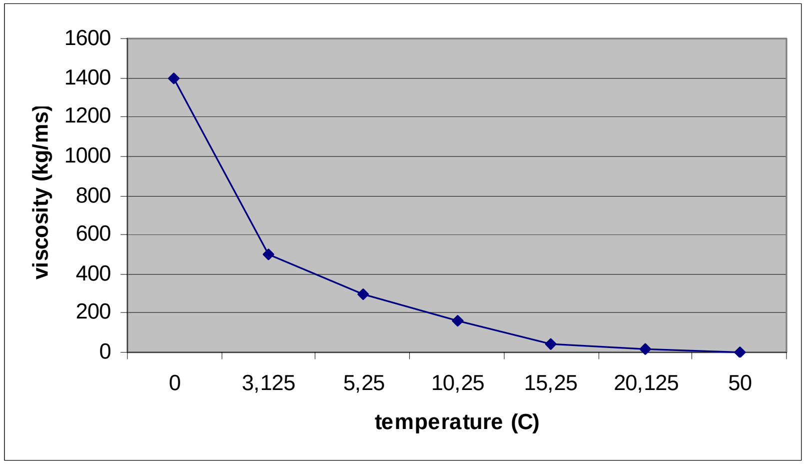


Main code based on fully-implicit structured multiblock techniques.

Modelling of the fuel-oil cooling inside the Prestige tanker.

- Case defined by the CIEMAT.
- 2D approach with specular symmetry on the right boundary. Left, top and bottom boundaries with vanishing velocities and constant temperature (2.6 ºC). Initial temperature 50 ºC.
- Thermophysical properties: ρ=1012 kg/m^3; c_p=1700 J/kg K; λ=0.13 W/m K; β=7.40·10-4 K^{-1}.





Mathematical formulation (RANS models). Incompressible flows or gases at low Mach numbers.

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot \overline{\vec{v}} = 0$$

$$\rho \frac{D\overline{\vec{v}}}{Dt} \approx -\nabla \overline{p} + \nabla \cdot \overline{\vec{\tau}} - \nabla \cdot \left(\rho \overline{\vec{v}'\vec{v}'}\right) - \rho\beta\left(\overline{T} - T_o\right)\vec{g}$$

$$\rho c_p \frac{D\overline{T}}{Dt} \approx -\nabla \cdot \overline{\vec{q}} + \nabla \cdot \left(\rho \overline{\vec{v}'T'}\right)$$

Turbulent shear stresses and heat fluxes:

$$\rho \overline{\vec{v}'\vec{v}'} = -2\mu_t \overline{\vec{\gamma}} + \frac{2}{3}\rho k \vec{\delta} \qquad \rho \overline{\vec{v}'T'} = -\frac{\lambda_t}{c_p}\nabla \overline{T} = -\frac{\mu_t}{\sigma_T}\nabla \overline{T}$$

Numerical method

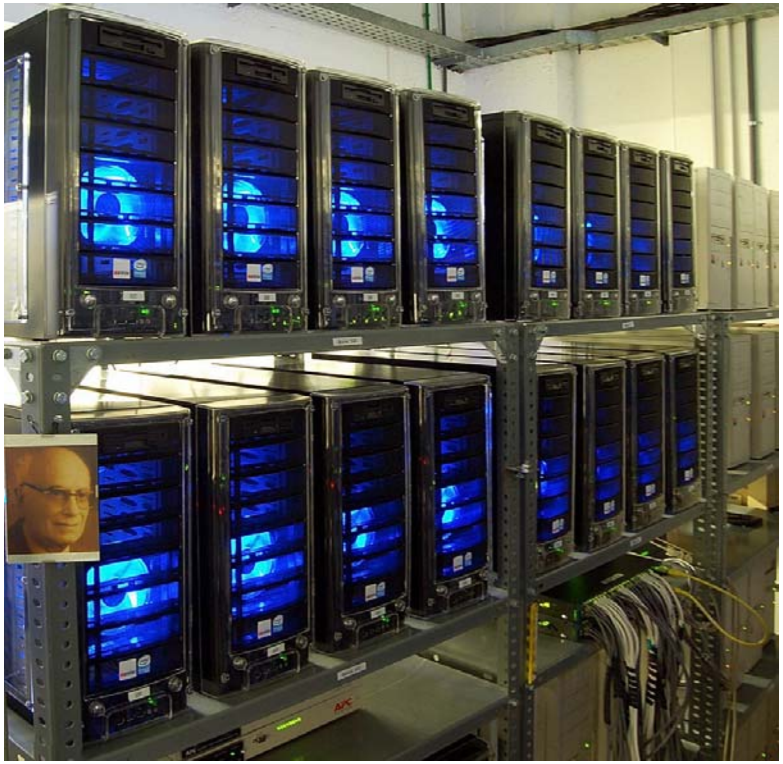
- *Finite volume techniques with semi-implicit differentiation in space and fully implicit in time, using Cartesian staggered grid.*
- *Pressure-based method (SIMPLEC). PLDS and CDS for convective and diffusive terms respectively.*
- *Multiblock strategy*
- *Mesh: (N_1 + N_2) x M. Mesh concentration near the walls. Constant Δt.*

Case	N_1	N_2	M	C.V.	Δt	Convergence criteria
Ref 1	100	80	200	36800	47.77	2 outer iterations
mesh	200	160	400	145600	47.77	2 outer iterations
dt	100	80	200	36800	4.777	2 outer iterations
nº ite	100	80	200	36800	47.77	20 outer ite. or heat imbalance $< 1\%$
Ref 2	110	90	210	42840	47.77	2 outer iterations

Computational infrastructure: PC cluster and MareNostrum supercomputer

Low cost **PC clusters** are **loosely coupled** parallel computers:

- Good ratio **CPU power / cost**
- Low bandwidth and **high latency** network



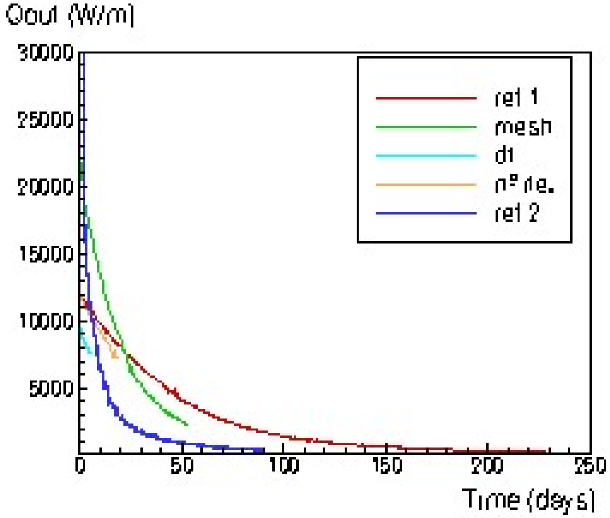
Supercomputers:

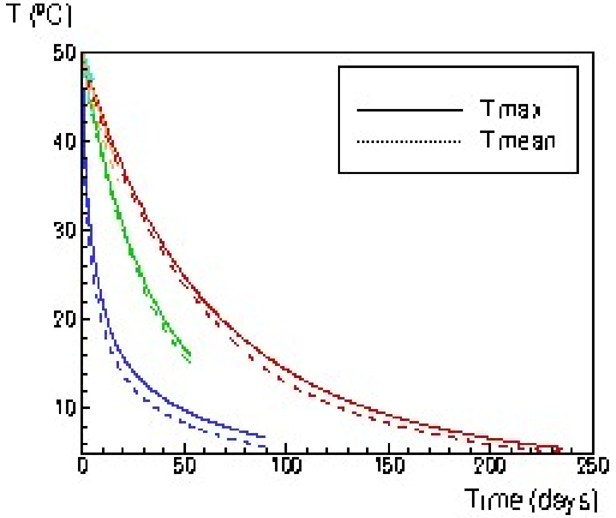
- Much bigger **number of CPU** and much higher price per CPU
- High bandwidth and **low latency** network

Some results

- *High computational cost. The introduction of subdomain (or multiblock) techniques (as a parallelization strategy) allows much lower computational time. Other techniques to reduce CPUtime: variable Δt (CFL strategies); semi-explicit methods (solid-fluid); more efficient solvers; variable grid concentration); ...*

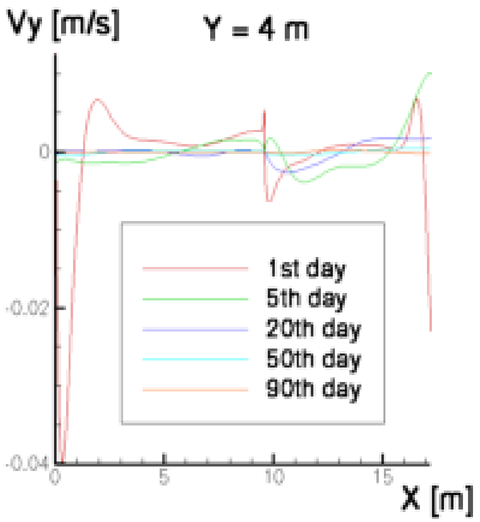
- *Heat transfer and temperature evolution (ref 2):*

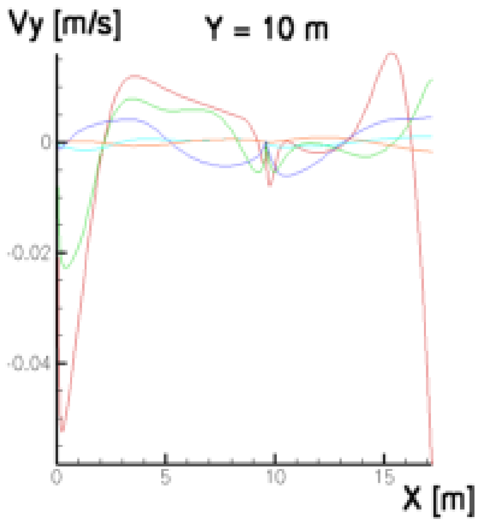


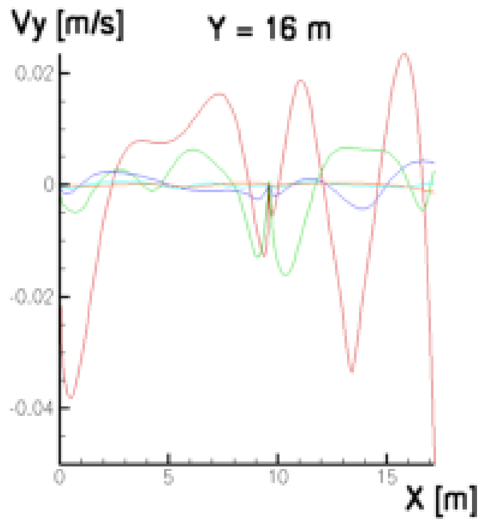


Some results:

- *The phenomenology at the first 20 days is mainly convective but, once the fluid is cold enough to became very viscous, the velocity decreases and the phenomenology is diffusive predominant.*
- *The inner tank is almost one degree hotter than the outer (5th day).*

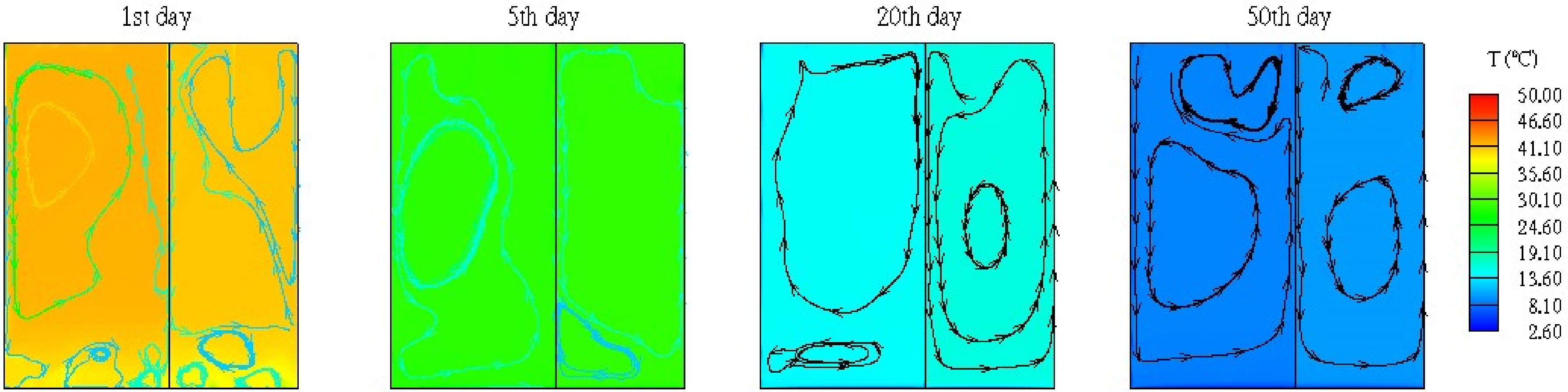






More results (ref 2)

- *1st day: relatively high velocities at the outer tank, specially at the left boundary due to natural convection. The inferior part of the system is the cooler one, with much more vortex (initial Rayleigh = $3.72 \cdot 10^{13}$). Mean temperature around 39 ºC.*
- *5th day: still movement into the tank, but considerably lower. Quite uniform temperature, around 30 ºC.*
- *From the 20th day velocities are almost null and temperature decrease has the form of an inverse exponential.*



Development of a new advanced turbulence model.

Governing equations

Incompressible Navier-Stokes coupled with the energy transport equation:

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

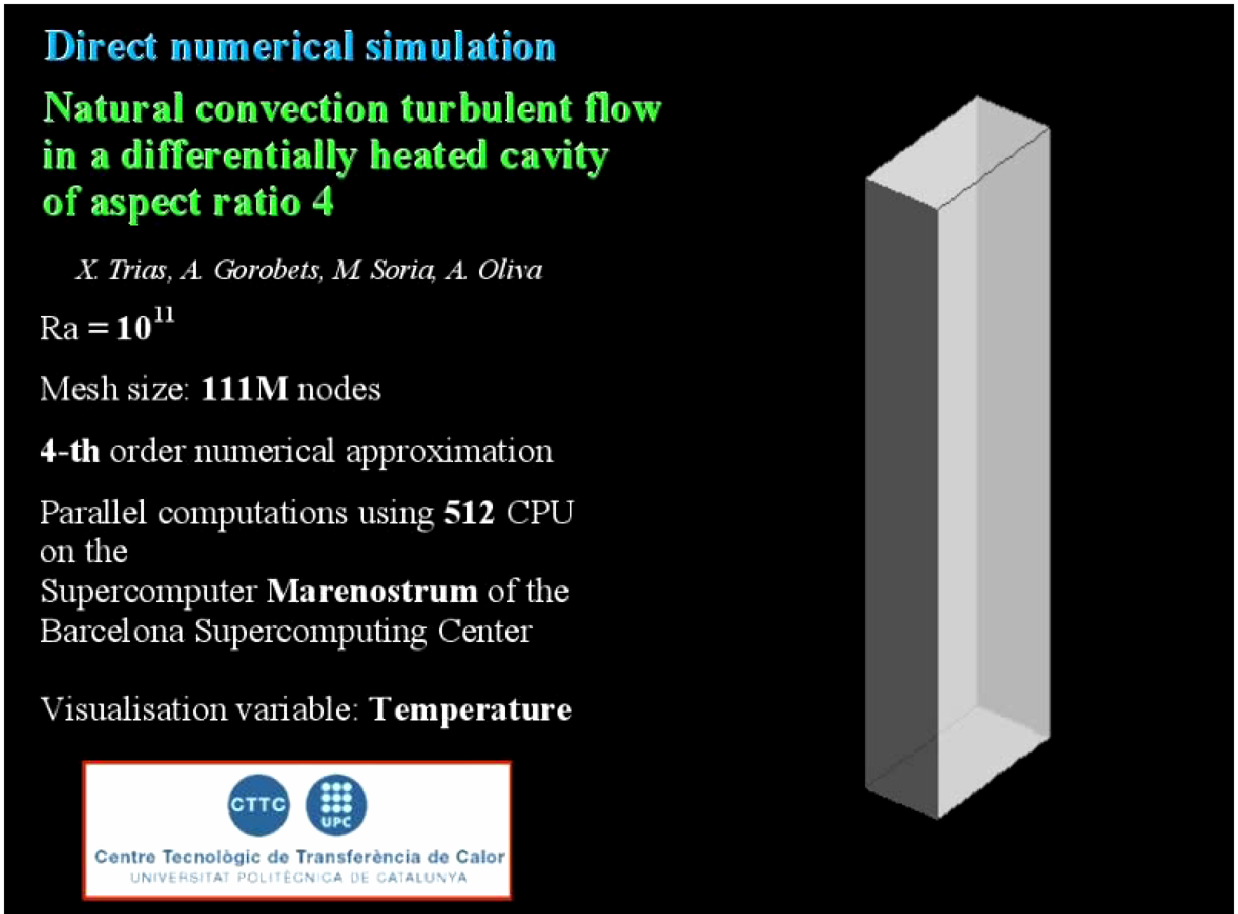
$$\frac{\partial \vec{v}}{\partial t} + C(\vec{v}, \vec{v}) = \mathbf{Pr}\, \nabla^2 \vec{v} - \frac{1}{\rho} \nabla p + \vec{f}$$

$$\frac{\partial T}{\partial t} + C(\vec{v}, T) = \nabla^2 T$$

Where $\vec{f} = (0,0, Ra \, \mathrm{Pr} \, T)$ *(Boussinesq approximation) and the* ***nonlinear convective term*** *is given by*

$$C(\vec{a}, \vec{b}) = (\vec{a} \cdot \nabla)\vec{b}$$

Current DNS research: Differentially heated cavity at $Ra=10^{11}$, $Pr=0.71$



Some details about **DNS simulation**:

- *Mesh size*: 128 x 680 x 1280 (**$111 \cdot 10^6$ nodes**)
- *Computing time*: ~3 months using **512 CPUs** at MareNostrum supercomputer
- 4^{th}-order symmetry-preserving discretization

Complexity of the flow:

- Boundary layers
- Stratified cavity core
- Internal waves
- Recirculation areas

Since the computational cost of a DNS simulation is prohibitive a **dynamically less complex mathematical formulation** *is sought. To do so, we consider smooth approximations (regularizations) of the nonlinear terms*

$$\frac{\partial \vec{v}_\varepsilon}{\partial t} + \widetilde{C}(\vec{v}_\varepsilon, \vec{v}_\varepsilon) = \mathbf{Pr}\,\nabla^2 \vec{v}_\varepsilon - \frac{1}{\rho}\nabla p_\varepsilon + \vec{f}_\varepsilon$$

$$\frac{\partial T_\varepsilon}{\partial t} + \widetilde{C}(\vec{v}_\varepsilon, T_\varepsilon) = \nabla^2 T_\varepsilon$$

Such approximations may fall in the **Large-Eddy Simulation** *(LES) concept,*

$$\frac{\partial \overline{\vec{v}_\varepsilon}}{\partial t} + C(\overline{\vec{v}_\varepsilon}, \overline{\vec{v}_\varepsilon}) = \mathbf{Pr}\,\nabla^2 \overline{\vec{v}_\varepsilon} - \frac{1}{\rho}\nabla \overline{p_\varepsilon} + \overline{\vec{f}_\varepsilon} + M_1(\overline{\vec{v}_\varepsilon}, \overline{\vec{v}_\varepsilon})$$

$$\frac{\partial \overline{T_\varepsilon}}{\partial t} + C(\overline{\vec{v}_\varepsilon}, \overline{T_\varepsilon}) = \nabla^2 \overline{T_\varepsilon} + M_2(\overline{\vec{v}_\varepsilon}, \overline{T_\varepsilon})$$

If the model terms were given by

$$M_1(\overline{\vec{v}_\varepsilon}, \overline{\vec{v}_\varepsilon}) = C(\overline{\vec{v}_\varepsilon}, \overline{\vec{v}_\varepsilon}) - \overline{\widetilde{C}(\overline{\vec{v}_\varepsilon}, \overline{\vec{v}_\varepsilon})}$$

$$M_2(\overline{\vec{v}_\varepsilon}, \overline{T_\varepsilon}) = C(\overline{\vec{v}_\varepsilon}, \overline{T_\varepsilon}) - \overline{\widetilde{C}(\overline{\vec{v}_\varepsilon}, \overline{T_\varepsilon})}$$

The main idea behind regularization methods is to **alter the convective term** *to* ***restrain the production of small scales*** *of motion by means of vortex-stretching*

However, ***since now*** *the* ***existing regularization models***

- *Leray model*
- *Navier-Stokes-alpha model*

Do not conserve *some of the* ***inviscid invariants***:

- Kinetic energy $\int_{\Omega} \vec{v} \cdot \vec{v} \, d\Omega$
- Enstrophy (in 2D) $\int_{\Omega} (\nabla \times \vec{v}) \cdot (\nabla \times \vec{v}) \, d\Omega$
- Helicity (in 3D) $\int_{\Omega} (\nabla \times \vec{v}) \cdot \vec{v} \, d\Omega$

The ***approximate convective operator*** *has to be* ***skew-symmetric***

$$(\widetilde{C}(\vec{a},\vec{b}),\vec{c}) = -(\widetilde{C}(\vec{a},\vec{c}),\vec{b})$$

This criterion yields the following class of approximations…

$$\frac{\partial \vec{v}_\varepsilon}{\partial t} + C_n(\vec{v}_\varepsilon, \vec{v}_\varepsilon) = \mathbf{Pr}\,\nabla^2 \vec{v}_\varepsilon - \frac{1}{\rho}\nabla p_\varepsilon$$

In which the convective term is smoothed according to:

$$C_2(\vec{a},\vec{b}) = \overline{C(\overline{\vec{a}},\overline{\vec{b}})}$$

$$C_4(\vec{a},\vec{b}) = C(\overline{\vec{a}},\overline{\vec{b}}) + \overline{C(\overline{\vec{a}},\vec{b}')} + \overline{C(\vec{a}',\overline{\vec{b}})}$$

$$C_6(\vec{a},\vec{b}) = C(\overline{\vec{a}},\overline{\vec{b}}) + C(\overline{\vec{a}},\vec{b}') + C(\vec{a}',\overline{\vec{b}}) + \overline{C(\vec{a}',\vec{b}')}$$

Where, $\vec{a}' = \vec{a} - \overline{\vec{a}}$

$$C_n(\vec{a},\vec{b}) = C(\vec{a},\vec{b}) + O(\varepsilon^n)$$

For any symmetric linear filter

Discretization of the convective operator: a symmetry-preserving discretization

The spatially discrete incompressible Navier-Stokes equations can be expressed as

$$\mathbf{H}\frac{d\mathbf{u_h}}{dt} + \mathbf{C}(\mathbf{u_h})\mathbf{u_h} + \mathbf{D}\mathbf{u_h} - \mathbf{M}^{\mathbf{T}}\mathbf{p_h} = \mathbf{0}$$

$$\mathbf{M}\mathbf{u_h} = \mathbf{0}$$

It can be shown that the ***convective matrix*** $\mathbf{C}(\mathbf{u_h})$ *has to be skew-symmetric,*

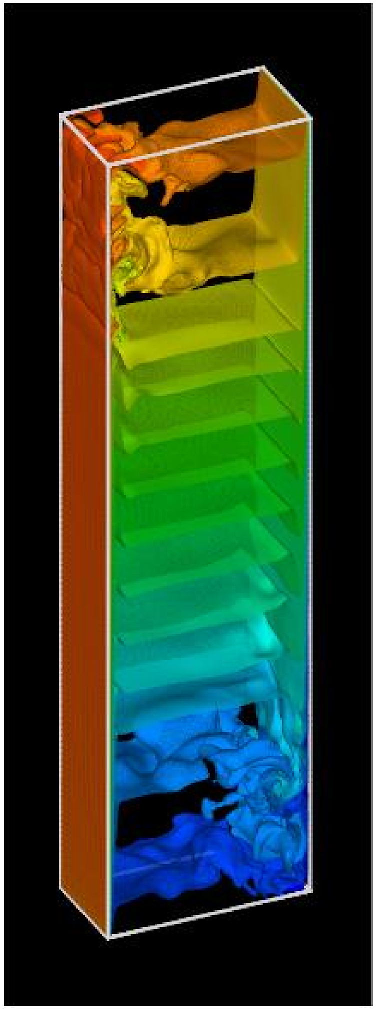
$$\mathbf{C}(\mathbf{u_h}) + \mathbf{C}^{\mathbf{T}}(\mathbf{u_h}) = \mathbf{0}$$

To ***preserve*** *the continuous* ***invariants*** *(kinetic energy, enstrophy in 2D and helicity in 3D) in a* ***discrete sense****.*

Results for a differentially heated cavity at Ra=10^{10} and Pr=0,71

- *DNS: mesh size*: 64 x 136 x 324; 4th-order sym.-preserv discret.
- *Regularization model* C_4 *is tested.*
- *Two very coarse meshes are considered:*

	DNS	RM1	RM2
Nx	64	8	8
Ny	136	17	13
Nz	324	40	30

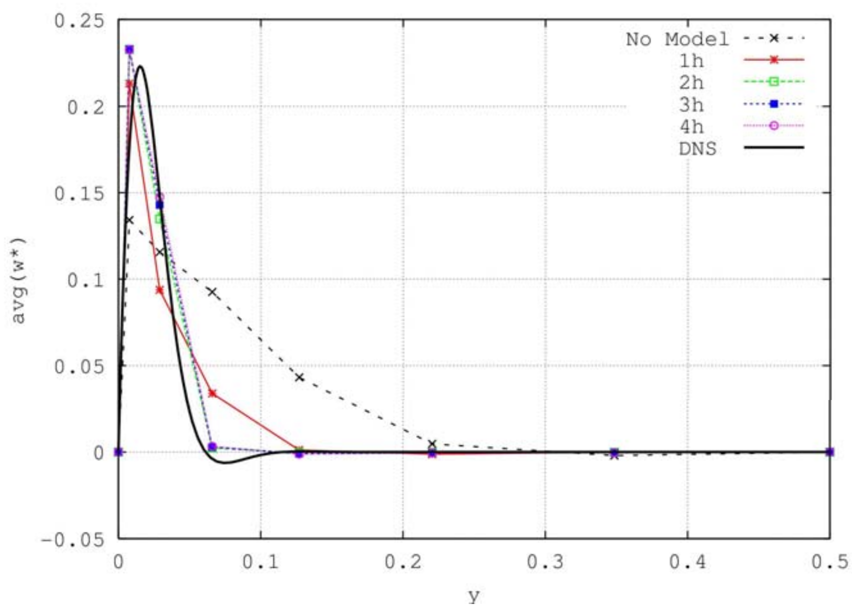


- *Ratio* ε/h *(filter length to the average grid width) is kept constant in all three spatial directions.*

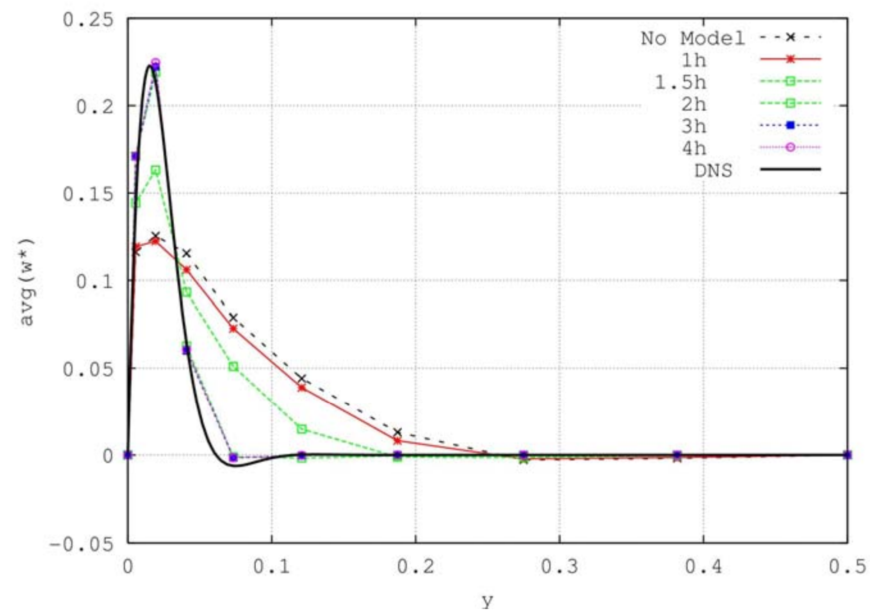
Results for a differentially heated cavity at Ra=10^{10}

Mean fields

8 x 13 x 30



8 x 17 x 40

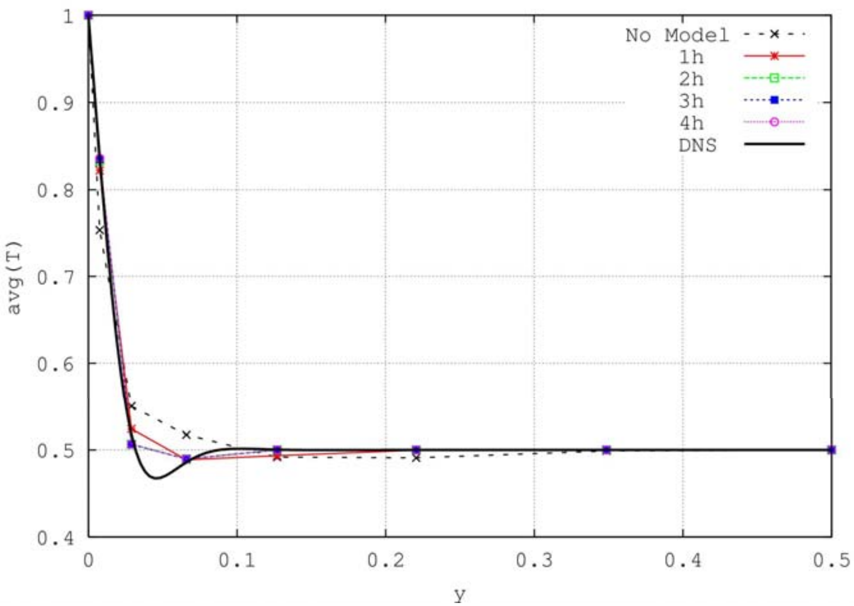


Averaged vertical velocity profile at the horizontal mid-height plane for different ε / h ratios

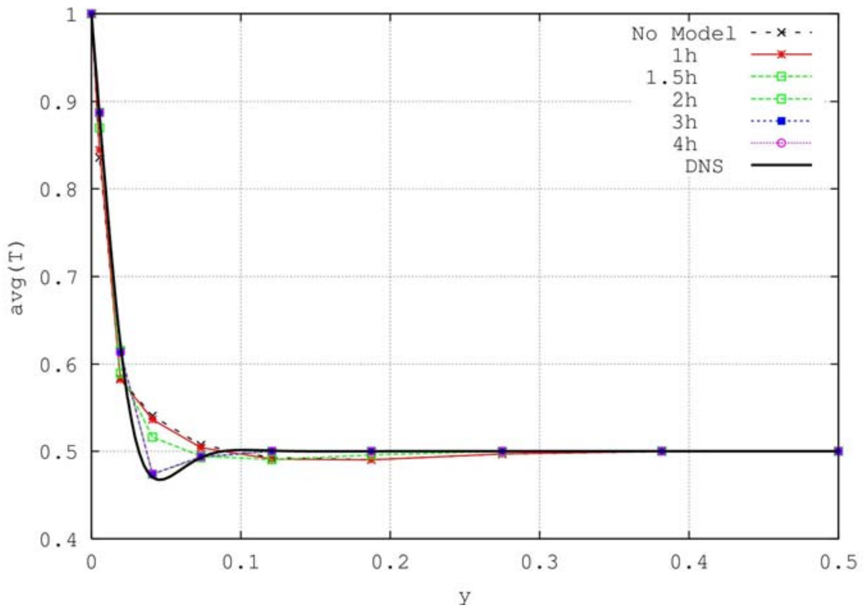
Results for a differentially heated cavity at Ra=10^{10}

Mean fields

8 x 13 x 30



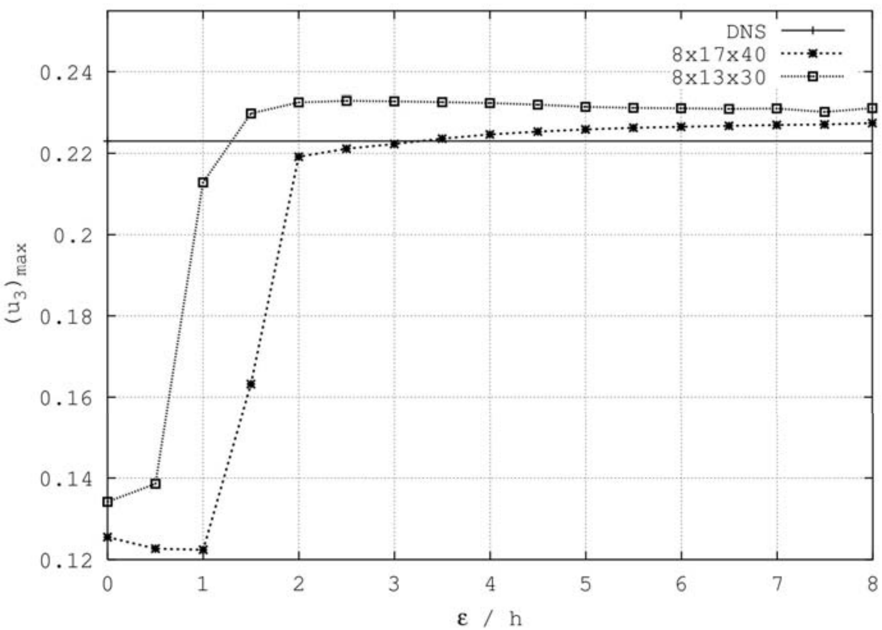
8 x 17 x 40



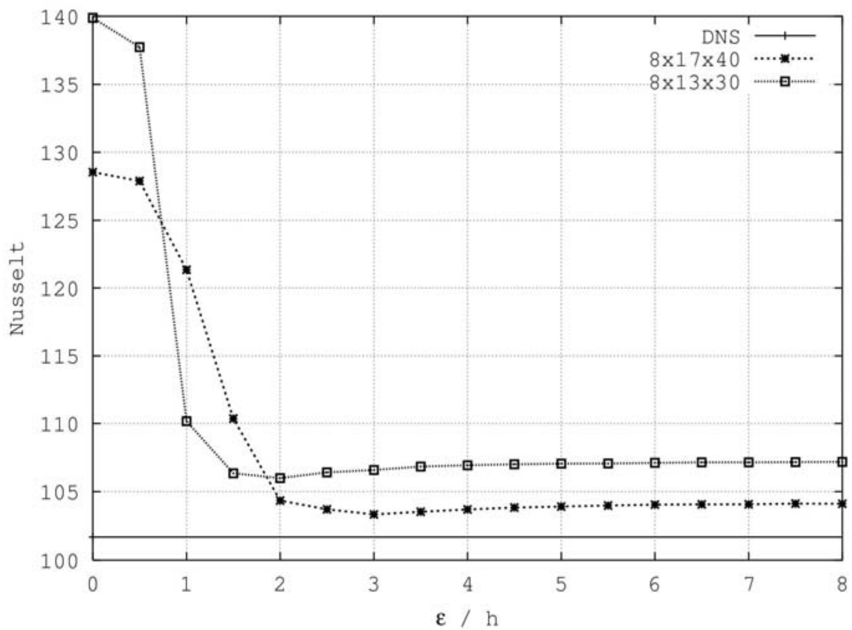
Averaged temperature profile at the horizontal mid-height plane for different ε/h ratios

Results for a differentially heated cavity at Ra=10^{10}
Convergence studies

w_{max}



Nusselt

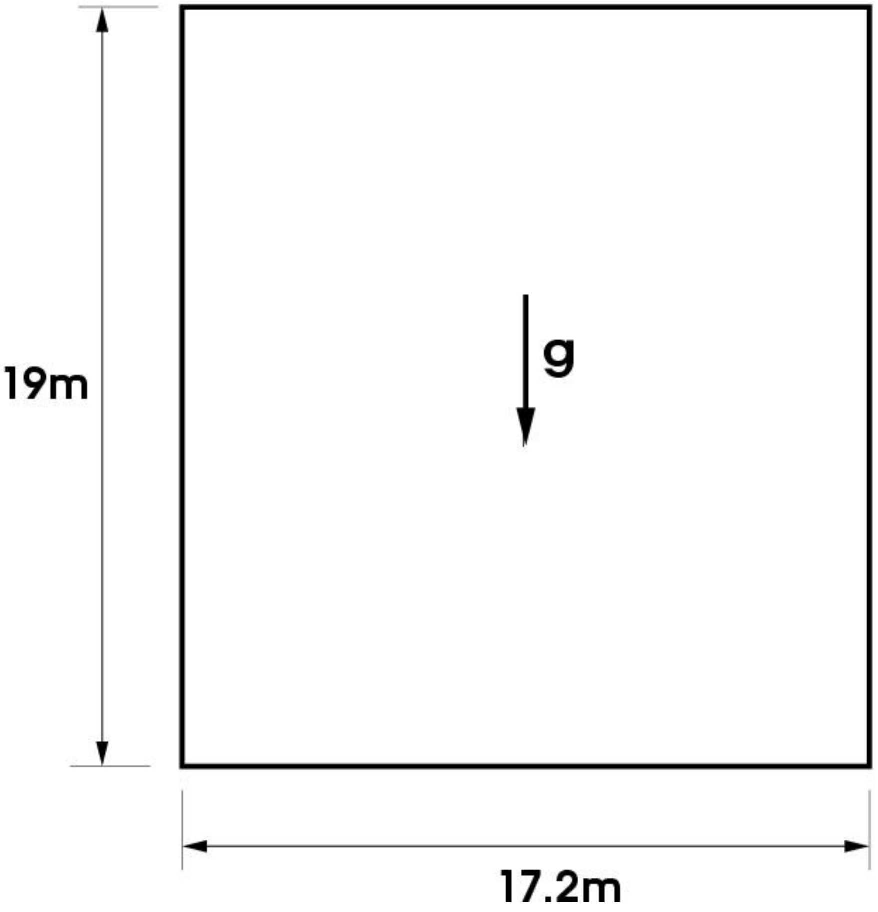


The maximum of the averaged vertical velocity at the horizontal mid-height plane and the overall averaged Nusselt number as a function of the ε/h ratio

Results for a tank cooling problem at very high Pr-number

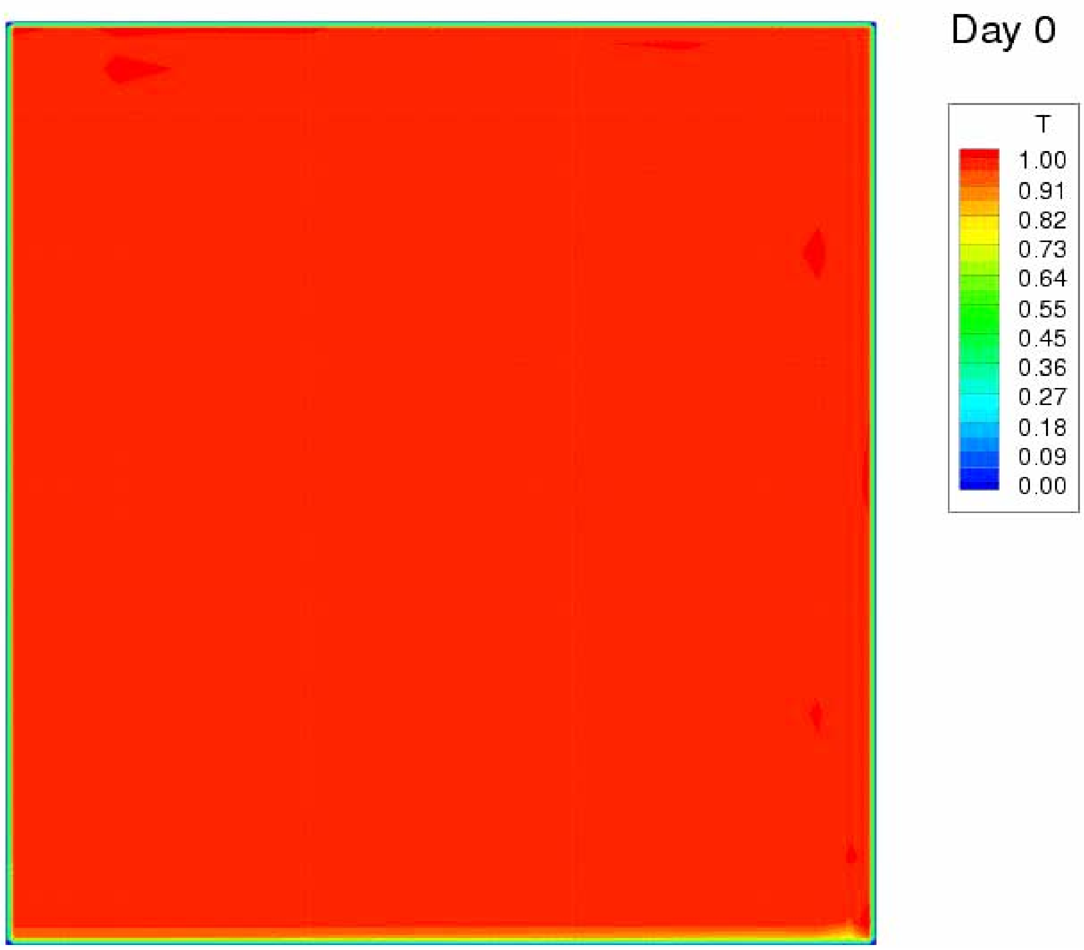
- Similar to the benchmark case defined by CIEMAT.
- 3D approach.
- Initial temperature: 50ºC
- Isothermal boundary conditions at 2.6ºC

- **Ra_H=3.72x10^{13}**
- **Pr =11115**



Results for a tank cooling problem at very high Pr-number

8 x 17 x 20

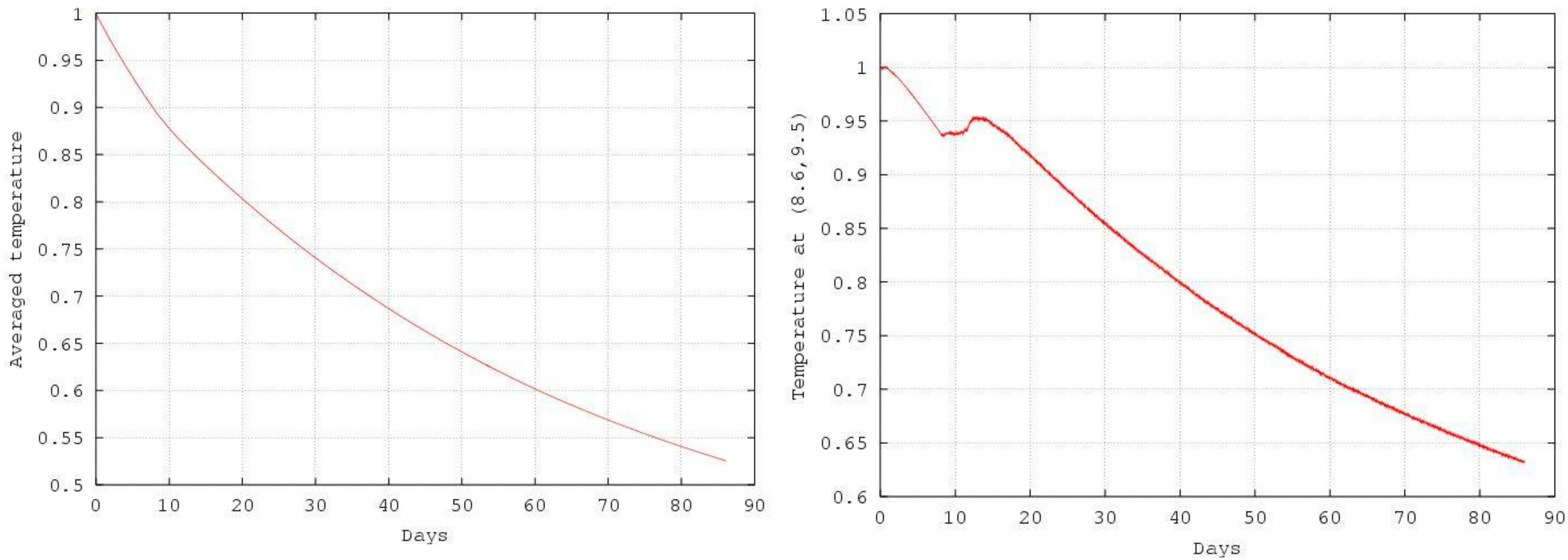


•*Even for* ***very coarse meshes*** *reasonable results has been obtained.*

•*Temperature evolution is in* ***good agreement*** *with the initial numerical studies.*

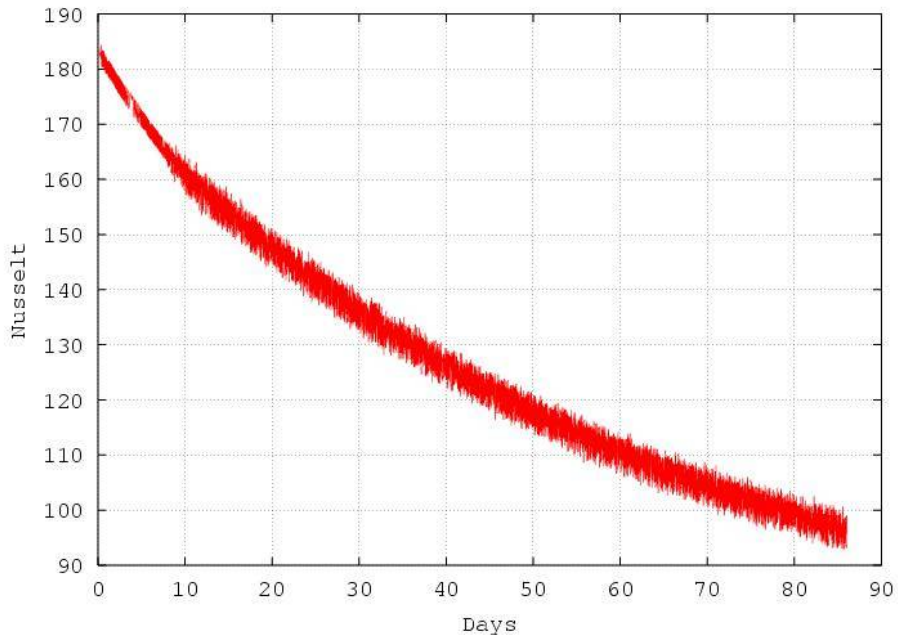
•*Since the time integration is fully explicit we are strongly limited by the* Δt *(CFL condition)*

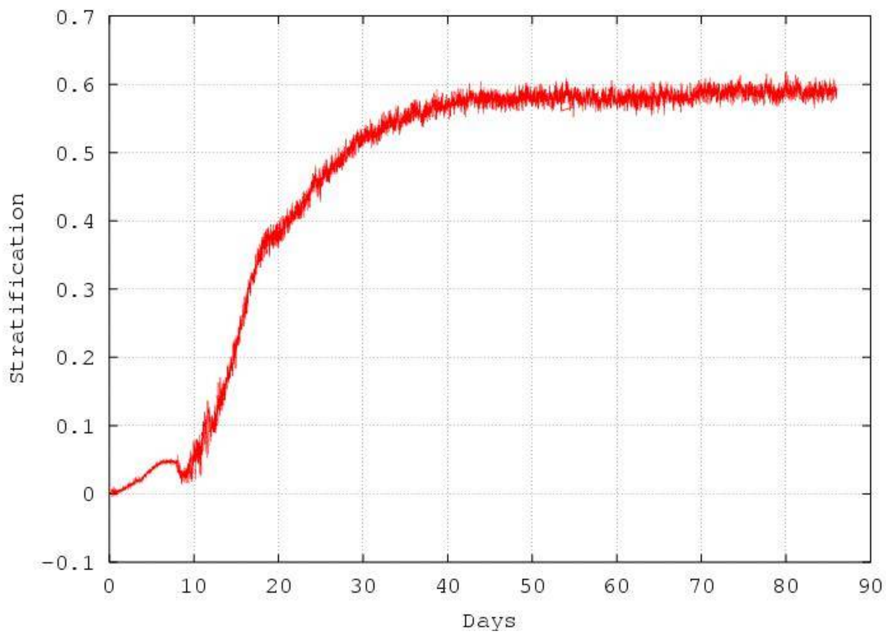
Results for a tank cooling problem at very high Pr-number



Evolution of the averaged temperature and the temperature at the centre of the cavity.

Results for a tank cooling problem at very high Pr-number





Evolution of the overall Nusselt at the left vertical wall and the temperature stratification at the centre of the cavity.

Conclusions and future actions

4. Conclusions and future actions

- A *CFD code* for the thermal and fluid dynamic behaviour of fuel-oil in sunk ships has been developed.
- The code is based on **structured meshes**. Complex geometries are treated using a **multiblock strategy**. Turbulence is solved by means of **RANS models**.
- Results of a benchmark case of the cooling process in the sunk tanker Prestige have been presented. **High computational effort** is required.
- A *new LES method* has been applied for a tank cooling problem at very high Pr-number

  The *main advantages* with respect the existing LES models can be summerized:

  - **Robustnest**. As the smoothed governing equations preserve the symmetry properties of the original NS equations the solution can not blow-up (in energy-norm; in 2D also enstrophy-norm). Moreover, it seems that even for very coarse meshes reasonably results can be obtained.
  - **Universality**. No *ad hoc* phenomenological arguments that can not be formally derived from the NS equations are used.

→ ***<u>Future research</u>*** should focus on the **extension** of the overall symmetry-preserving for formulation for CRM-LES to **unstructured general meshes**….

Moreover, a **semi-implicit formulation** must be implemented in order to avoid the severe Δt restrictions.

4. Final remarks

Turbulence modelling:
RANS
CRM-LES
DNS

Numerical Methods:
STRUCTURED MULTIBLOCK
PARALLELIZATION
TECHNIQUES

Numerical simulation of fuel-oil in sunk ships

More basic studies on Turbulence modelling
DNS & CRM-LES
(CTTC)

New CFD code development
Numerical methods (unstructured meshes, stronger couplings, parallelization,…)
Turbulence modelling (RANS, hybrid RANS-LES, CRM-LES,…)
(TF)