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SIMULATION OF PCM MELTING PROCESS IN A DIFFERENTIALLY HEATED ENCLOSURE

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INTRODUCTION

- This study deals with a numerical investigation on the melting process of a PCM in a rectangular enclosure differentially heated;
- A FEM-based code is used in order to solve Navier-Stokes and energy equations in the considered system;
- The industrial framework of the study is the thermal storage for thermodynamic solar power plants;
- The main goal of this study consists, at the present step of the work, in validating the numerical tool by comparison with experimental results previously published.

MATHEMATICAL MODEL

- Homogeneous method [1] (Enthalpy method): one single equation is used to solve the temperature field both in the solid and in the liquid domain of the system:

$$\frac{\partial H}{\partial t} = k\nabla^2 T + Q + \rho C \mathbf{U} \cdot \nabla T \quad \text{where} \quad \begin{cases} dH = \rho C(T) dT \\ H(T) = \int_{T_1}^{T_2} \rho C(T)\, dT \end{cases}$$

[1] Lewis R.W., Nithiarasu N., Seetharam K.N., Fundamentals of the Finite Element Method for Heat and Fluid Flow, Wiley

MATHEMATICAL MODEL

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where

$$\begin{cases} dH = \rho C(T) dT \\ H(T) = \int_{T_1}^{T_2} \rho C(T) \, dT \end{cases}$$

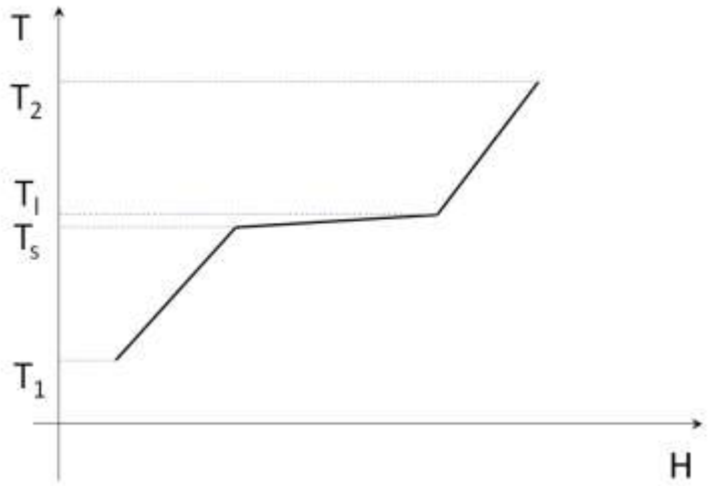
➢ During solid phase heating, melting and further heating of liquid phase, the enthalpy function can be written as in following:

$$H(T) = \int_{T_1}^{T_s} \rho C_s(T) dT + \int_{T_s}^{T_l} \rho \left[C_{sl}(T) + \frac{dL}{dT} \right] dT + \int_{Tl}^{T_2} \rho C_l(T) dT$$

(1) *Lewis R.W., Nithiarasu N., Seetharam K.N., Fundamentals of the Finite Element Method for Heat and Fluid Flow, Wiley*

MATHEMATICAL MODEL

➢ The previous formulation is based on the hypothesis that phase change in the considered medium happens with a small temperature variation, therefore (T_l – T_s):



$$H(T) = \int_{T_1}^{T_s} \rho C_s(T)dT + \int_{T_s}^{T_l} \rho\left[C_{sl}(T) + \frac{dL}{dT}\right]dT + \int_{Tl}^{T_2} \rho C_l(T)dT$$

MATHEMATICAL MODEL

- By defining the thermal capacity as:

$$\frac{\partial H}{\partial t} = \frac{\partial H}{\partial T}\frac{\partial T}{\partial t} \qquad C_{eq} = \frac{\partial H}{\partial T}$$

the equation energy:

$$\frac{\partial H}{\partial t} = k\nabla^2 T + Q + \rho C \mathbf{U}\cdot\nabla T$$

becomes:

$$C_{eq}\frac{\partial T}{\partial t} = k\nabla^2 T + Q + \rho C_{eq}\mathbf{U}\cdot\nabla T$$

MATHEMATICAL MODEL

- Being:

$$H(T) = \int_{T_1}^{T_s} \rho C_s(T)dT + \int_{T_s}^{T_l} \rho \left[C_{sl}(T) + \frac{dL}{dT} \right] dT + \int_{Tl}^{T_2} \rho C_l(T)dT$$

$$C_{eq} = \frac{\partial H}{\partial T}$$

we can write:

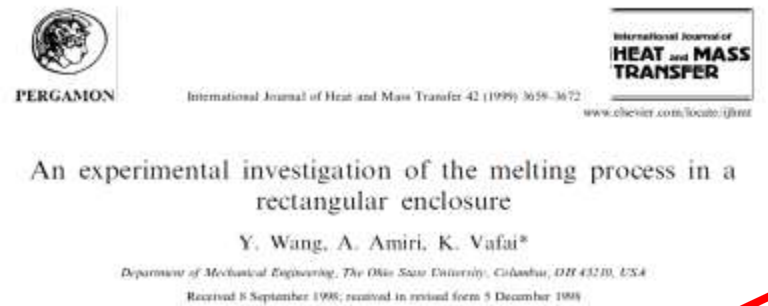
$$C_{eq} = \rho C_s \qquad \Leftrightarrow \qquad (T < T_s)$$

$$C_{eq} = \rho C_{sl} + \rho \frac{L}{T_l - T_s} \qquad \Leftrightarrow \qquad (T_s \le T \le T_l)$$

$$C_{eq} = \rho C_l \qquad \Leftrightarrow \qquad (T > T_l)$$

REFERENCE EXPERIMENTAL SET-UP

- Rectangular enclosure filled by paraffin and differentially heated



PERGAMON

International Journal of Heat and Mass Transfer 42 (1999) 3659–3672
www.elsevier.com/locate/ijhmt
International Journal of HEAT and MASS TRANSFER

An experimental investigation of the melting process in a rectangular enclosure

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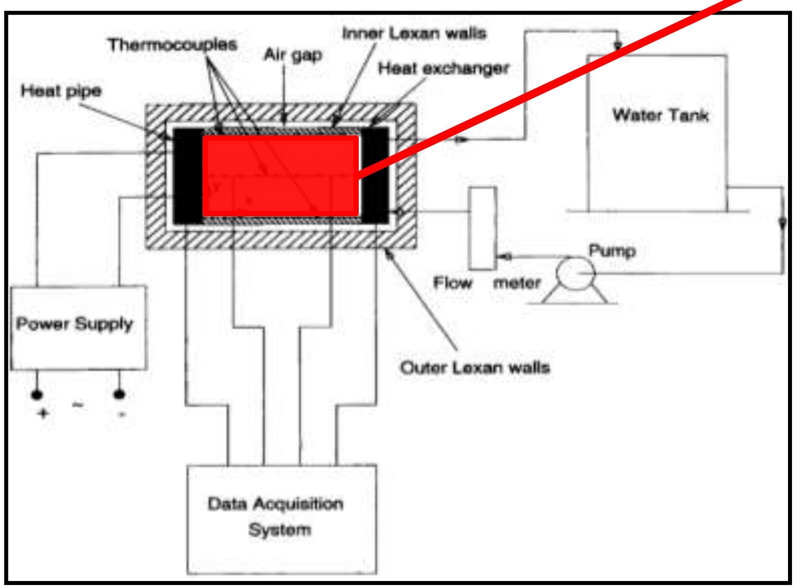
Department of Mechanical Engineering, The Ohio State University, Columbus, OH 43210, USA

Received 8 September 1998; received in revised form 5 December 1998

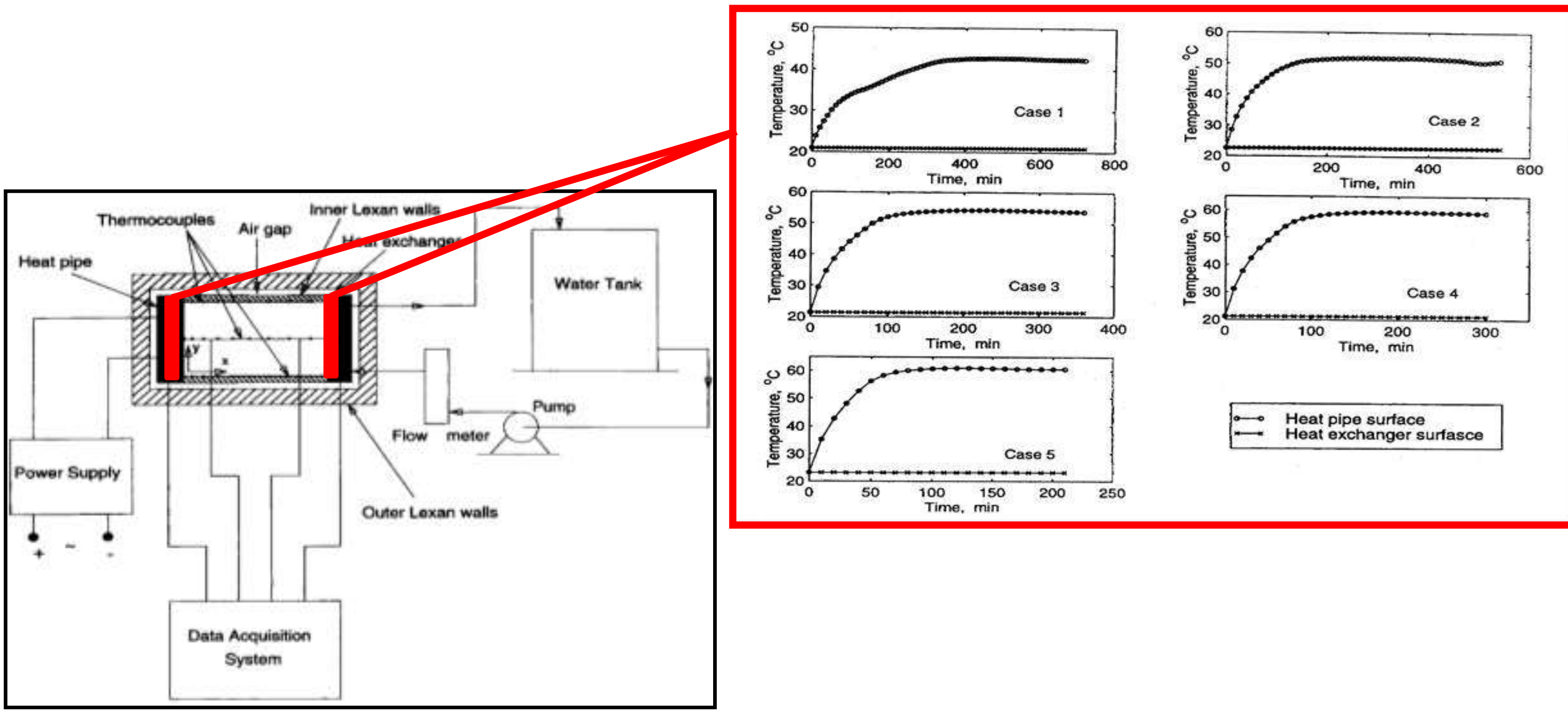


Liquid phase	Solid phase
$\rho = 1100\ \mathrm{kg\ m^{-3}}$	$\rho = 1120\ \mathrm{kg\ m^{-3}}$
$c = 2260\ \mathrm{J\ kg^{-1}\ K^{-1}}$	$c = 2260\ \mathrm{J\ kg^{-1}\ K^{-1}}$
$k = 0.188\ \mathrm{W\ m^{-1}\ K^{-1}}$	$k = 0.188\ \mathrm{W\ m^{-1}\ K^{-1}}$

$\beta = 7.6 \times 10^{-4}\ \mathrm{K}$ $\quad h_{sl} = 150.5\ \mathrm{kJ\ kg^{-1}}$ $\quad T_m = 34°\mathrm{C}$

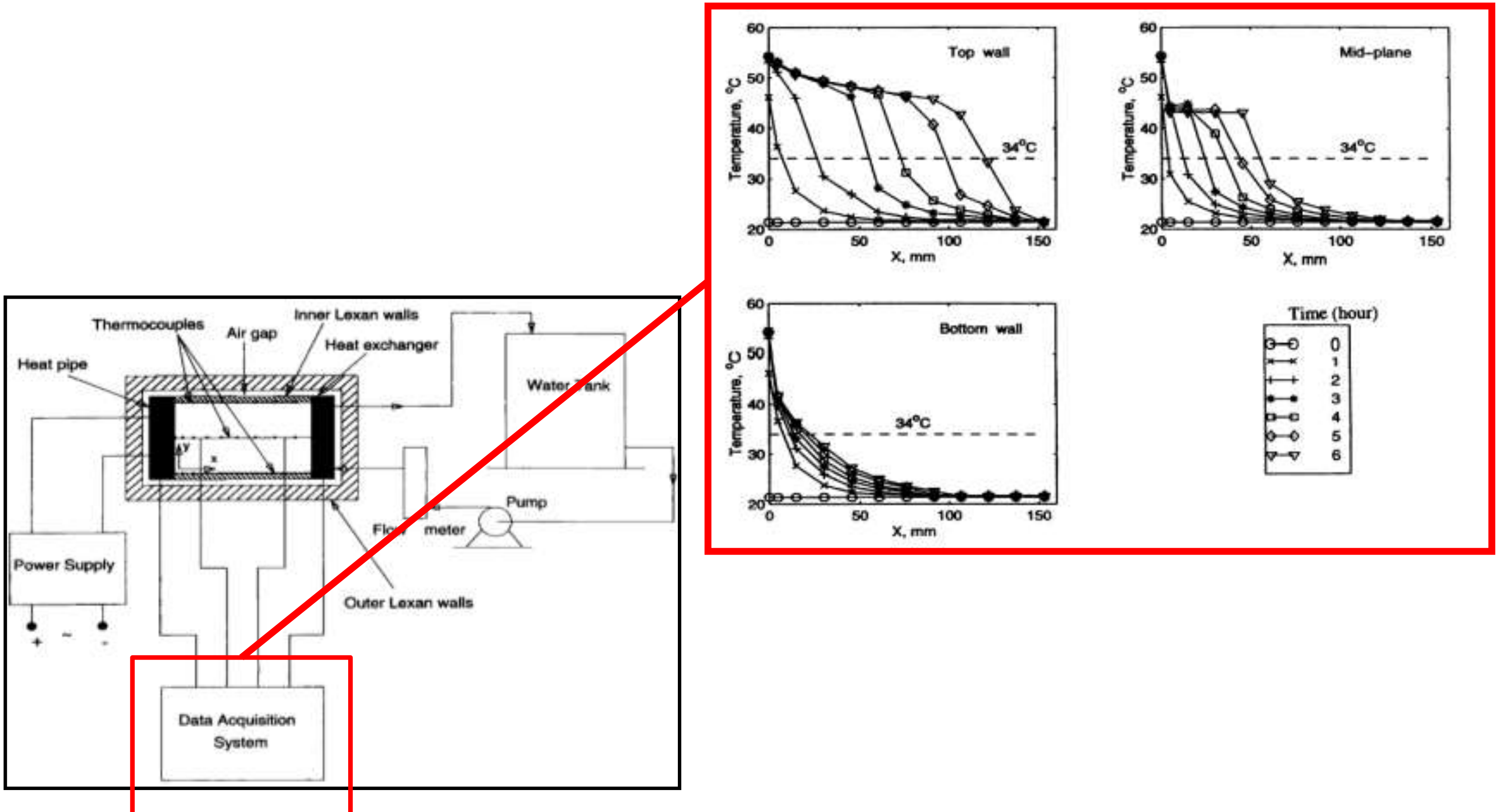
REFERENCE EXPERIMENTAL SET-UP

➢ Time evolution of the “hot wall” temperature during 5 different test-cases (the “cold wall” is kept at constant temperature)



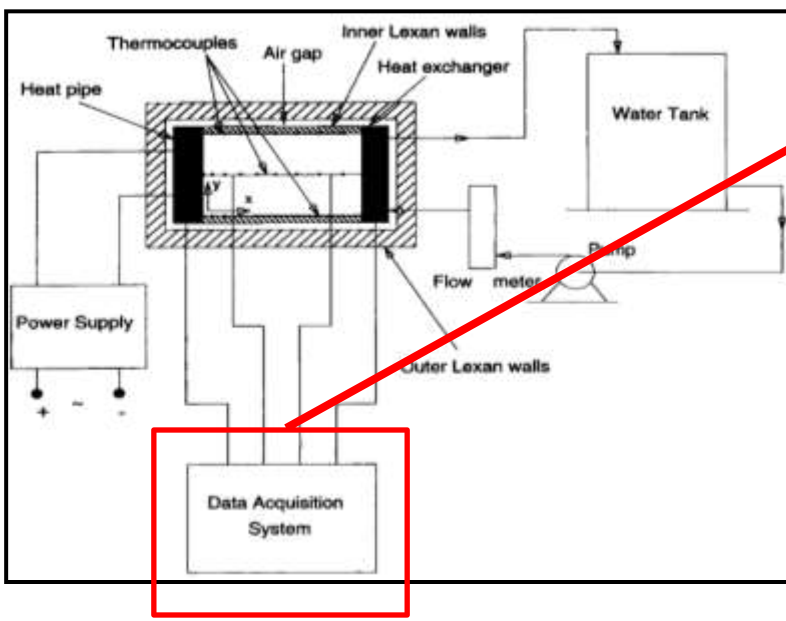
REFERENCE EXPERIMENTAL SET-UP

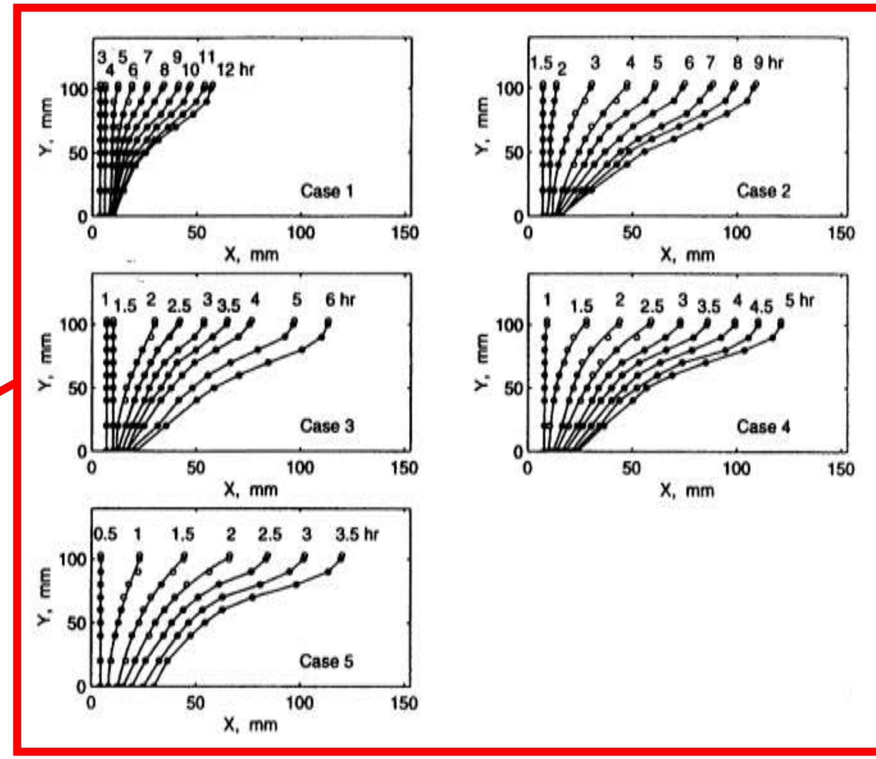
➢ Experimental acquisition > Spot temperature at several locations



REFERENCE EXPERIMENTAL SET-UP

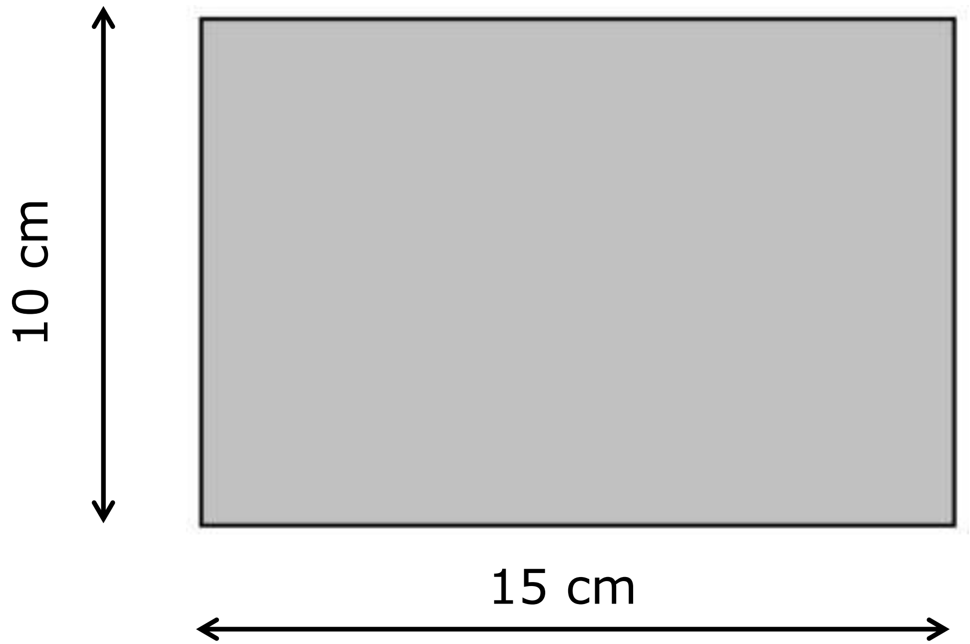
- Experimental acquisition > Solid/liquid interface (T_melting) position





NUMERICAL MODEL

➢ Test-case model > Geometry

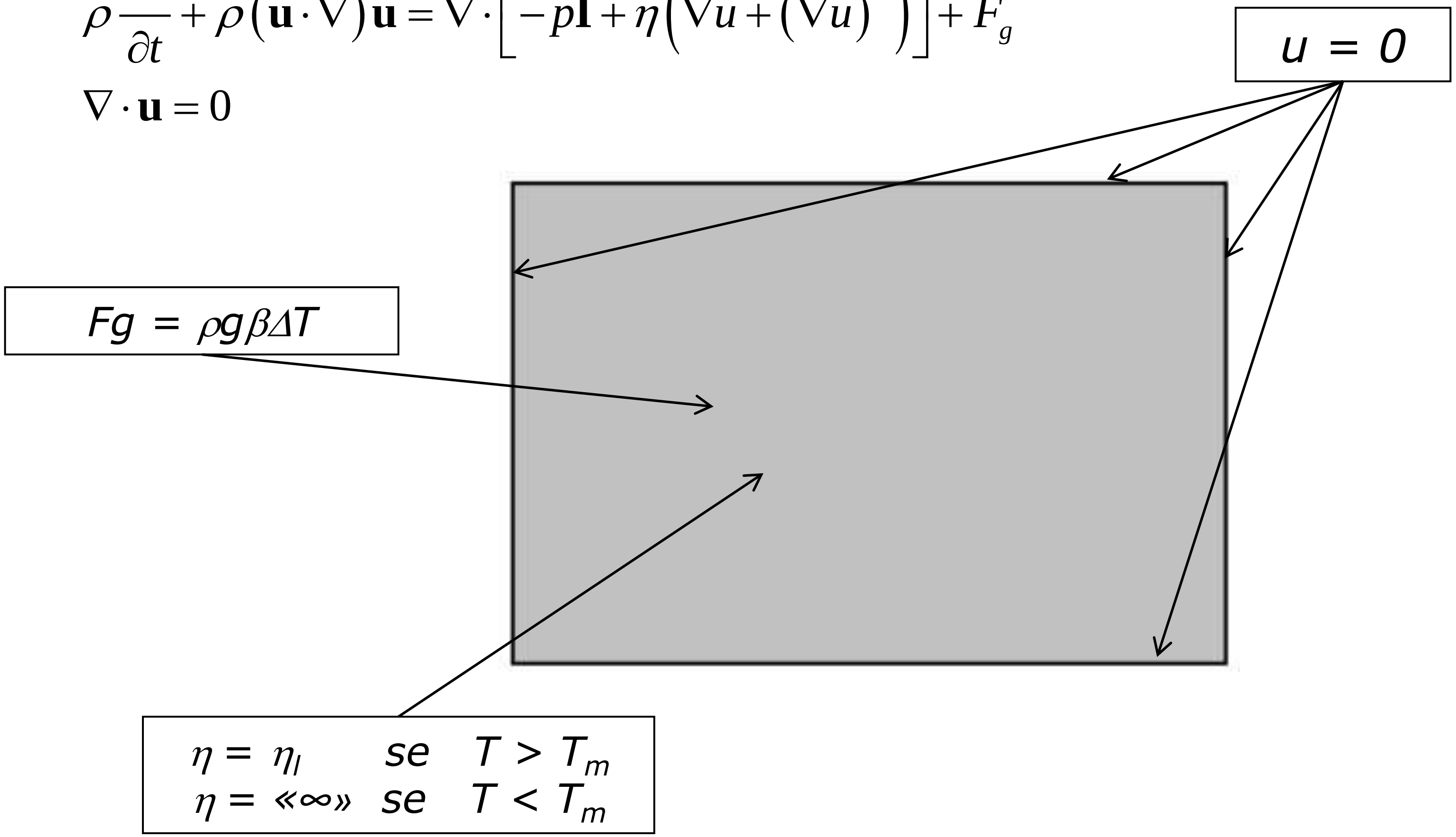


NUMERICAL MODEL

- Test-case model > Fluid-dynamics

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + \eta\left(\nabla u + (\nabla u)^{T}\right)\right] + F_g$$

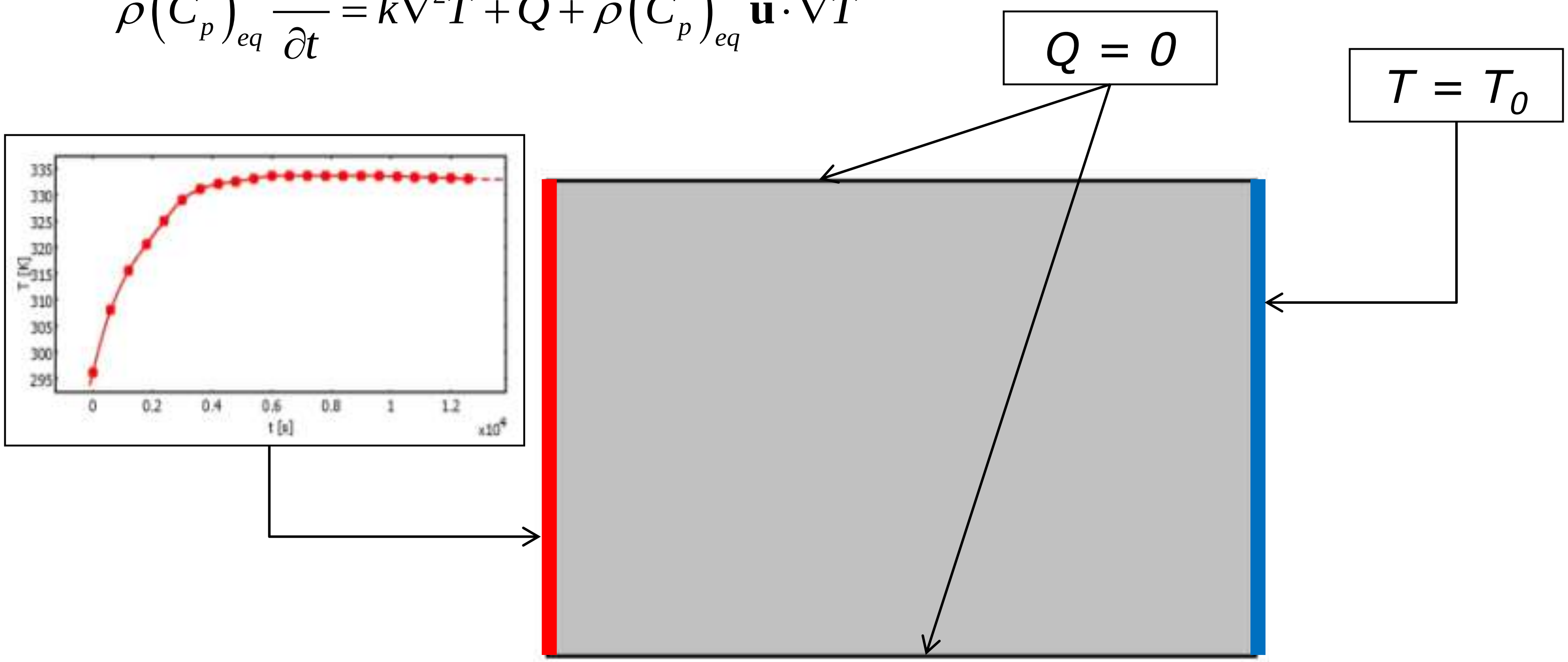
$$\nabla\cdot\mathbf{u} = 0$$



NUMERICAL MODEL

- Test-case model > Thermal analysis

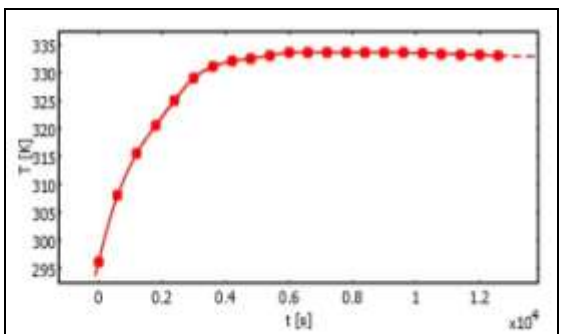
$$\rho\left(C_p\right)_{eq}\frac{\partial T}{\partial t}=k\nabla^2 T+Q+\rho\left(C_p\right)_{eq}\mathbf{u}\cdot\nabla T$$

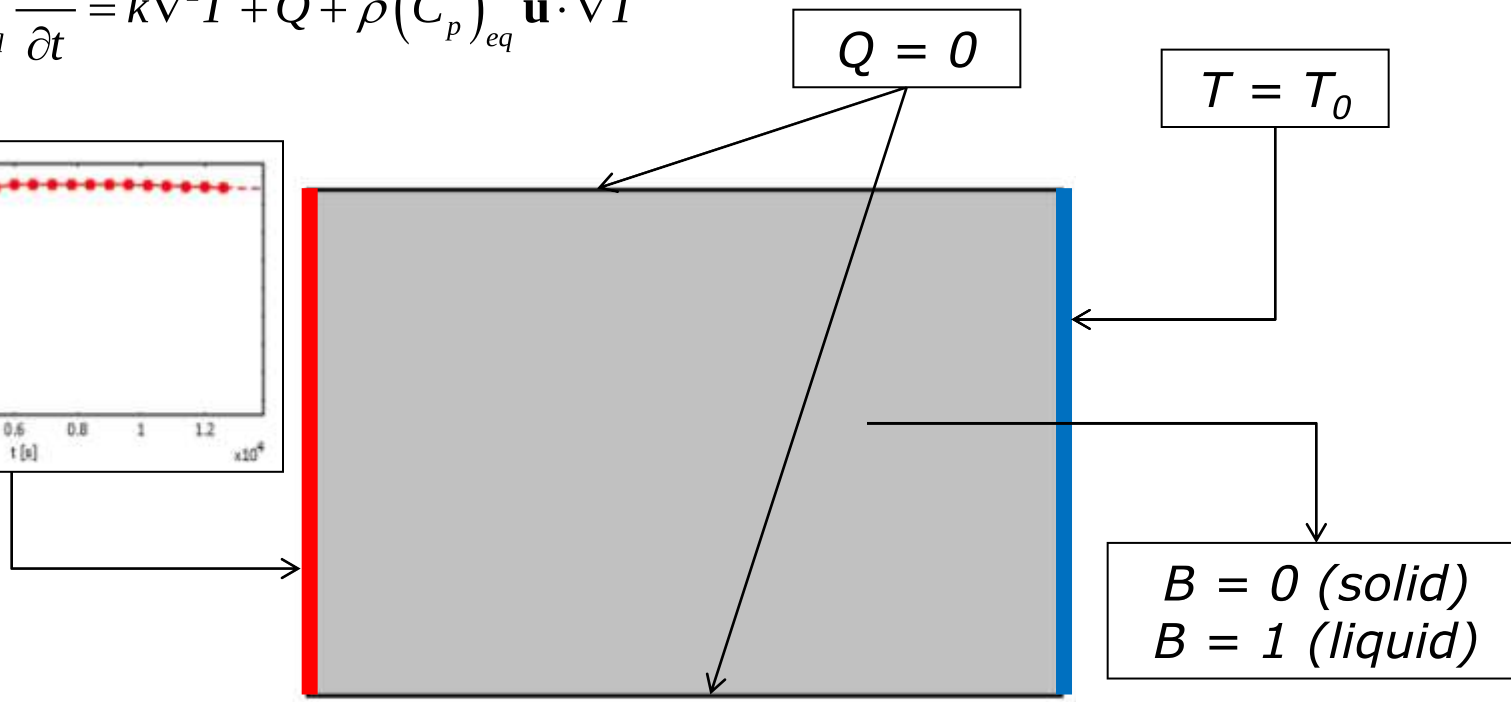


NUMERICAL MODEL

- Test-case model > Thermal analysis

$$\rho\left(C_p\right)_{eq}\frac{\partial T}{\partial t}=k\nabla^2 T+Q+\rho\left(C_p\right)_{eq}\mathbf{u}\cdot\nabla T$$





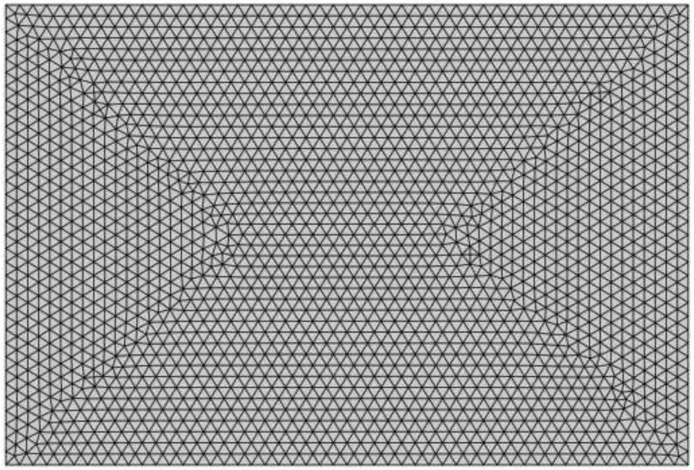
if [(T<(T$_m$-DT)) or (T>(T$_m$+DT))] then (Cp$_{eq}$=Cp) also (Cp$_{eq}$=Cp+H/DT)

DT = 0,01 °C

NUMERICAL MODEL

➢ Test-case model > Numerical solution

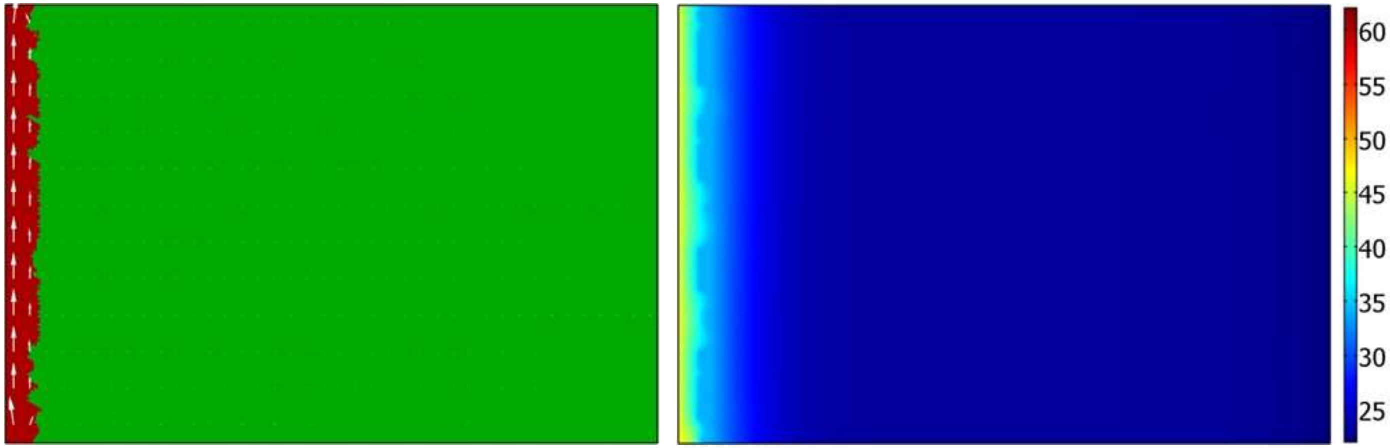
- Continuous equations discretized by a F.E. method on no-structured and no-uniform mesh made of triangular Lagrange elements of order 2



- Time-marching performed by an Implicit Differential-Algebraic (IDA) solver based on a variable-order and variable-step-size Backward Differentiation Formulas (BDF)
- Nonlinear system of equations solved at each time step by a modified Newton-Raphson algorithm
- Algebraic systems of equations coming from differential operators discretization solved by a PARDISO package
- Output time-step of 60 seconds

RESULTS

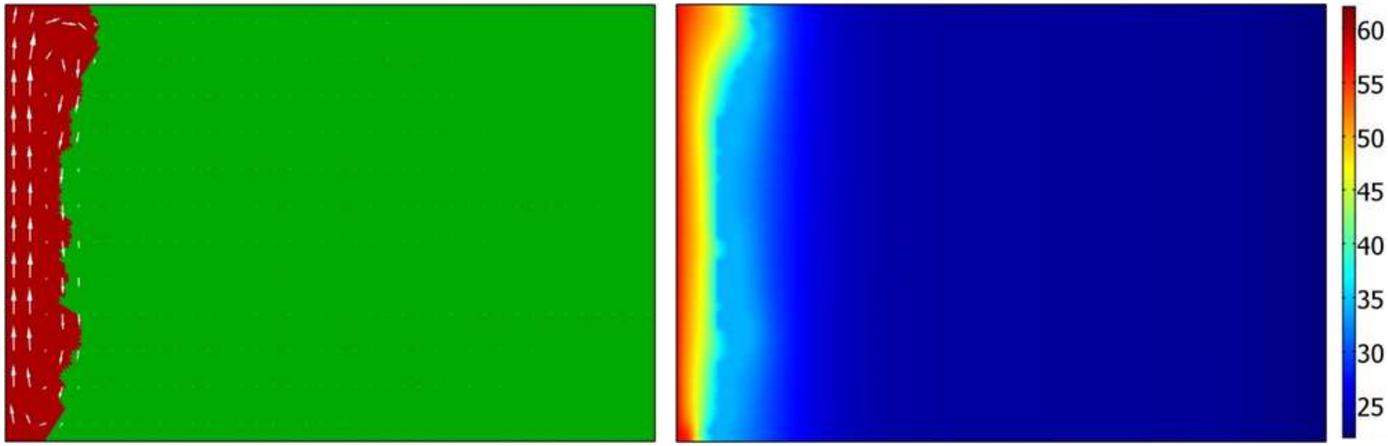
- Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 1800 sec

RESULTS

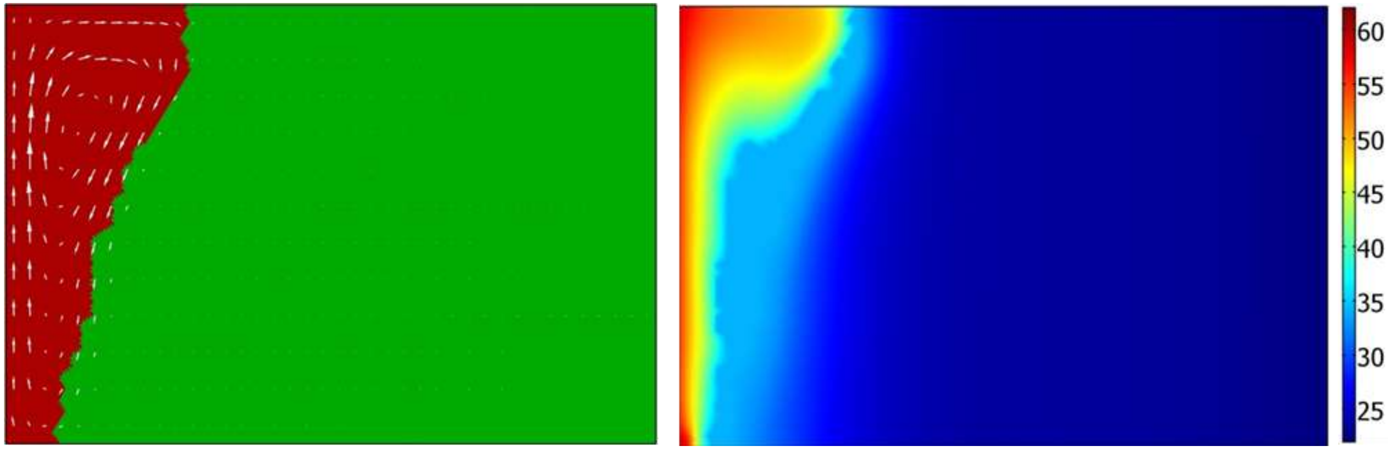
➢ Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 3600 sec

RESULTS

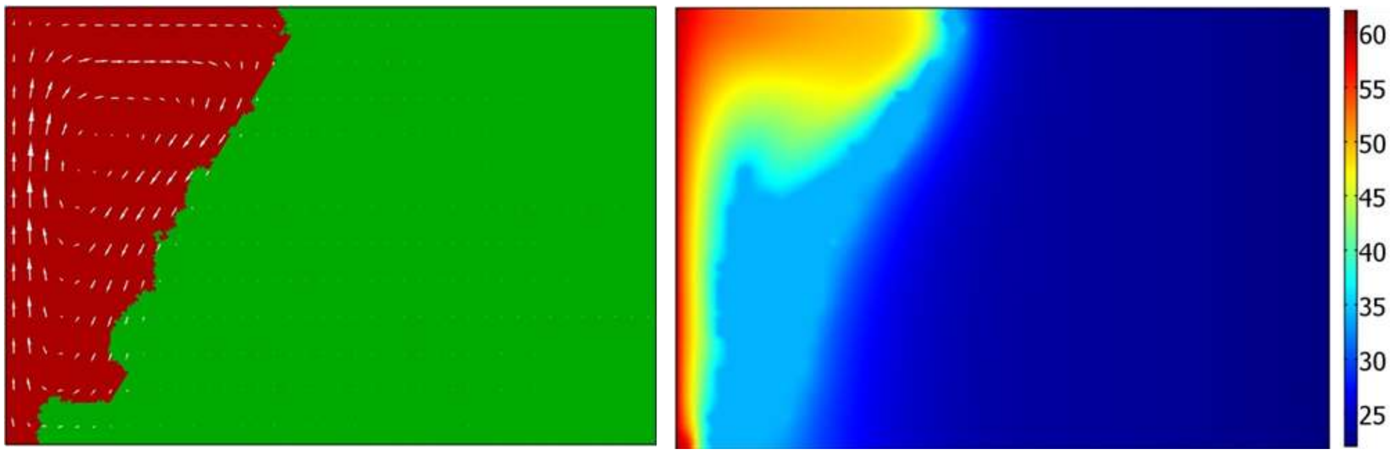
➢ Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 5400 sec

RESULTS

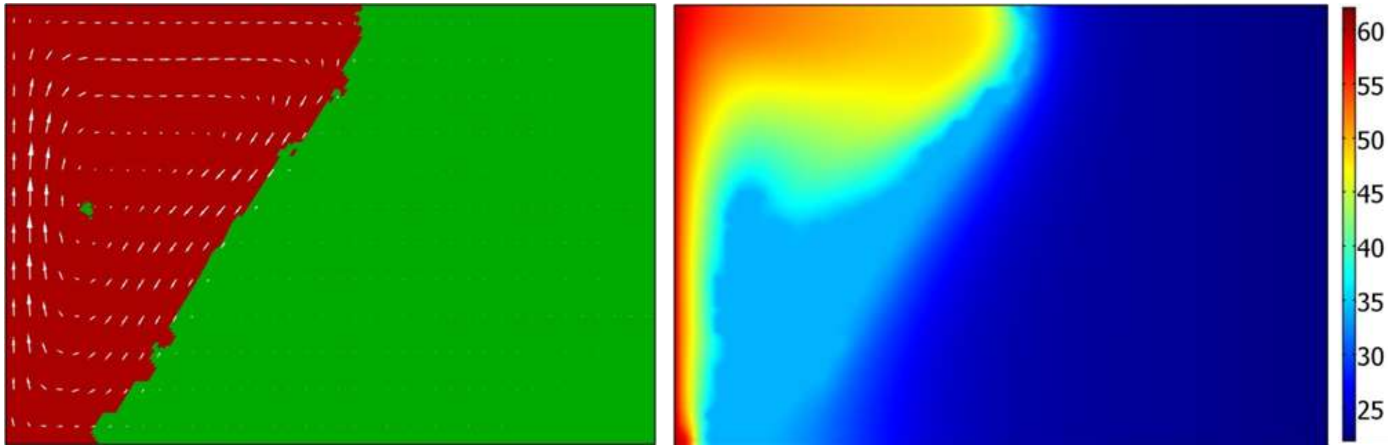
➢ Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 7200 sec

RESULTS

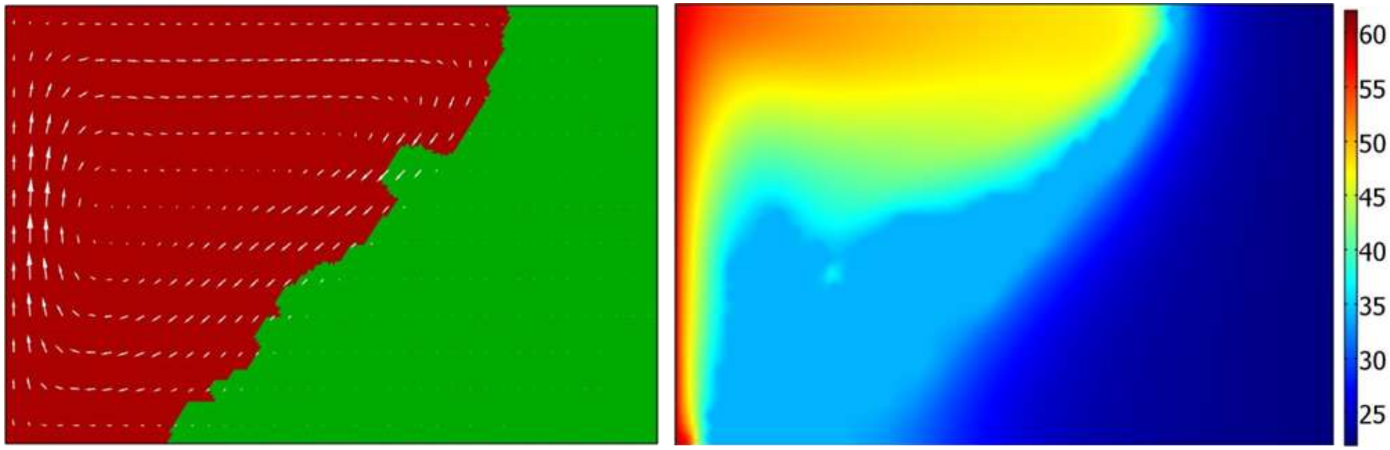
➢ Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 9000 sec

RESULTS

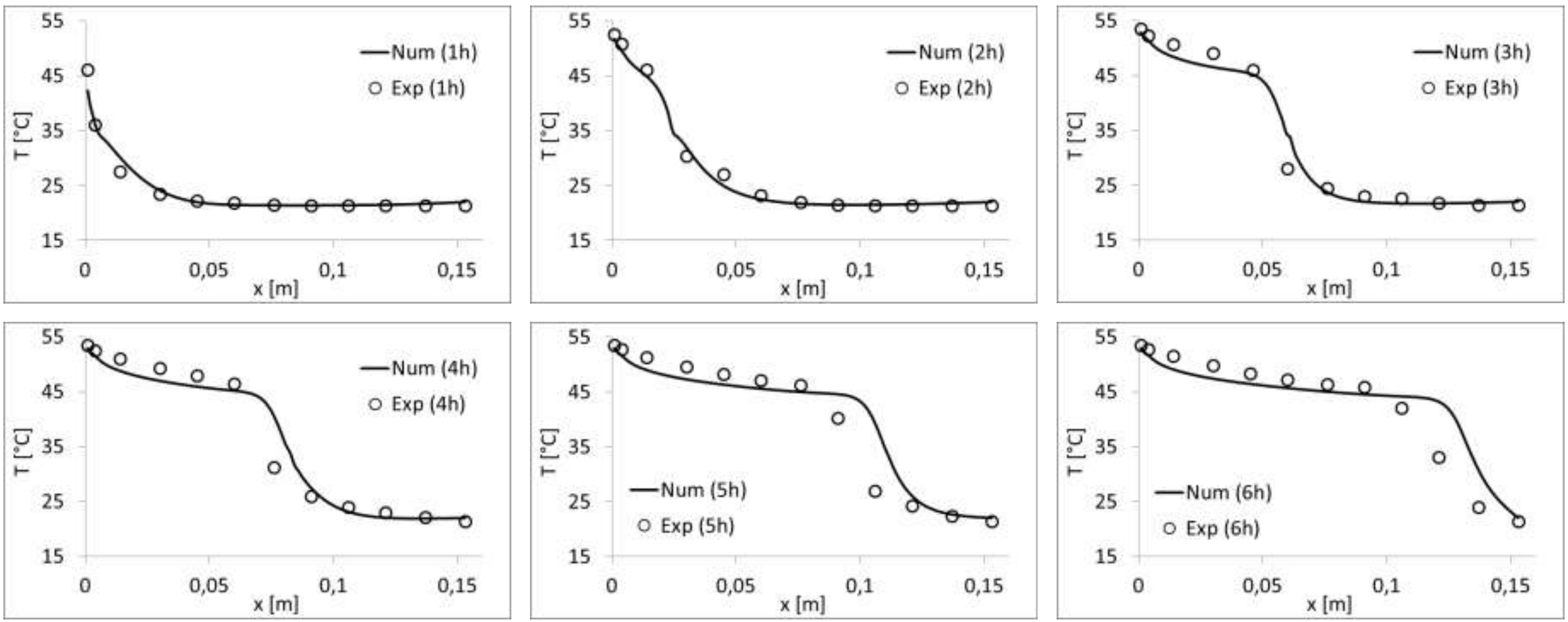
➢ Velocity field (white arrows), physical phase (red for liquid and green for solid) and temperature field (scale of colors):



Test-case #5 – Time: 12000 sec

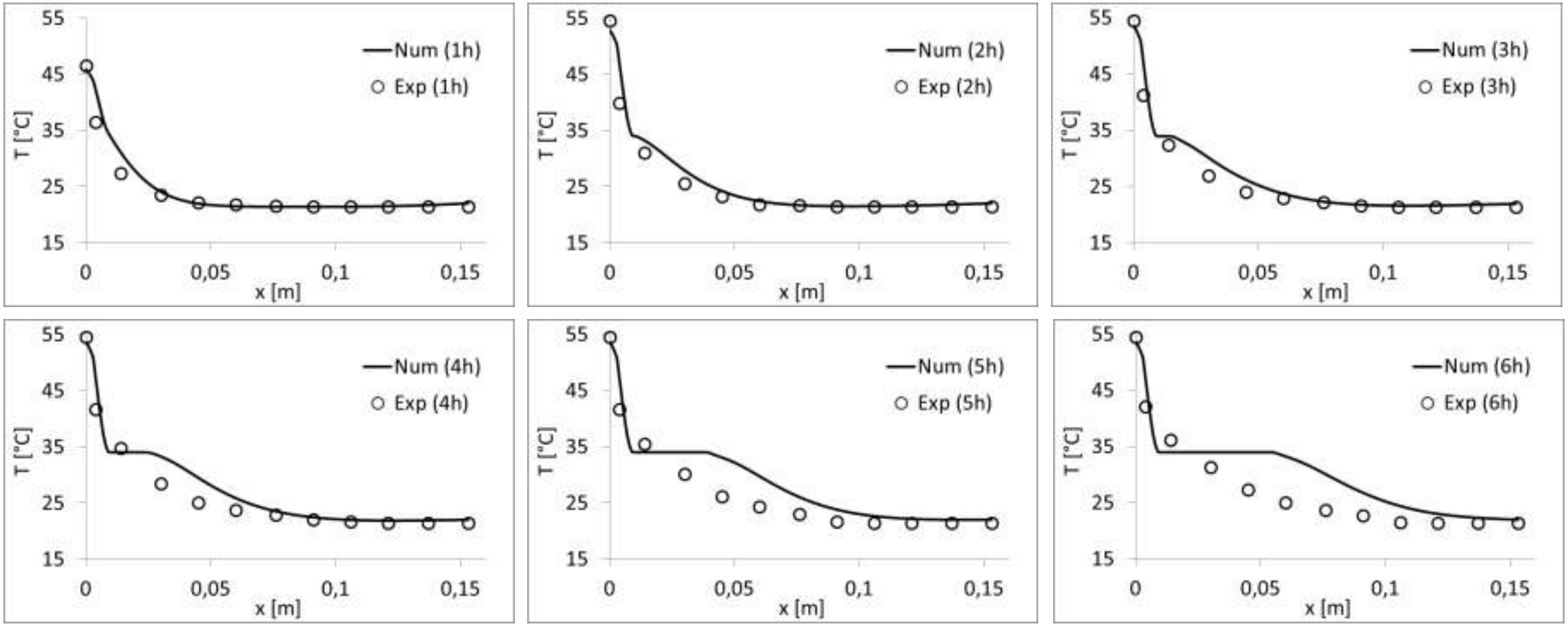
VALIDATION

➢ **Temperature distribution** along the **upper wall** of the enclosure: comparison between **experimental** and **numerical** results at several time instants



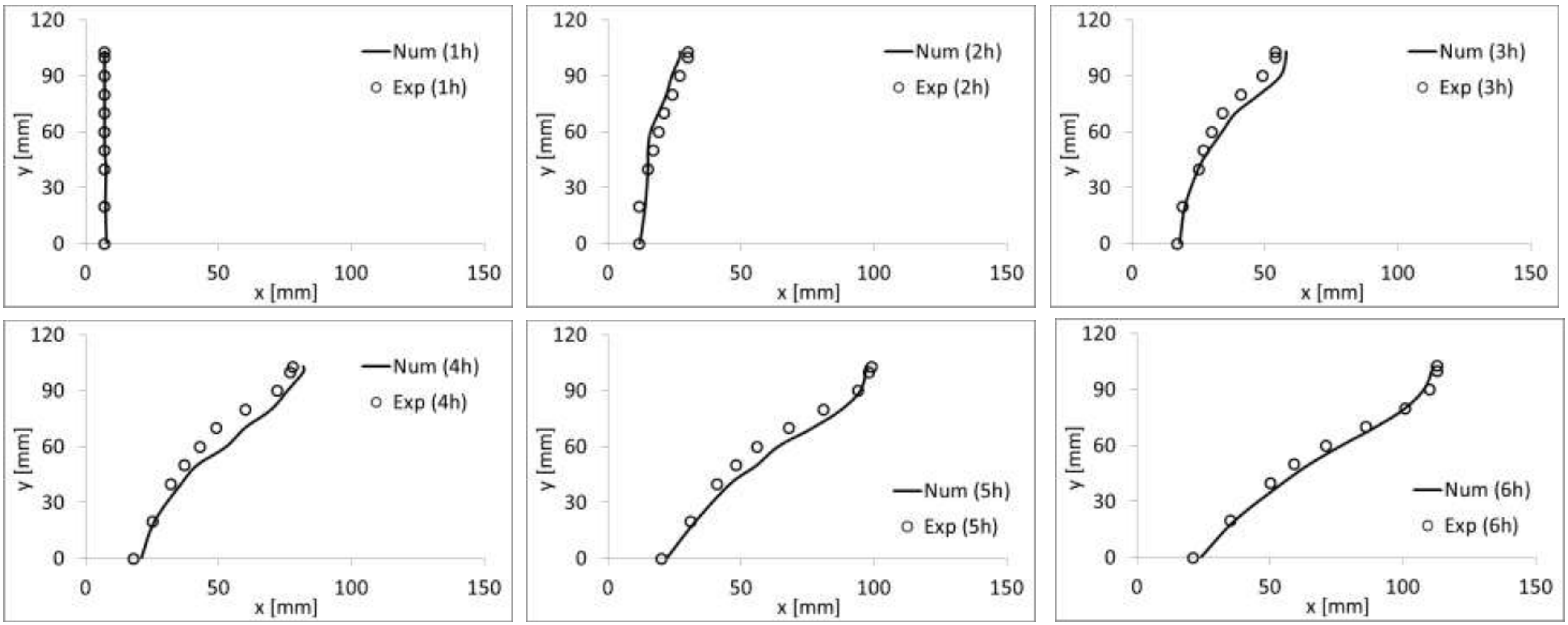
VALIDATION

➢ **Temperature distribution** along the **bottom wall** of the enclosure: comparison between **experimental** and **numerical** results at several time instants



VALIDATION

➢ **Solid/liquid interface position**: comparison between **experimental** and **numerical** results at several time instants



CONCLUSIONS

- The **melting process** of a **PCM** in a differentially heated rectangular enclosure is **numerically simulated**. The **enthalpy method** is **adopted** for modelling heat transfer and the solid phase is regarded as a liquid having an almost infinite viscosity.

- The **solid-liquid interface location** and **the thermal maps obtained** for several transient heating conditions well **highlight natural convection effects**, **enhancing heat transfer in the top portion of the cavity**.

- **Results are successfully compared with experimental data** previously published and concerning an analogue system. The shapes of the melt front obtained at various times from computations well fit with experiments. Quantitatively **comparison between numerical and experimental results show good agreement.**

- From comparisons, the **proposed numerical approach** appears validated and **suitable for use in the pre-design of PCM storage systems.**

THANK YOU FOR YOUR ATTENTION

This study has been developed at:

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