Cooling Performance of Macro-Encapsulated Phase Change Material (PCM) Panels: Experimental Investigation and FEM Modelling

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Presentation for the Marcel Herman Price 2023

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Presentation Outline

- **Introduction**
- Experimental Methodology
- Experimental Investigation
- Finite Element Method
- Simulation Investigation
- Take home messages

Introduction : Research Institute

International Centre for Indoor Environment and Energy

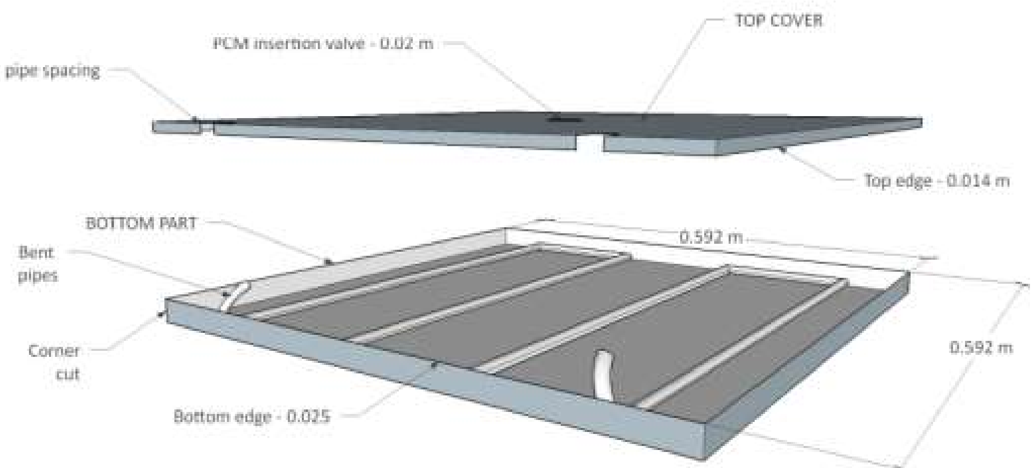
DTU

- Leading institute for indoor environment research
- Cutting edge facilities for the studied technology
- Phase Change Materials expertise

Introduction : Context & Technology

Building Operation => 27% of total GHG Emissions

# of air conditioners : x3 by 2050



Radiant panels containing **Phase Change Materials (PCM)**

- Thermal Comfort ↑
- Energy consumption/cost ↓
- Easy installation

Cooling Performance of Macro-Encapsulated Phase Change Material (PCM) Panels: Experimental Investigation and FEM Modelling

Bibliographic review
+
DTU knowledge

2 main radiant cooling technologies:
- **Active** (RCP, radiators)
- **Passive** (TABS, MEPs)

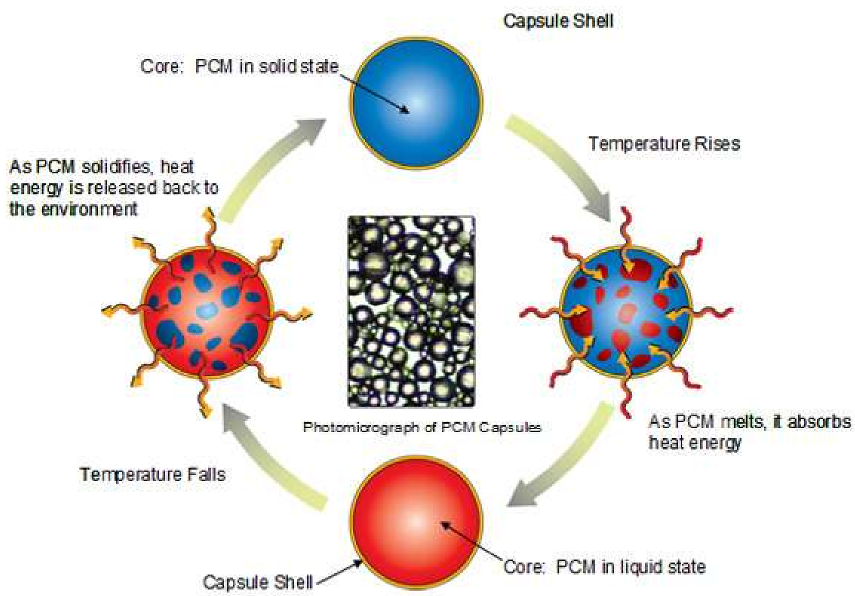
MEPs = **active radiant cooling system** (high load) ?

PCM panels **simulation tools** rely on alternatives geometries + hypotheses

Imprecision introduced by these tools ?
(determined **using FEM**)

Cooling Performance of Macro-Encapsulated **Phase Change Material (PCM)** Panels: Experimental Investigation and FEM Modelling

Solid-Liquid PCM



PCM Properties

+ High heat density → **Thermal storage**
    + Temperature fluctuations ↓
    + Energy Efficiency ↑
    + Peak shaving & Load shifting

- Low heat conducicitivy of materials
- High production costs

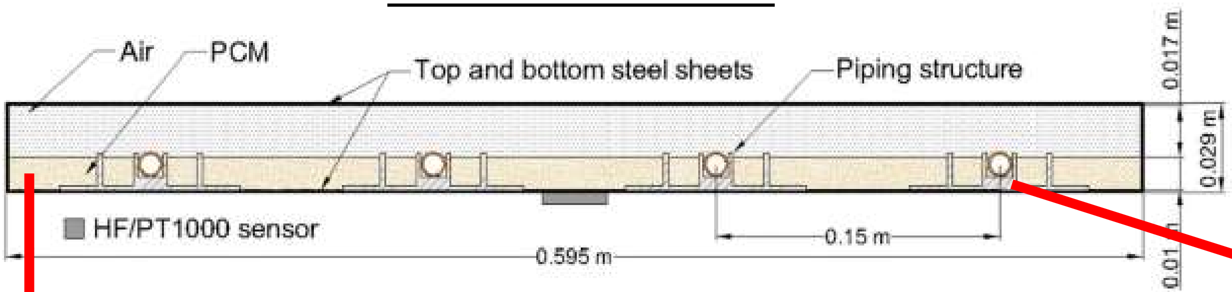
- **Phase change temperature range**
  (often matched with operative temperature range)

Experimental Methodology

- Panels
- Ceiling
- Heat Gains
- Ventilation

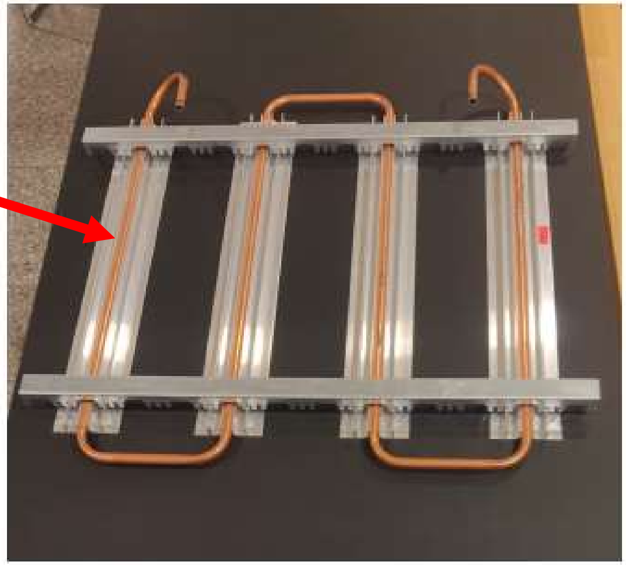
Cooling Performance of **Macro-Encapsulated** Phase Change Material (PCM) **Panels**: Experimental Investigation and FEM Modelling

Panel Cross Section

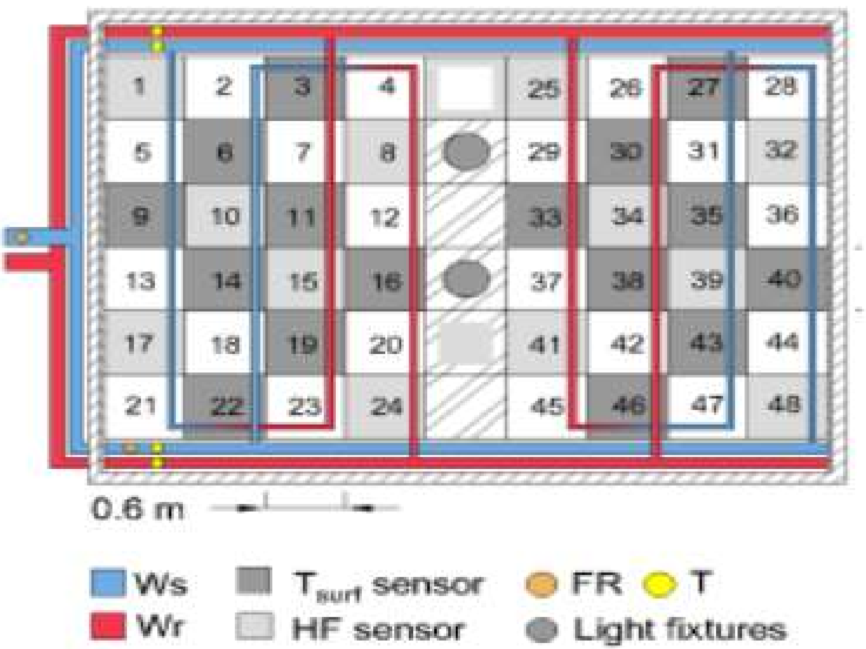


Rubitherm RT24 : Paraffin

Pipe Profile

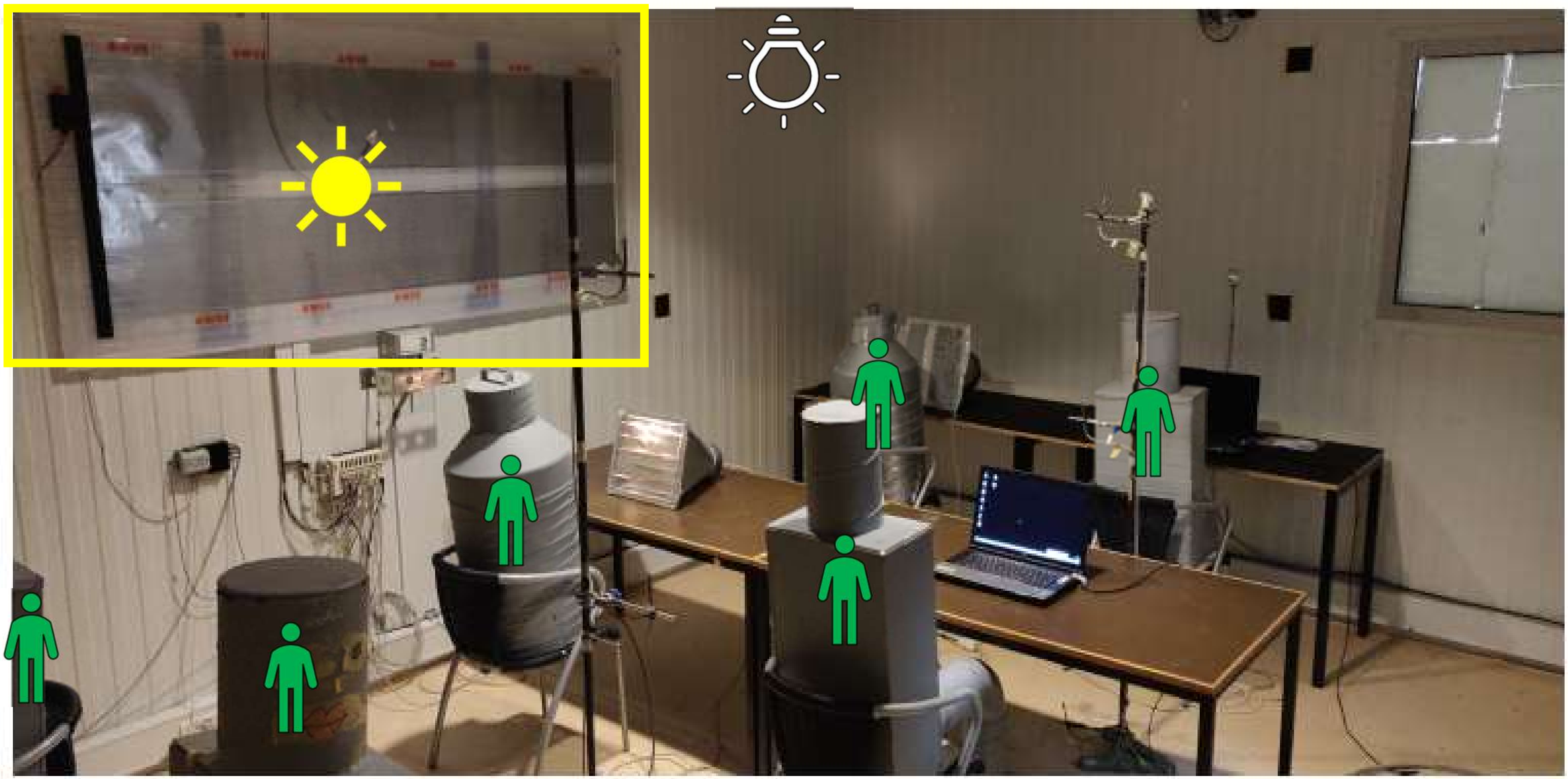


Test Chamber : Ceiling



- Suspended Ceiling : **48 panels**
- **Temperature and/or heat flux sensors**
- **4 water intakes and exhausts** : even cooling

Test Chamber : Heat Gains

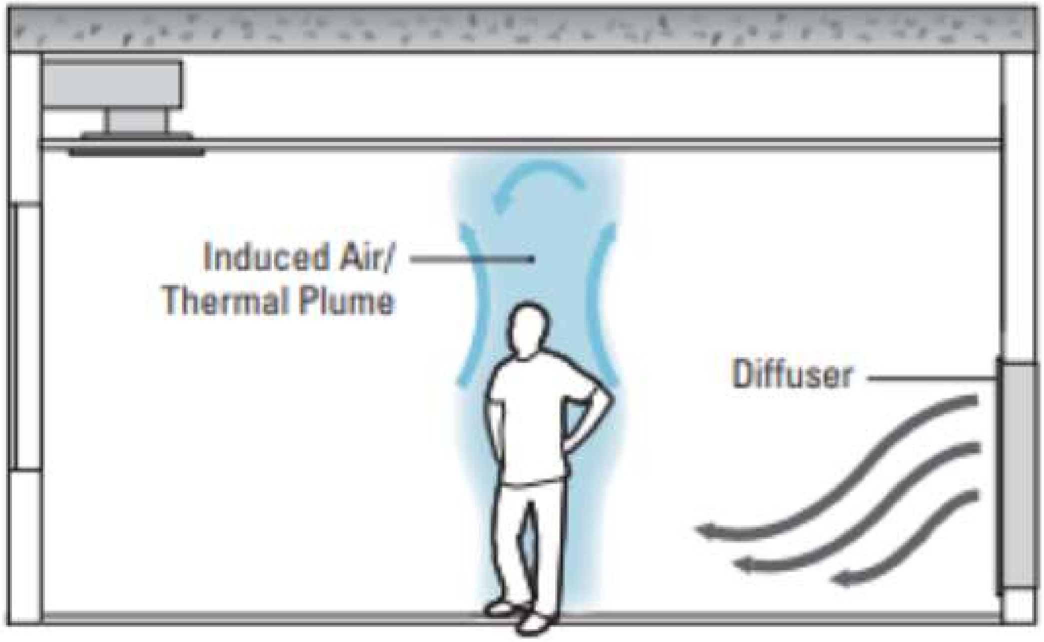


Test Chamber : Ventilation

Diffuser

Exhaust

Displacement Ventilation
(**Uniform air movement)**



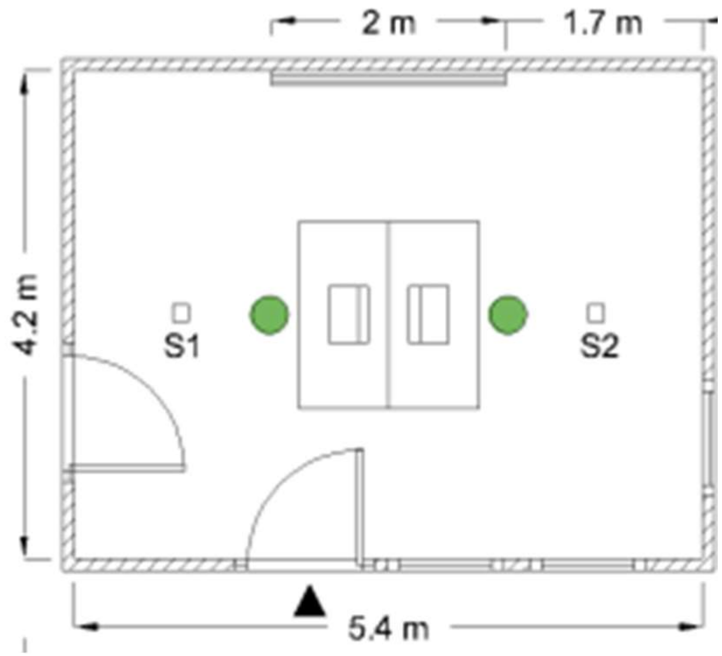
Experimental Investigation

4 comparisons of exp. scenarios

Comparison 1 : Heat Gain Increase

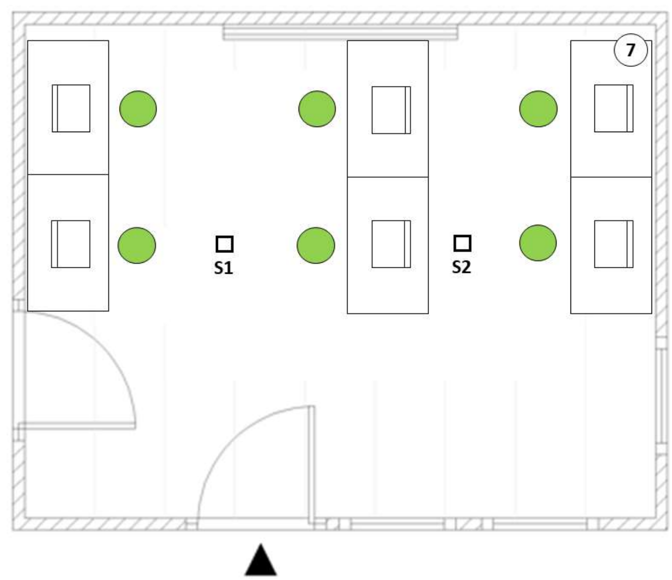
- **Night active 18°C** water circulation
- **22°C** night setpoint (when water circulation stops)

Reference Scenario



286W of occupancy heat gains

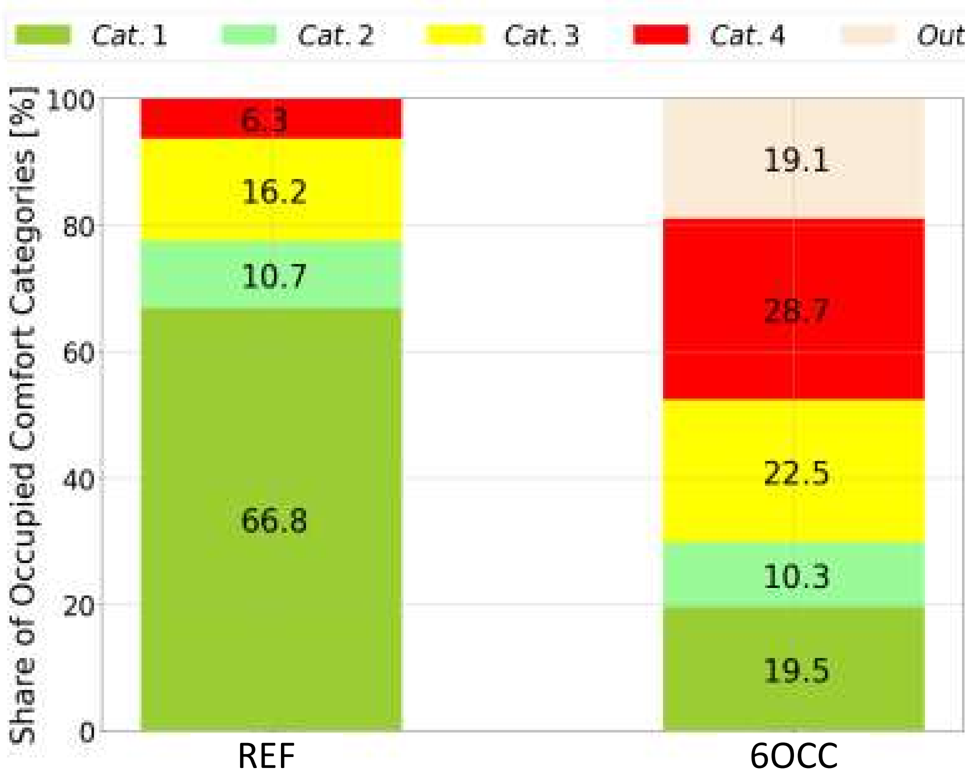
6OCC Scenario



786W of occupancy heat gains

Comparison 1 : Heat Gain Increase

Thermal Comfort



77.5 % **29.8 %**

- T° ranges from ISO standards
- PPD = Predicted Percentage of Dissatisfied

Category	PPD [%]	$RANGE_{T,c}$ [°C]
I	< 6	23.5-25.5
II	< 10	23-26
III	< 15	22-27
IV	< 25	21-28

At least **Cat.2** is targeted : comfortable for work

Comparison 1 : Heat Gain Increase

Heat Extraction

Scenario	REF	6OCC
Use of water circulation (D|N) [h:m]	0|5:42	0|8:26
Panel Average Heat Extraction Rate [W/m^2]	6.8	**10.7**
Heat Extracted by circulated water [Wh/m^2]	264.6	**465.2**
Time share in Cat.II [%]	77.5 %	**29.8 %**

- Panel Extraction Power ↑
- Heat Extracted ↑
- Thermal Comfort ↓

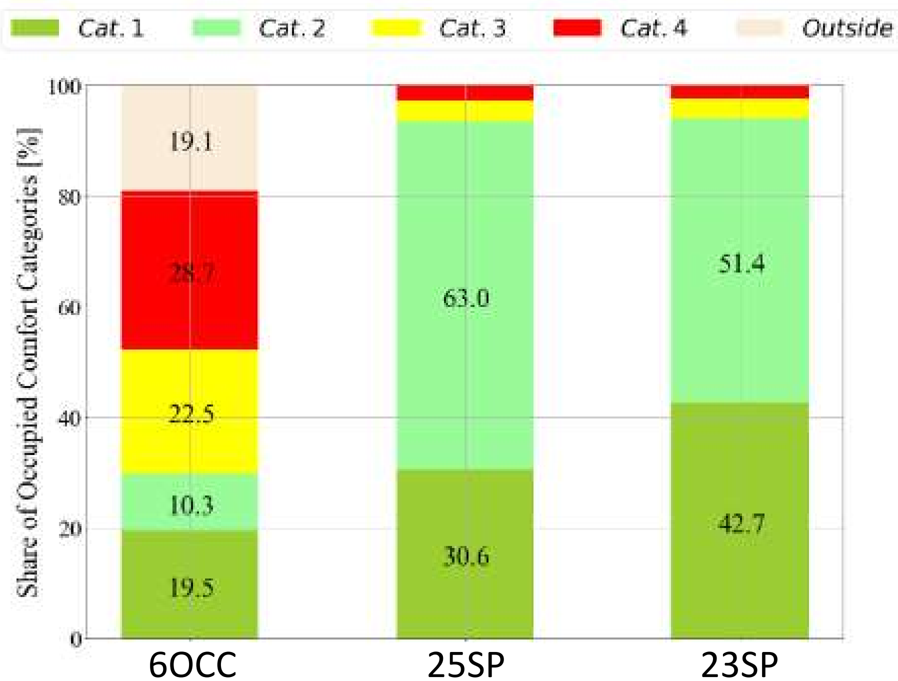
More heat extraction required for 6 occupants

Comparison 2 : Day-active Water Control and Set-points

6OCC → 25SP → 23SP

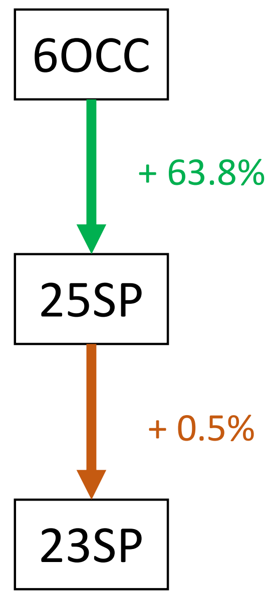
+ day active water circulation
: 25°C day setpoint

23°C day setpoint
(water circulation activates)



6OCC	25SP	23SP
29.8 %	**93.6 %**	**94.1 %**

Thermal Comfort Improvement



Comparison 2 : Day-active Water Control and Set-points

6OCC → **25SP** → **23SP**

+ day active water circulation
: 25°C day setpoint

23°C day setpoint
(water circulation activates)

Heat Extraction (per unit of panel area)

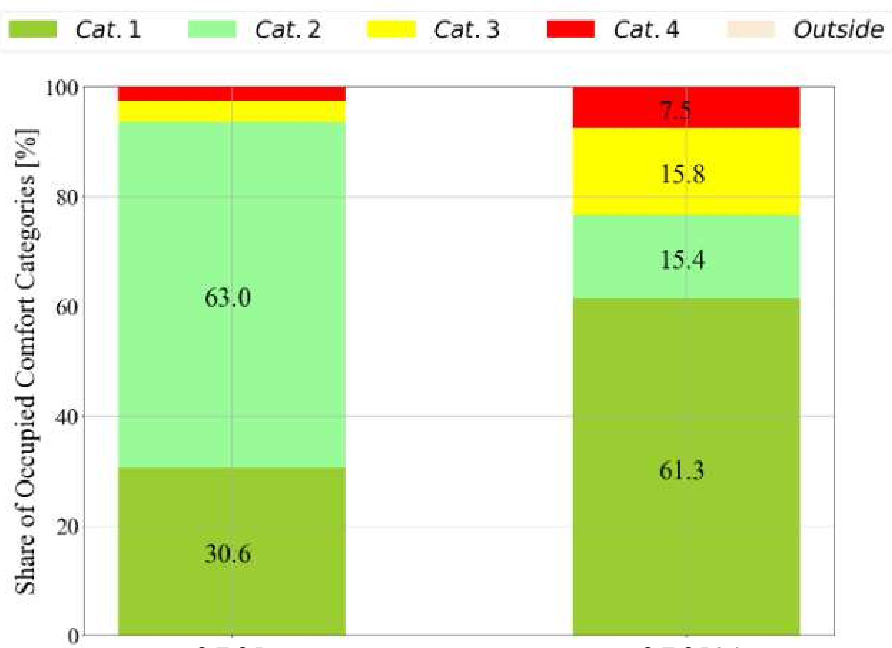
Scenario	6OCC	25SP	23SP
Use of water circulation (D|N) [h:m]	0|8:26	**8:09|5:39**	**9:32|5:35**
Panel Average Heat Extraction Rate [W/m^2]	10.7	**12.3**	**12.8**
Heat Extracted by circulated water [Wh/m^2]	465.2	**597.8**	**626**
Time share in Cat.2 [%]	29.8	**93.6**	**94.1**

- **System performance ↑**
- **Max. Performance of water system reached**
- **Water circulation use ↑**

Comparison 3 : Addition of Ventilation

25SP → **25SPV**

+ ventilation: 20°C inlet air temperature & 210 m^3/h air flowrate



25SP
93.6 %

25SPV
76.3 %

Thermal Comfort Evolution

25SP → 23SP: - 17.3%

- **Too cold in the room**
- **Thermal Comfort ↓**

Comparison 3 : Addition of Ventilation

25SP → **25SPV**

+ ventilation: 20°C inlet air temperature & 210 m^3/h air flowrate

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Heat Extraction

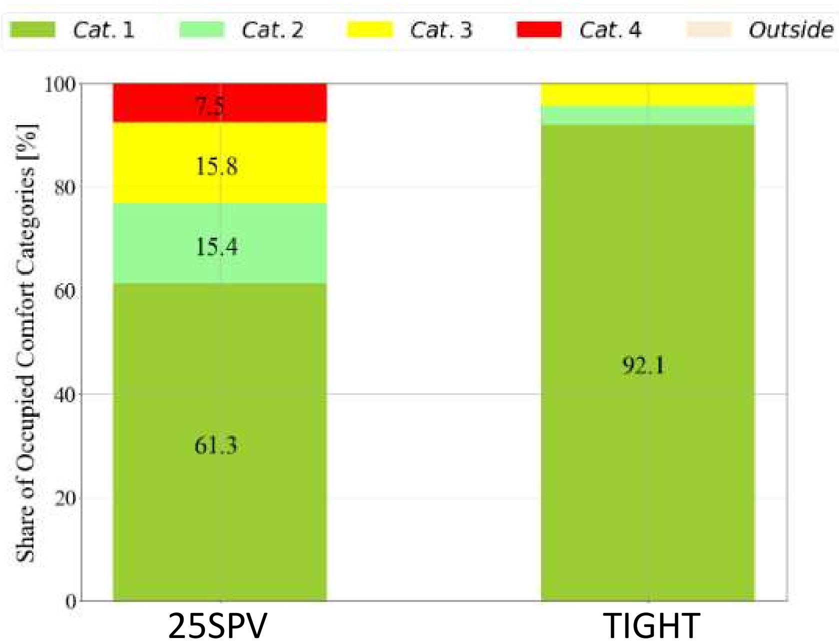
Scenario	25SP	25SPV
Use of water circulation (D|N) [h:m]	8:09|5:39	**0|6:18**
Panel Average Heat Extraction Rate [W/m^2]	12.3	7.6
Mean **Ventilation** Heat Extraction Rate [W/m^2]	/	**27.2**
Heat Extracted by **circulated water** [Wh/m^2]	597.8	**302.2**
Heat Extracted by **ventilation** [Wh/m^2]	0	**277.1**
Time share in Cat.2 [%]	93.6	**76.3**

- **Ventilation** too present
- Water system performance + thermal comfort ↓
- TABS similar operation (only night water circ.)

Comparison 4 : Attempt of Tight Control

25SPV → **TIGHT**

ventilation: (20->22)°C inlet T° **& (210->152) m^3/h** flowrate
Night and day water circulation setpoints set to 23°C



76.3 % **95.8 %**

Thermal Comfort Improvement

25SPV → TIGHT: + 19.5%

- **Good adjustments of ventilation**
- **Excellent thermal comfort**

Comparison 4 : Attempt of Tight Control

25SPV → **TIGHT**

ventilation: (20->22)°C inlet T° **& (210->152) m^3/h** flowrate
Night and day water circulation setpoints set to 23°C

Heat Extraction

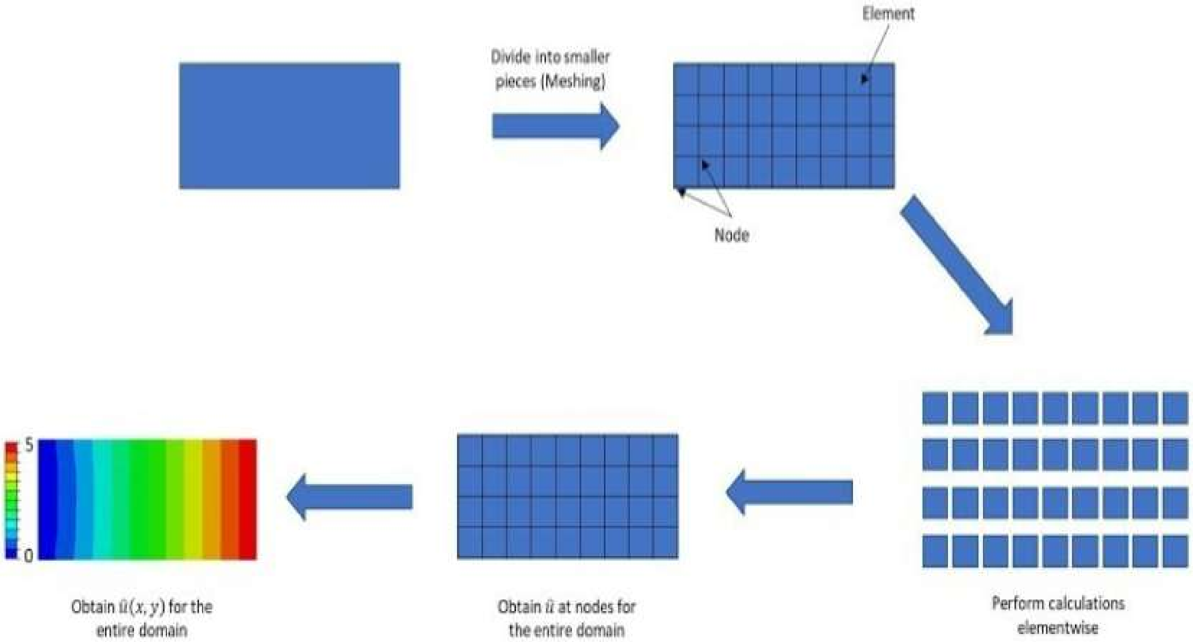
Scenario	25SPV	TIGHT
Use of water circulation (D|N) [h:m]	0|6:18	**9:45|2:51**
Panel Average Heat Extraction Rate [W/m^2]	7.6	11.4
Mean Ventilation Heat Extraction Rate [W/m^2]	27.2	**12.43**
Heat Extracted by circulated water [Wh/m^2]	302.2	**558**
Heat Extracted by ventilation [Wh/m^2]	277.1	**127.4**
Time share in Cat.2 [%]	76.3	**95.8**

- **Ventilation** less dominant
- **Excellent** thermal comfort
- **Radiant system** similar operation
- **More water circulation**

Finite Element Method

Finite Element Method (FEM)

FEM basic concept



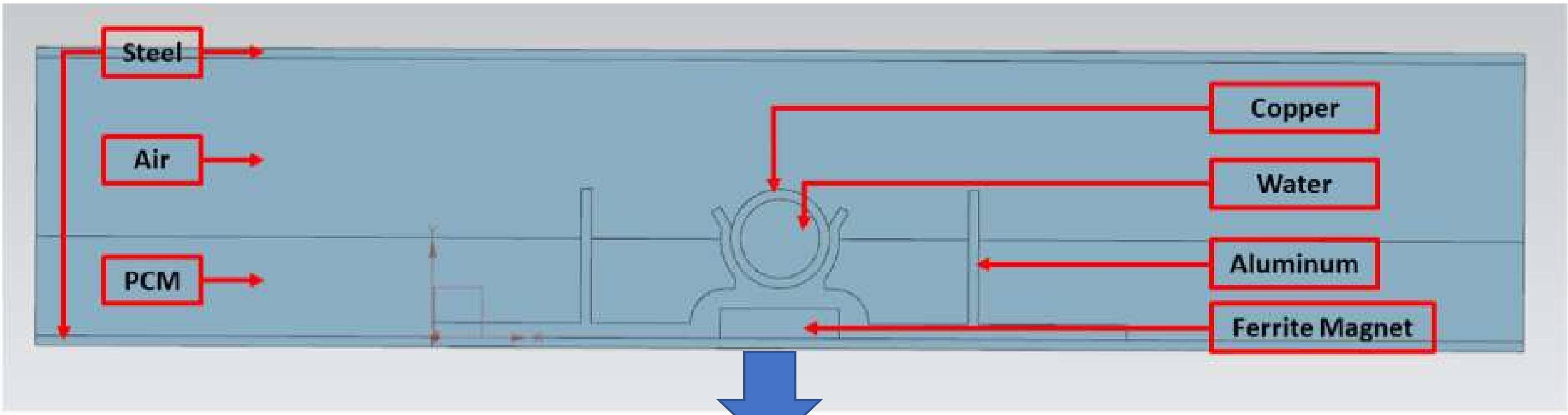
+ Geometry taken into account
+ Precise results
- Critical analysis of results or validation required

Simulation Investigation

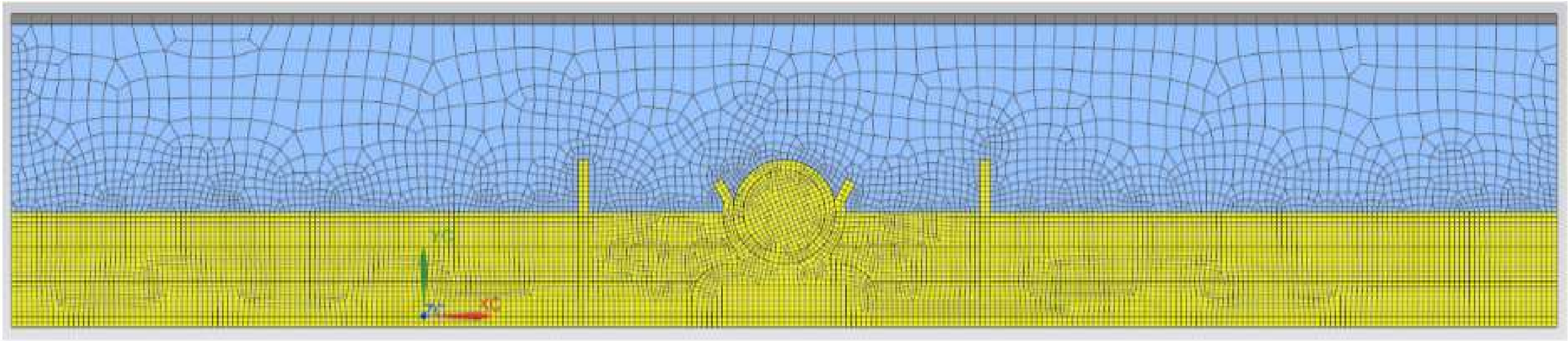
Design and validation of three 2D transient models

Realistic Model : Geometry based on panel measurements

Geometry and materials



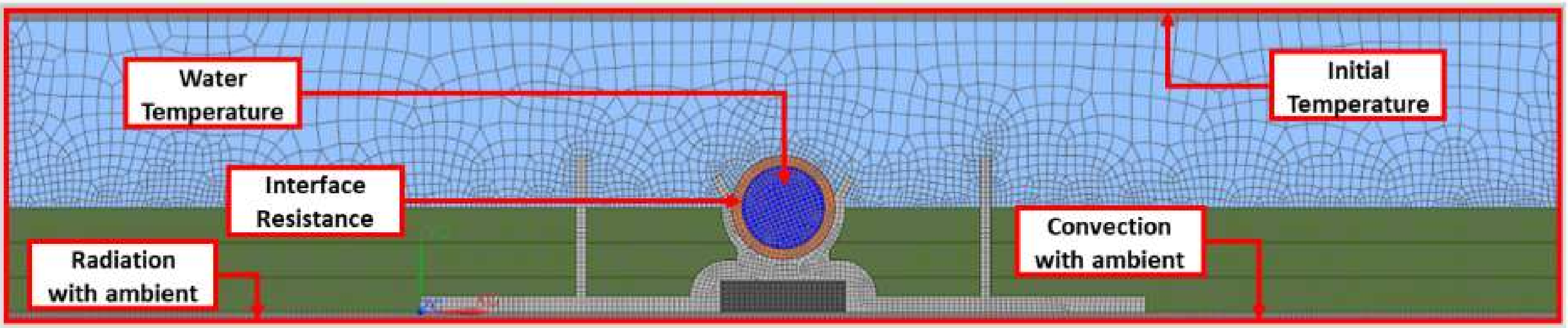
Meshing



Study on element size has been done for yellow part

Realistic Model : Geometry based on panel measurements

Boundary Conditions for simulation (occupancy)

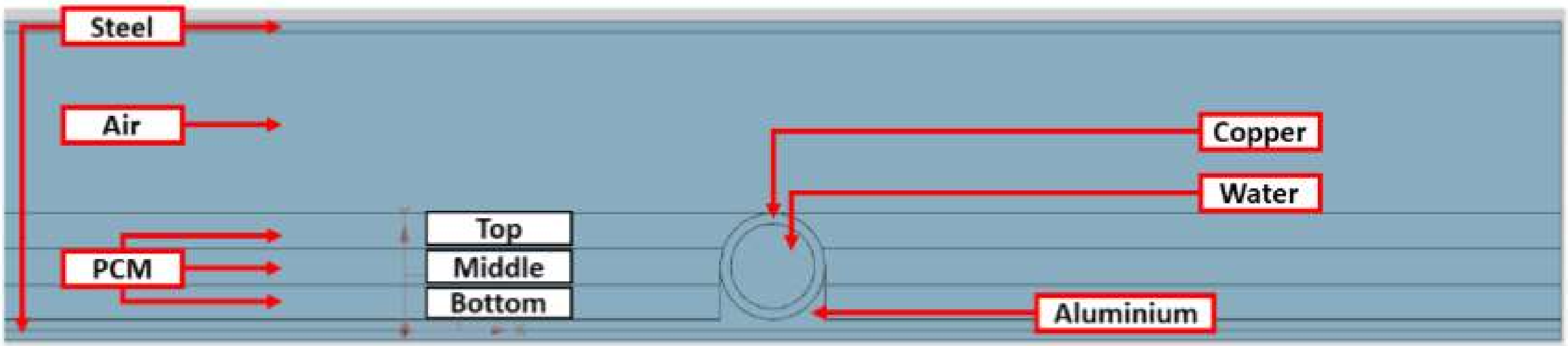


	Panel Surface T°	Panel Power (sensors)	Panel Power (theoretical correlation)
Model	$\lvert RMSE_T \rvert$	$RMSE_{\dot{Q}}$	$RMSE_{\dot{Q},Th}$
Non-occupancy	0.17 [°C]	0.042 [kW]	0.036 [kW]
Occupancy	0.43 [°C]	0.051 [kW]	0.024 [kW]
Max. admissible	1.5 [°C]	0.06 [kW]	0.06 [kW]

- **Validation using RMSE**
- **Comparison with measurements from REF scenario**
- **Realistic model validated**

Simpler Model : Geometry with simplified aluminum fin

Geometry and materials



Validation

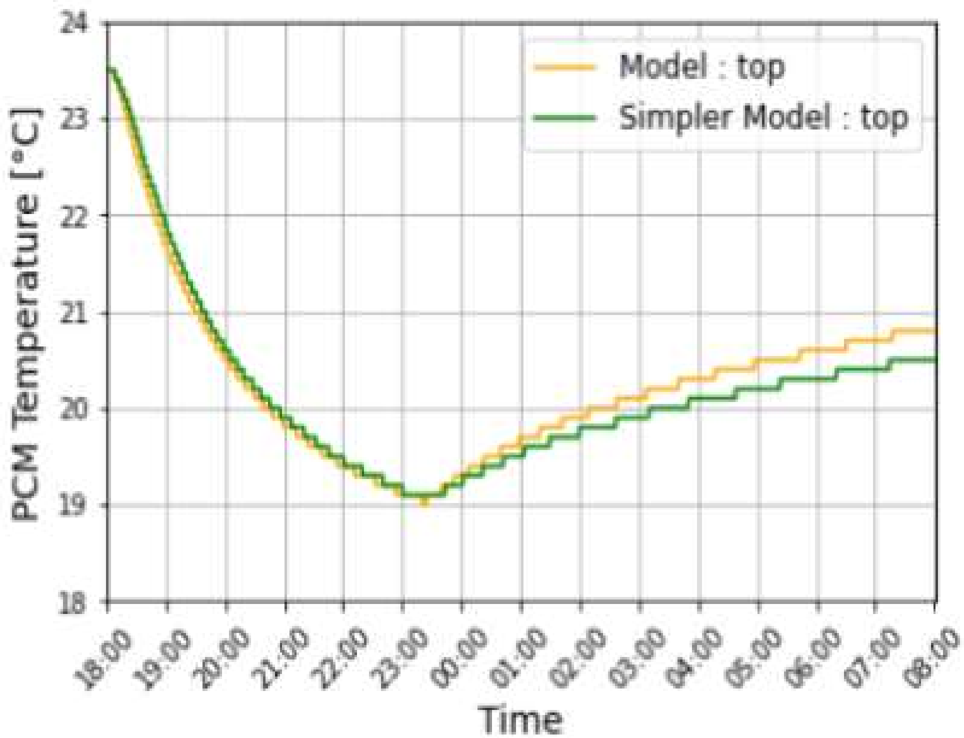
Model	$\lvert RMSE_T \rvert$	$RMSE_{\dot{Q}}$	$RMSE_{\dot{Q},Th}$
Non-occupancy	0.17 [°C]	0.042 [kW]	0.036 [kW]
Occupancy	0.43 [°C]	0.051 [kW]	0.024 [kW]
Non-occupancy (Simpler)	0.13 [°C]	0.064 [kW]	0.017 [kW]
Occupancy (Simpler)	0.36 [°C]	0.058 [kW]	0.013 [kW]
Max. admissible	1.5 [°C]	0.06 [kW]	0.06 [kW]

Model validated using :

- **temperature measurements**
- **theoretically computed heat fluxes**
- **Almost validated using HF sensors**

Simpler Model : Geometry with simplified aluminum fin

Study on PCM vertical temperature stratification



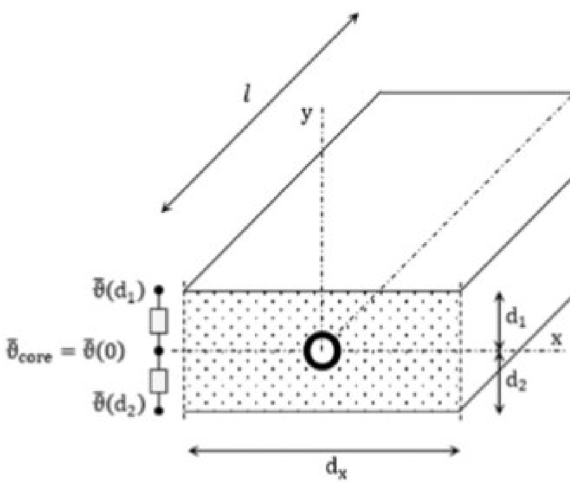
Comparison of top PCM layer temperature evolution for realistic and simpler models

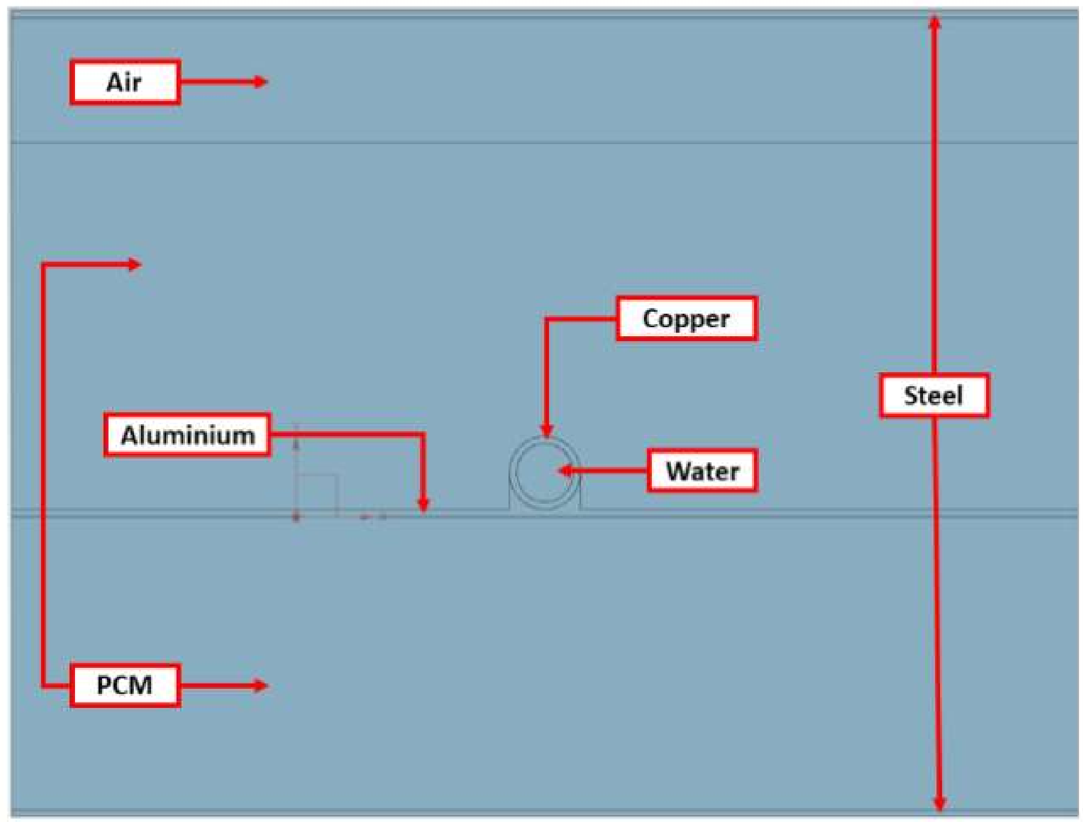
PCM top layer T° evolves **faster** for realistic model

Aluminum fins **enhance** PCM layer vertical thermal conductivity

TABS Model : Geometry of the Type 399 TABS model of TRNSYS

Geometry and materials





TABS Model : Geometry of the Type 399 TABS model of TRNSYS

Assumption

Altering PCM properties (**density, thermal conductivity**) compensate for this change in geometry

$$k = \frac{A_{PCM,TABS}}{A_{PCM,simpler}} \approx 11.5$$

$$\lambda_{PCM,TABS} = k \times \lambda_{PCM,simpler} \text{ , } \rho_{PCM,TABS} = \frac{\rho_{PCM,simpler}}{k}$$

Validation

Model	$\lvert \mathrm{RMSE_T} \rvert$	$\mathrm{RMSE}_{\dot{\mathrm{Q}}}$	$\mathrm{RMSE}_{\dot{\mathrm{Q}},\mathrm{Th}}$
Non-occupancy	0.17 [°C]	0.042 [kW]	0.036 [kW]
Occupancy	0.43 [°C]	0.051 [kW]	0.024 [kW]
Non-occupancy (TABS equivalent)	0.17 [°C]	0.063 [kW]	0.035 [kW]
Occupancy (TABS equivalent)	0.51 [°C]	0.043 [kW]	0.031 [kW]
Max. admissible	1.5 [°C]	0.06 [kW]	0.06 [kW]

Model validated using :

- **temperature measurements**
- **theoretically computed heat fluxes**
- **Almost validated using HF sensors**

Take Home Messages

MEPs = **active radiant cooling system** (high load) ?

- **YES.** Depends on:

  T° setpoints & ventilation parameters
- **Excellent** Thermal Comfort
- Panel heat extraction ↑
- Cost : More water circulation

Imprecision introduced by these tools ?
(determined **using FEM**)

- Realistic, Simpler and Type 399 equivalent models **validated**
- Aluminum structure **enhances** PCM layer vertical thermal conductivity

FEM models assumptions

Assumptions and parameters

- Purely thermal model (no flow)
- PCM has constant density
- Constant material properties w.r. to temperature
- Operative temperatures = ambient temperatures
- Adiabatic upper plate of the panel
- Simulation inputs were measurements or computed using theoretical correlations/usual values
- Simulation outputs were **panel center** surface temperature and heat flux