CFD Analysis of Heat Removal Capability in a Natural Circulation Loop with Phase Change Material

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Introduction

Background

- Need for passive cooling in case of total loss of power after Fukushima nuclear accident

- Design passive cooling system to accelerate natural convection using encapsulated PCM for performance improvement

- Since the passive cooling system varies in performance depending on a lot of complex effects, an evaluation of heat removal performance improvement using CFD is performed when PCM is used.

- It is necessary to numerically determine whether the heat removal performance of the passive cooling system can be improved using PCM capsules.

PCM

- PCM (Phase Change Material)

-A material that changes phase at a constant temperature and uses latent heat absorbed and released.

-NASA develops spacecraft, space suit filling materials, and commercializes iceboxes, refrigerator truck, etc. as cold and heat storage materials.

-Promote natural convections through high latent heat and density changes in the phase change process

Encapsulated PCM to prevent it from flowing out.

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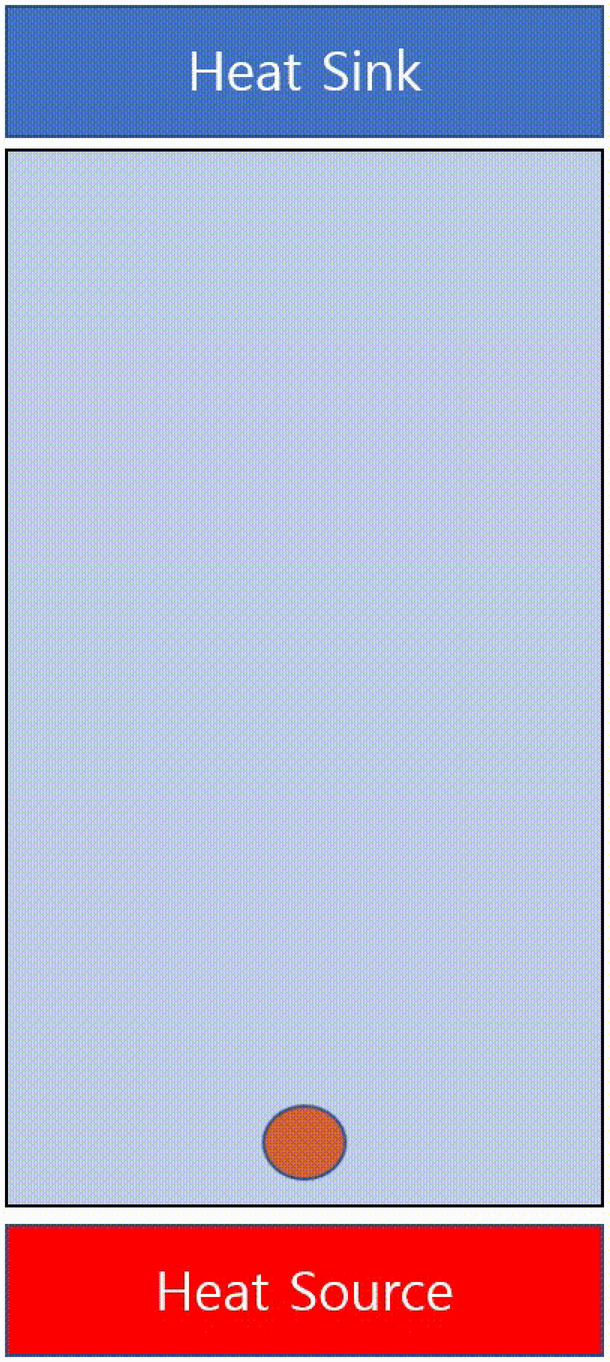


Research Design

Research Design, Process

PCM Capsule
PCS design

CFD
Application

Result value
Evaluation

PCM capsule property setting

Passive cooling system design

Physics, Mesh, IC, BC

Result value evaluation
Result analysis

Research Design

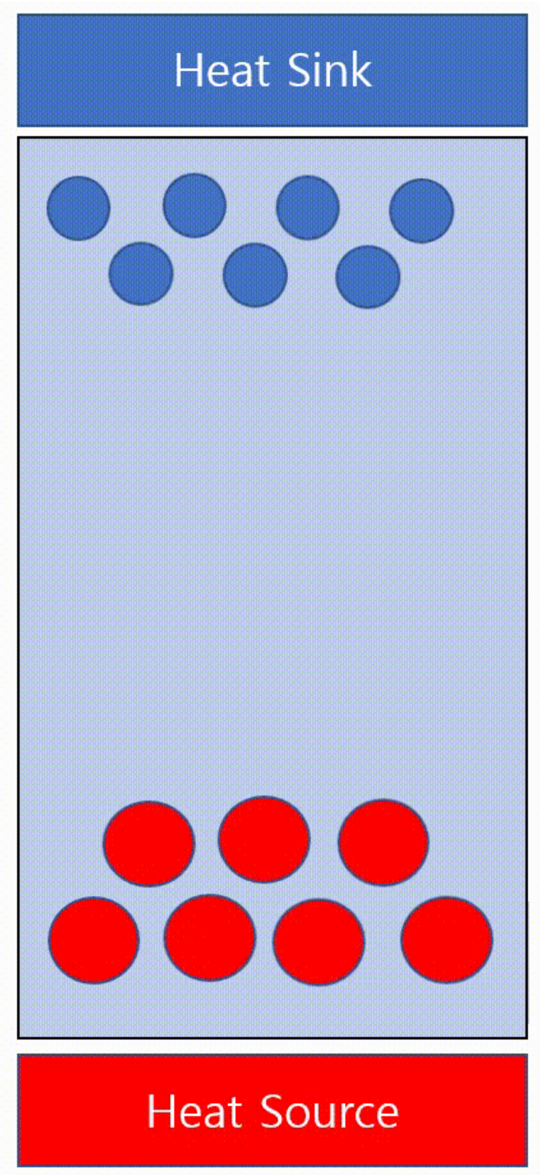
Water + PCM capsule
Passive Cooling System

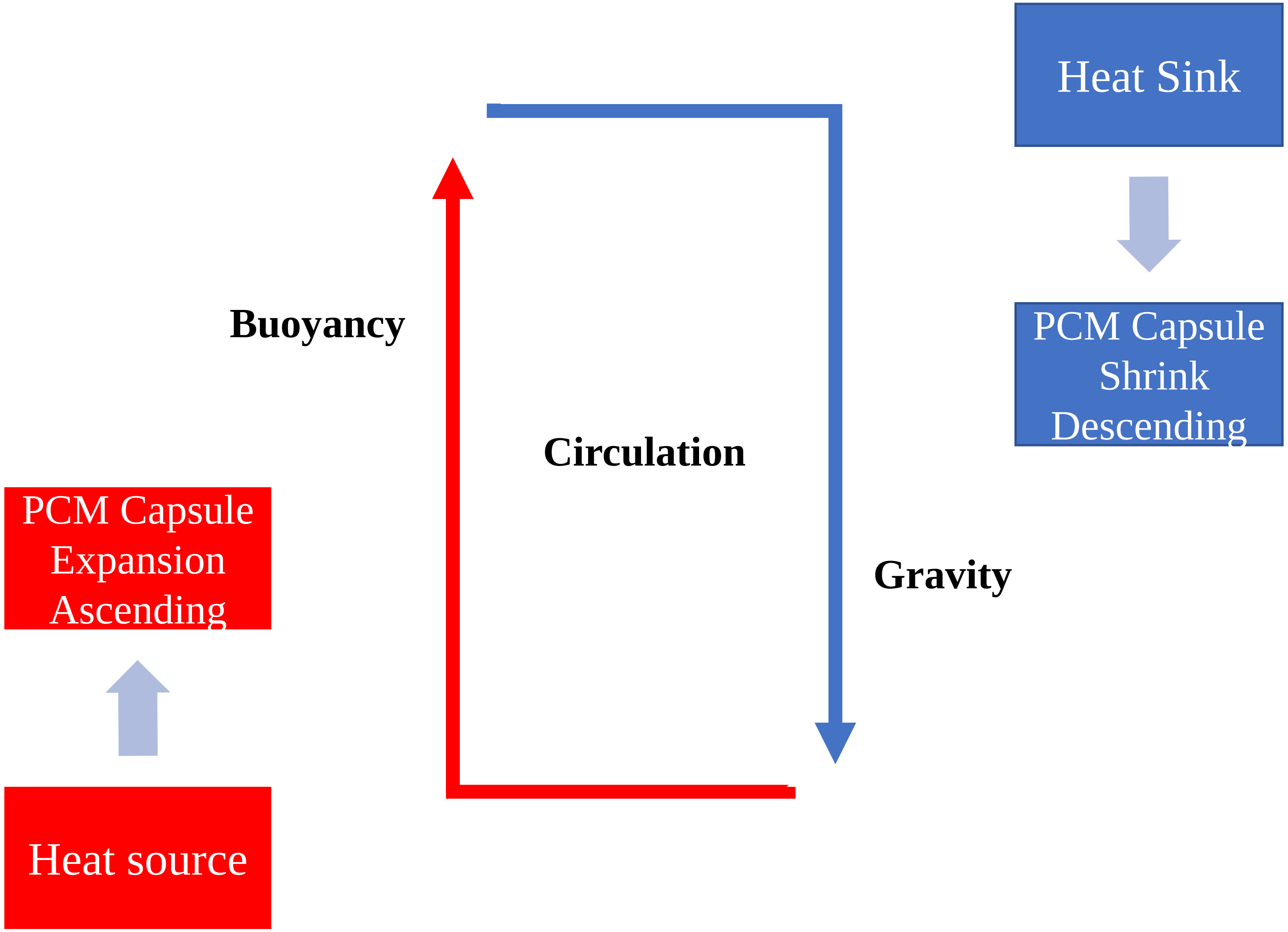
Water
Passive Cooling System

Input	Output
System geometry	Mean temperature
Physics	Q_{in}
Mesh	Q_{out}
Initial condition	Mass flow rate
Boundary condition	Water velocity

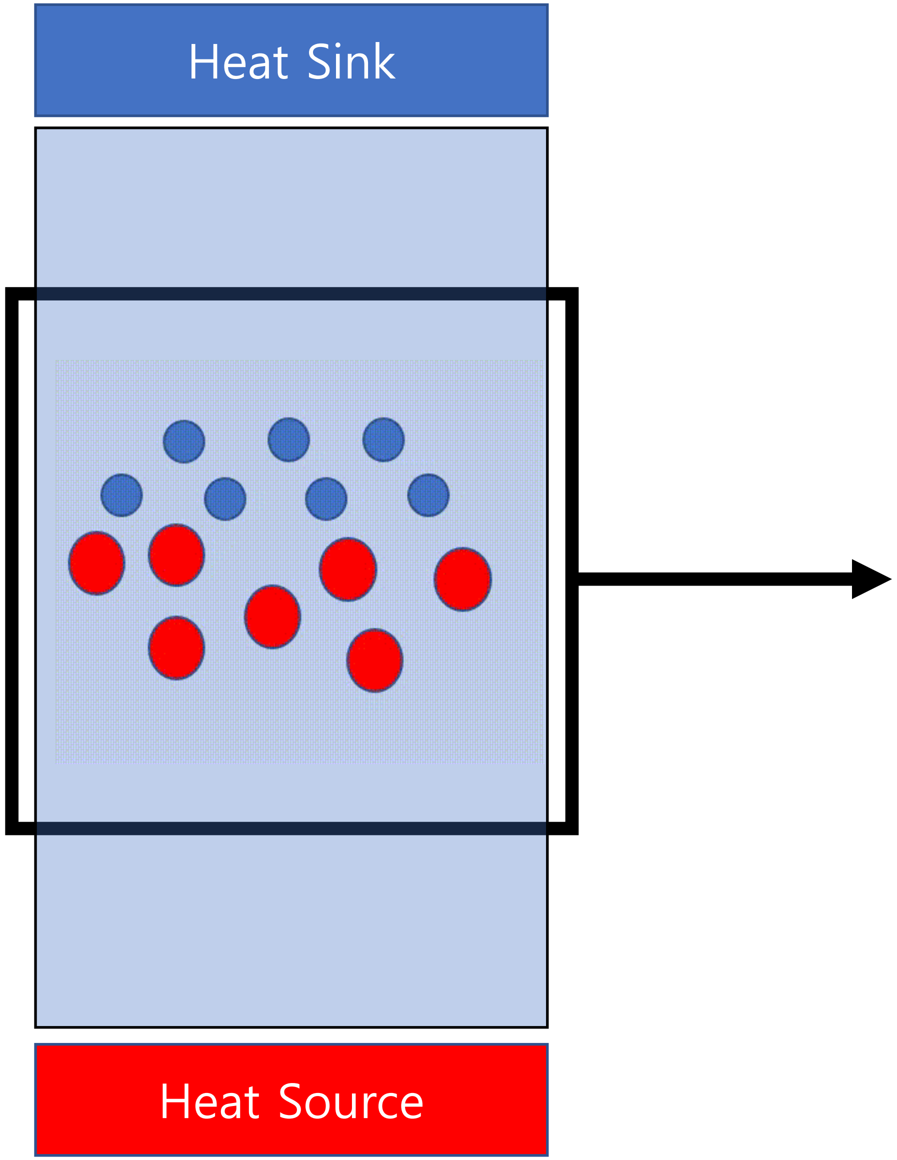
CFD Application Method

Geometry


Heat Sink
Heat Source

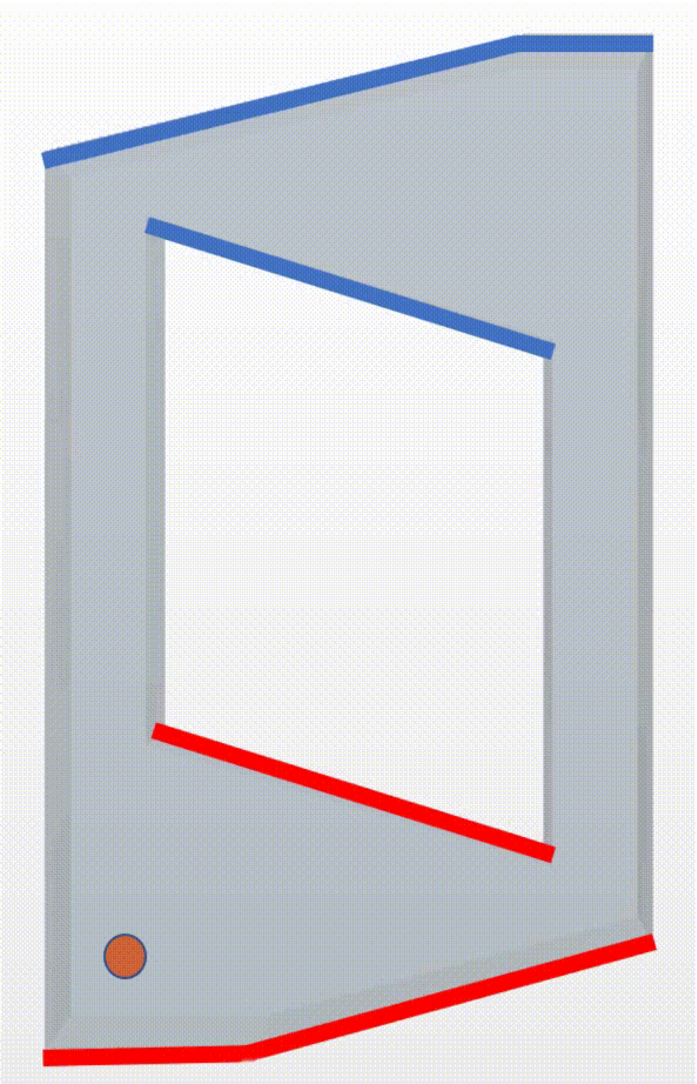

Heat Sink
PCM Capsule
Shrink
Descending
Buoyancy
Circulation
Gravity
PCM Capsule
Expansion
Ascending
Heat source

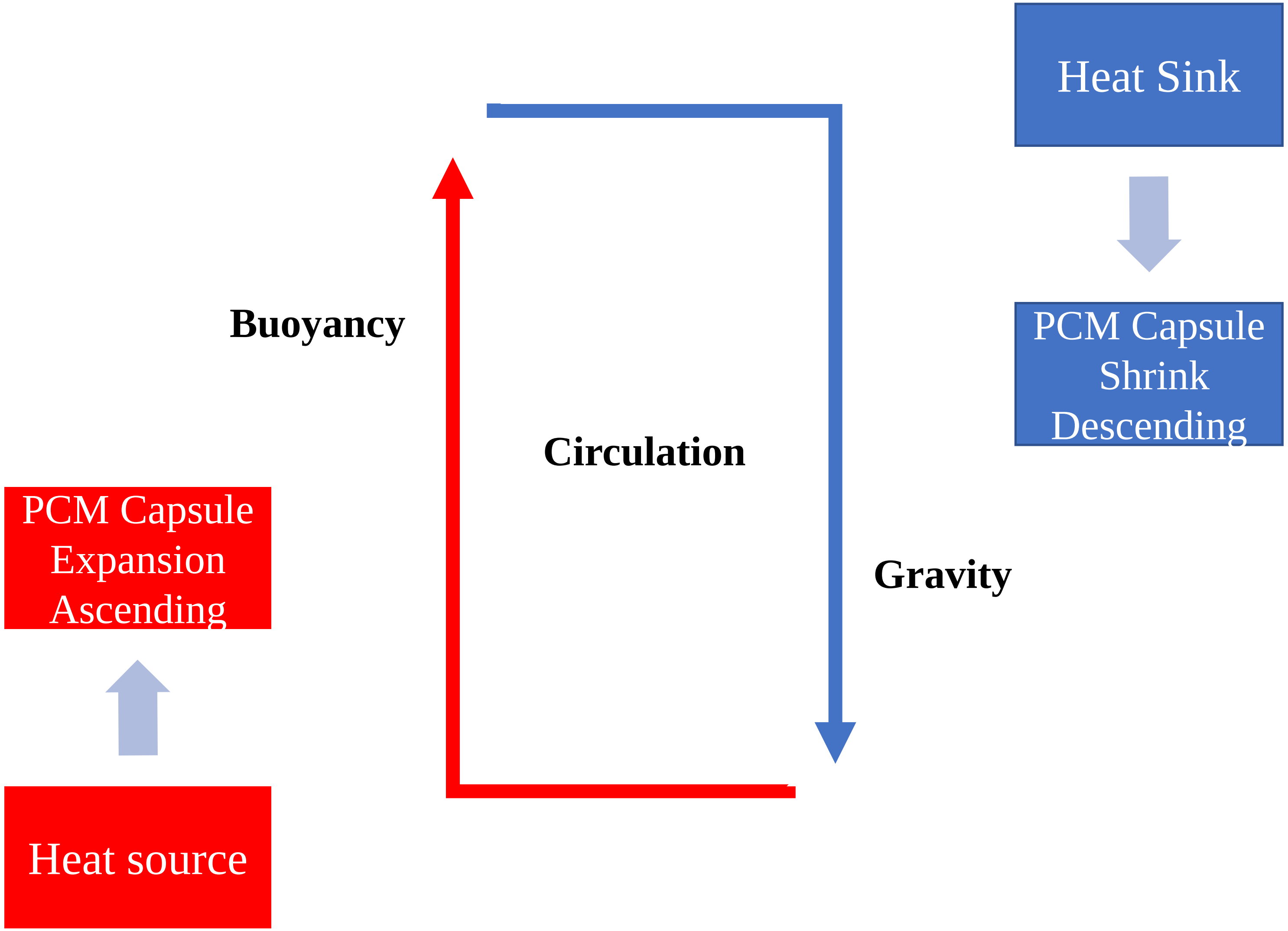
Geometry



Poor Circulation due to overlapping paths of circulating PCM capsules

Geometry




Heat Sink
PCM Capsule
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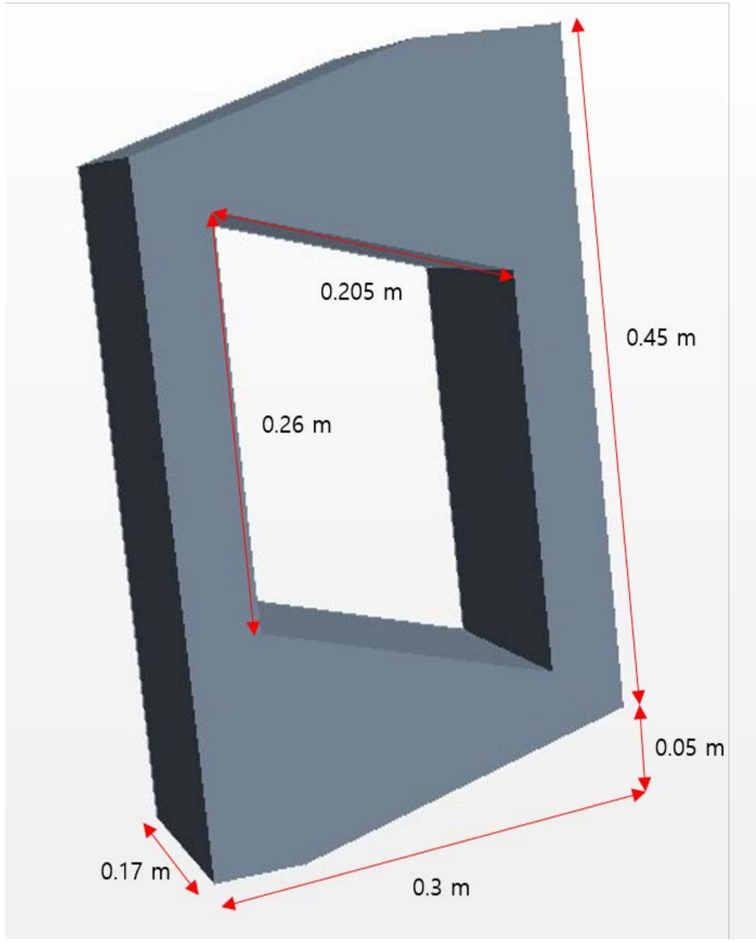
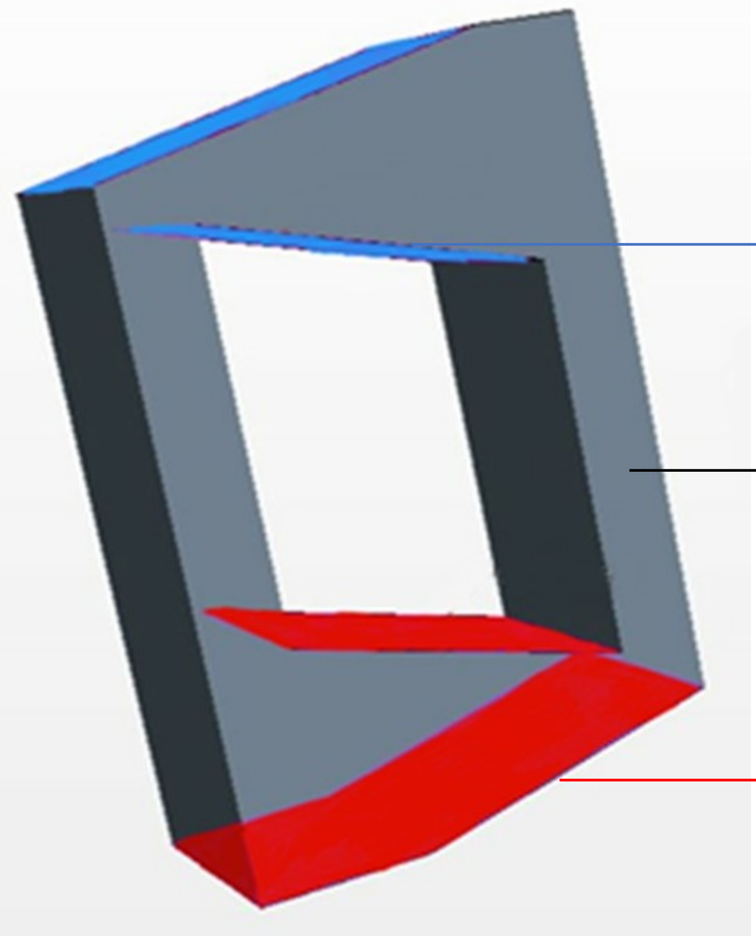
Geometry



< System Specification >

Width	0.3 m
Depth	0.17 m
Height	0.5 m
Volume	20.5 L

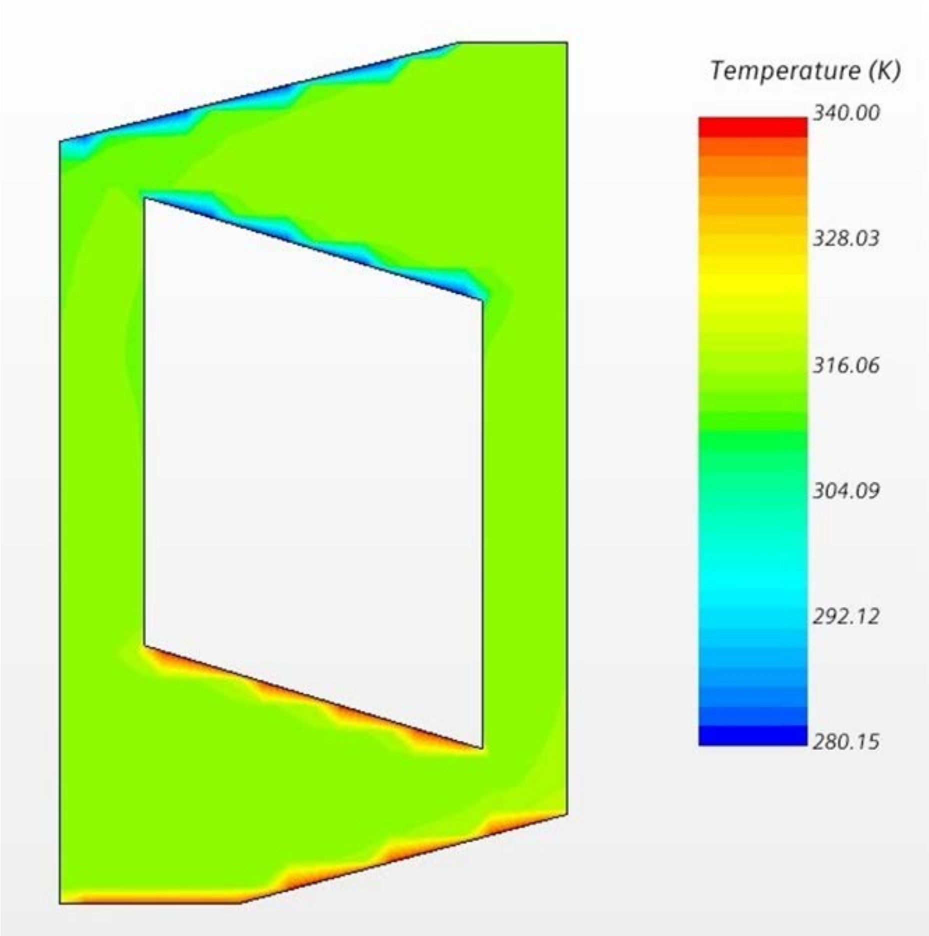
Geometry



Static Temperature 280 K

Adiabatic

Static Temperature 340 K



Physics

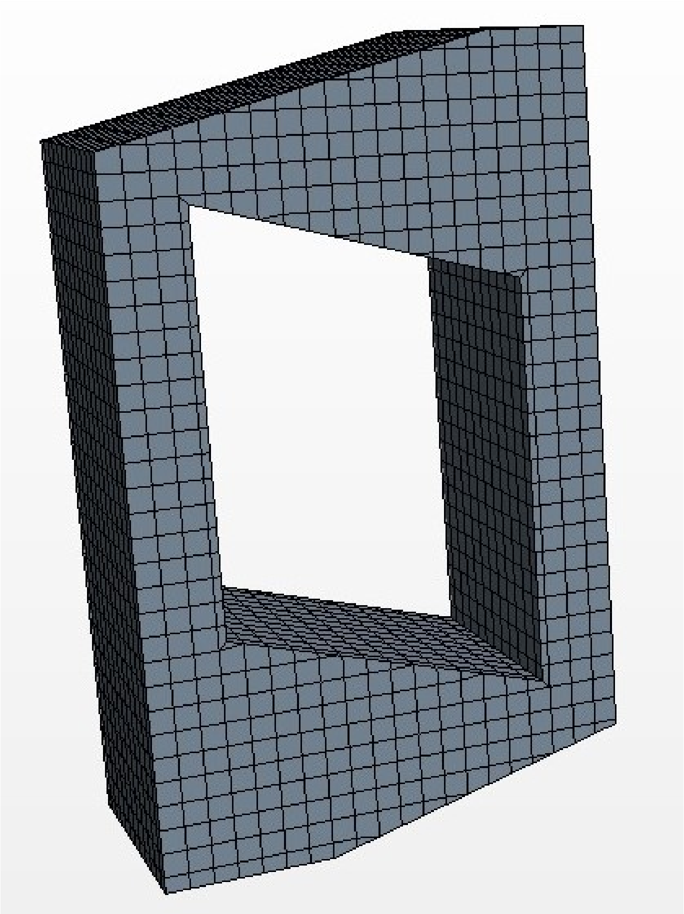
- K – epsilon turbulence model
- Segregated Flow
- Two layer all y+ wall treatment

} **Turbulent heat transfer analysis**

- Lagrangian Multiphase
- Discrete Element Model (DEM)

} **PCM Capsule Tracking**

Mesh

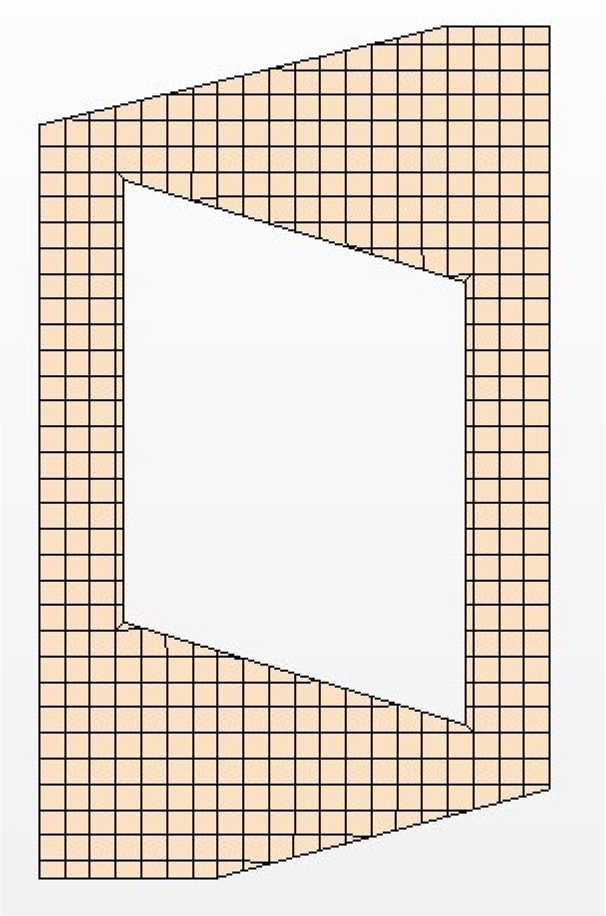


Meshing Method: Trimmed mesh

Base size: 0.015 m

Surface growth rate: 1.3

Mesh



Meshing Method: Trimmed mesh

Base size: 0.015 m

Surface growth rate: 1.3

PCM Capsule Property

Particle diameter	0.01 m
Initial particle temperature	300 K
Melting temperature	310 K
Latent heat	202,000 J/ kg
Specific heat	3000 J/kg K
Number of PCM	503
Total mass of PCM capsules	0.2765 kg
Mass fraction of PCM capsules	1.35 %
PCM Capsule Density	1050 kg/m^3 (Solid state) 930 kg/m^3 (Liquid state)

PCM

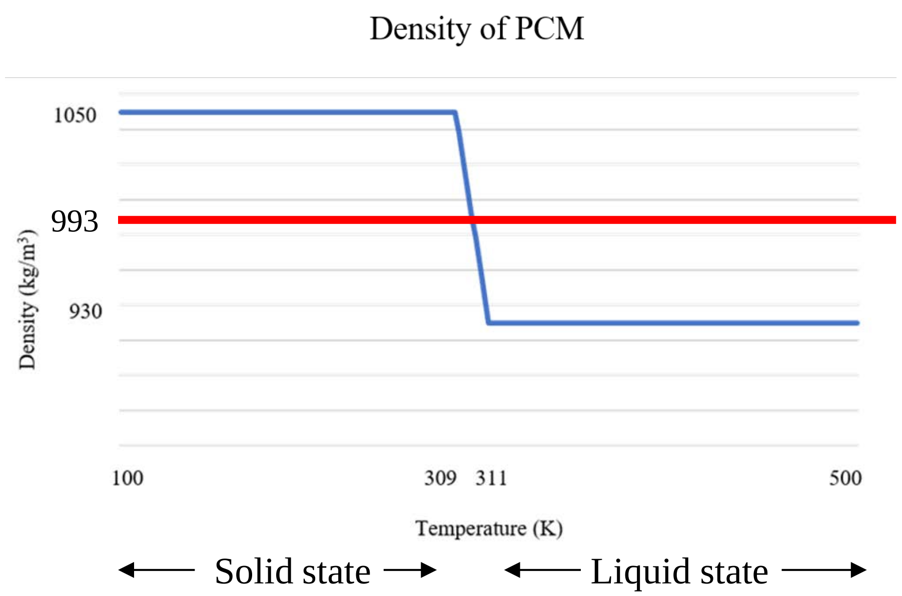
ρ
Density

C_p
Specific Heat

PCM

ρ

Density



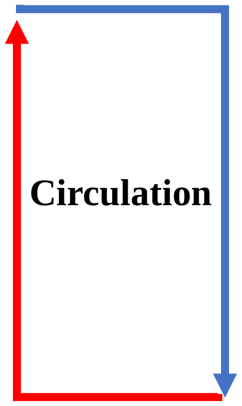
Gravity

Buoyancy

Gravity

Buoyancy

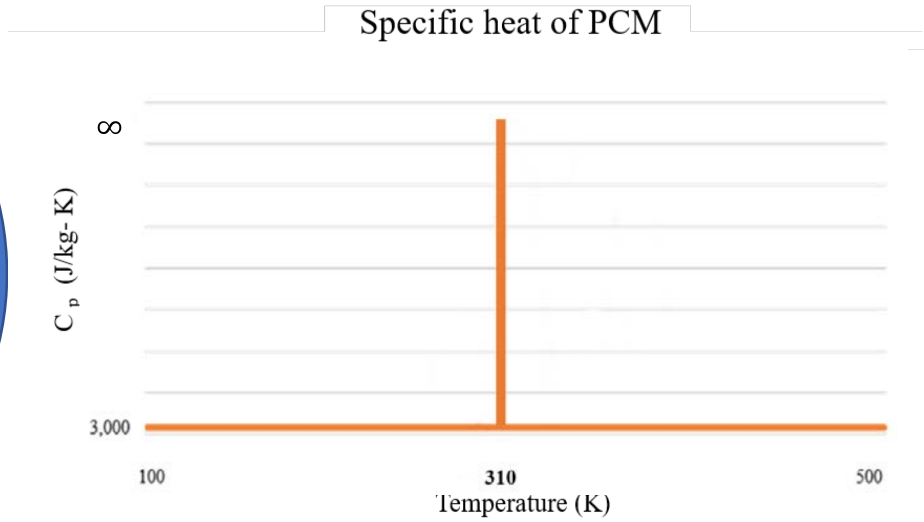
Gravity

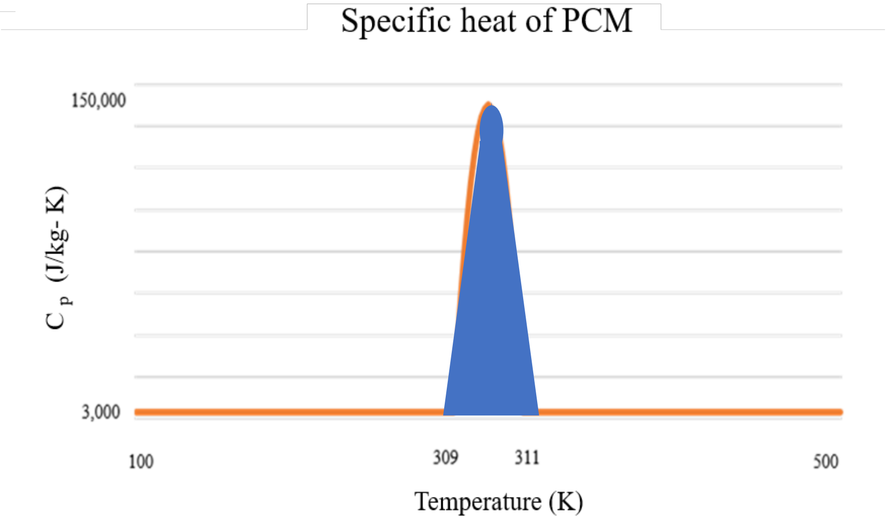


Buoyancy

PCM

C_p
Specific Heat





20,2000 J/kg

$$C_p(T) = -147000T^2+9.114\times 10^7\,T-1.412655\times 10^{10}$$

$$(309\ K < T < 311\ K)$$

CFD Summary

Geometry : Natural Circulation Loop

Physics: K – epsilon turbulence model, Segregated Flow

Two layer all y+ wall treatment,

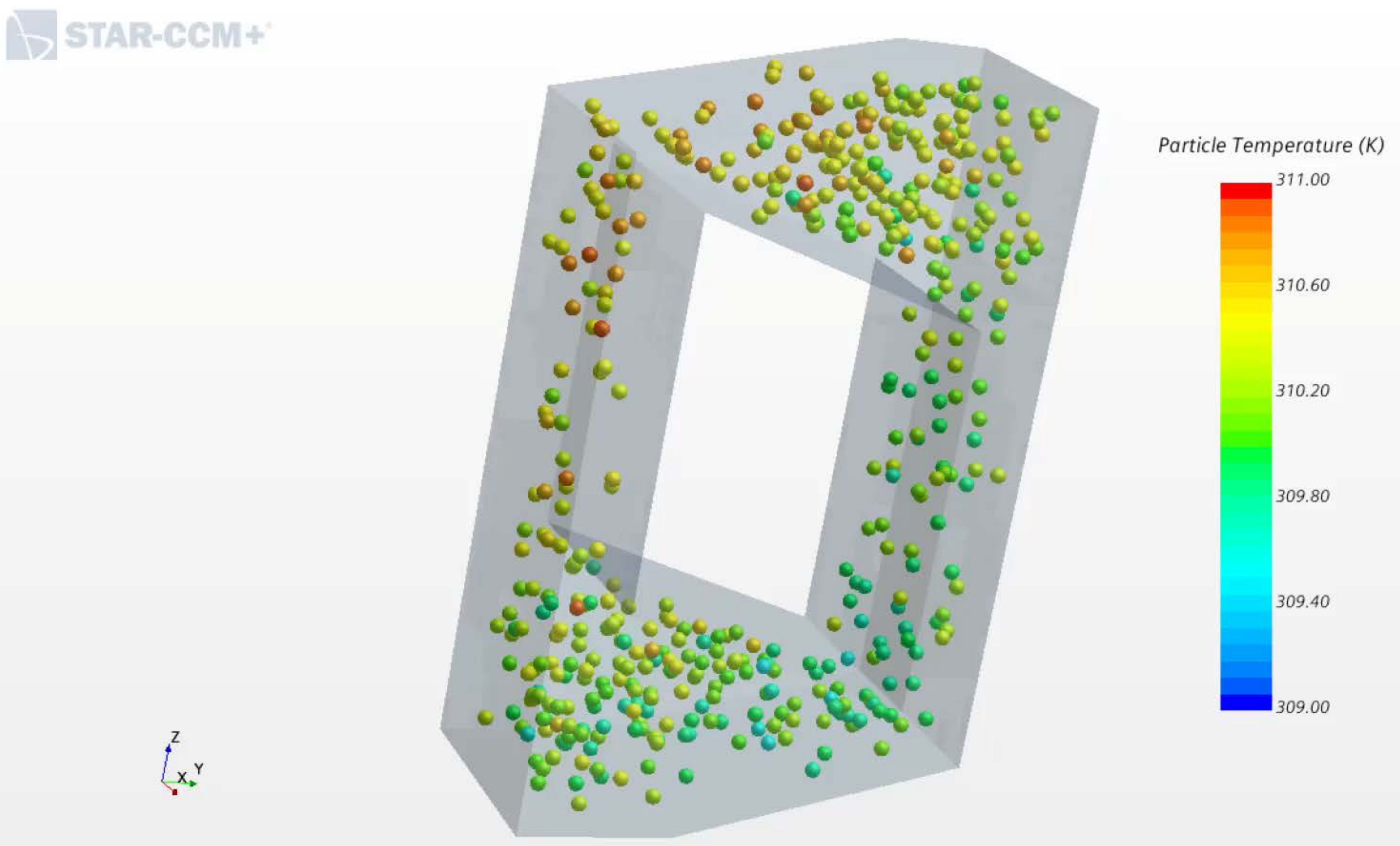
Discrete Element Model (DEM), Lagrangian Multiphase

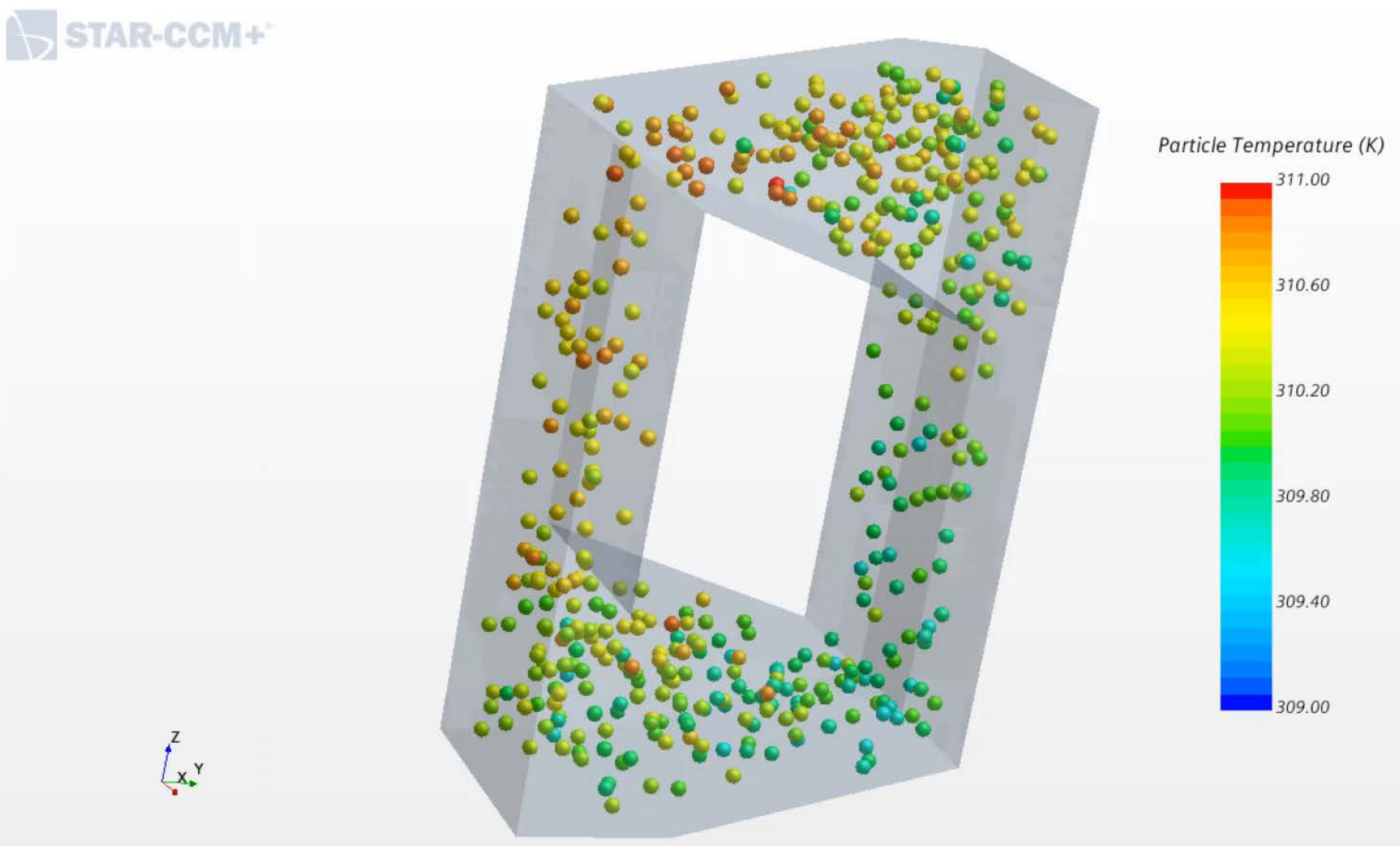
Mesh: Trimmed cell Mesher

Initial condition: Temperature 300 K (Water, PCM capsule)

Boundary condition: **Heat source 340 K (Static Temp.)**
Heat sink 280 K (Static Temp.)
Other adiabatic

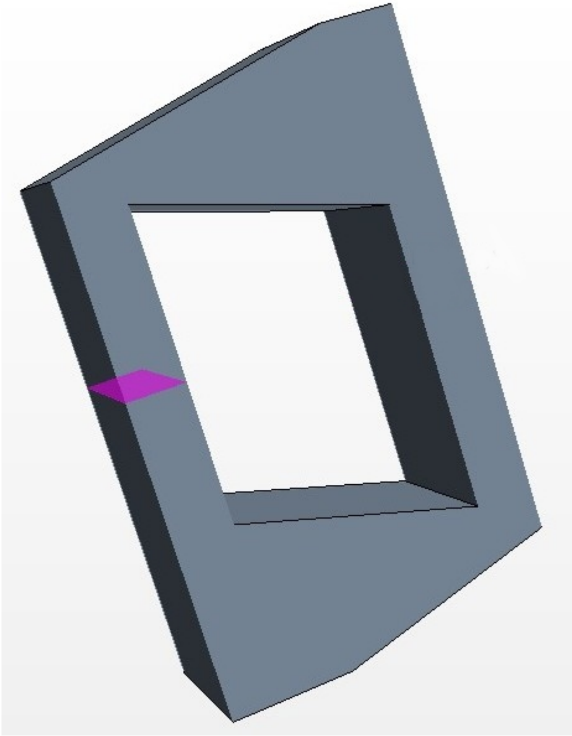
Result


STAR-CCM+
Particle Temperature (K)
311.00
310.60
310.20
309.80
309.40
309.00
Z
X
Y


STAR-CCM+
Particle Temperature (K)
311.00
310.60
310.20
309.80
309.40
309.00
Z
X
Y

Result

Output	Water	Water + PCM
Mean temperature	314.60 K	310.58 K
Q_{in}	1140.1 W	5280.09 W
Q_{out}	-1137. 549 W	-5226.566 W
$\Delta Q/Q_{in}$	0.224 %	1.01 %
Mass flow rate	0.1578 kg/s	0.2404 kg/s
Water velocity	0.01875 m/s	0.02844 m/s

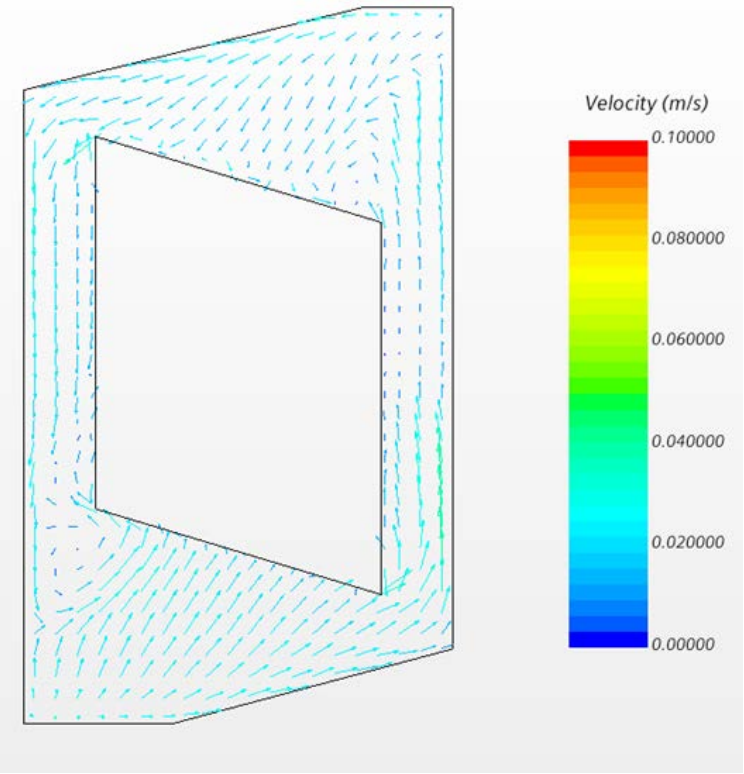


Result Analysis

- **Increased heat transfer due to increased flow rate**

  - **Drag force is applied between PCM capsules and fluids due to the buoyancy of the PCM to improve the natural convection heat transfer of the fluid.**

Result Analysis



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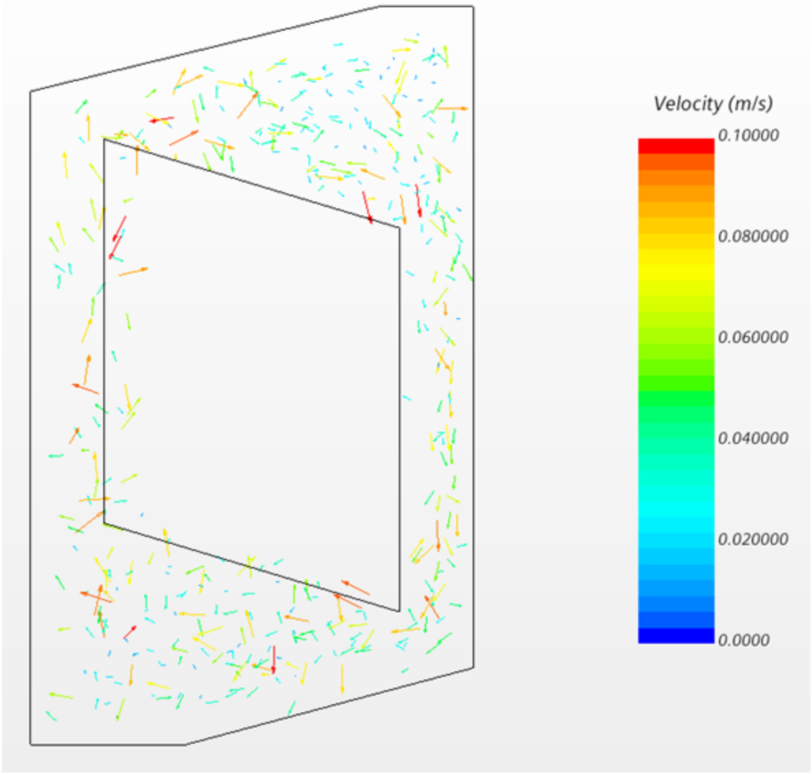

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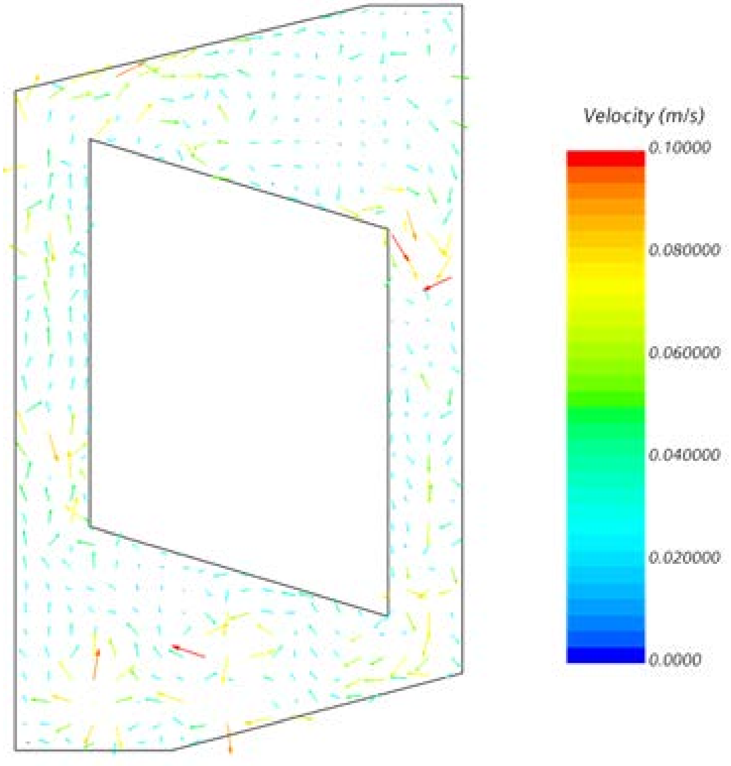


Water Velocity | **PCM Velocity** | **PCM +Water Velocity**

0.01875 m/s → 0.02844 m/s

50 % increased

Result Analysis

- **Increased heat transfer due to reduced temperature change of water due to high latent heat of PCM**

- **Heat Source**

$$\dot{Q}_{Convection} = hA(T_{hot} - T_{water})$$

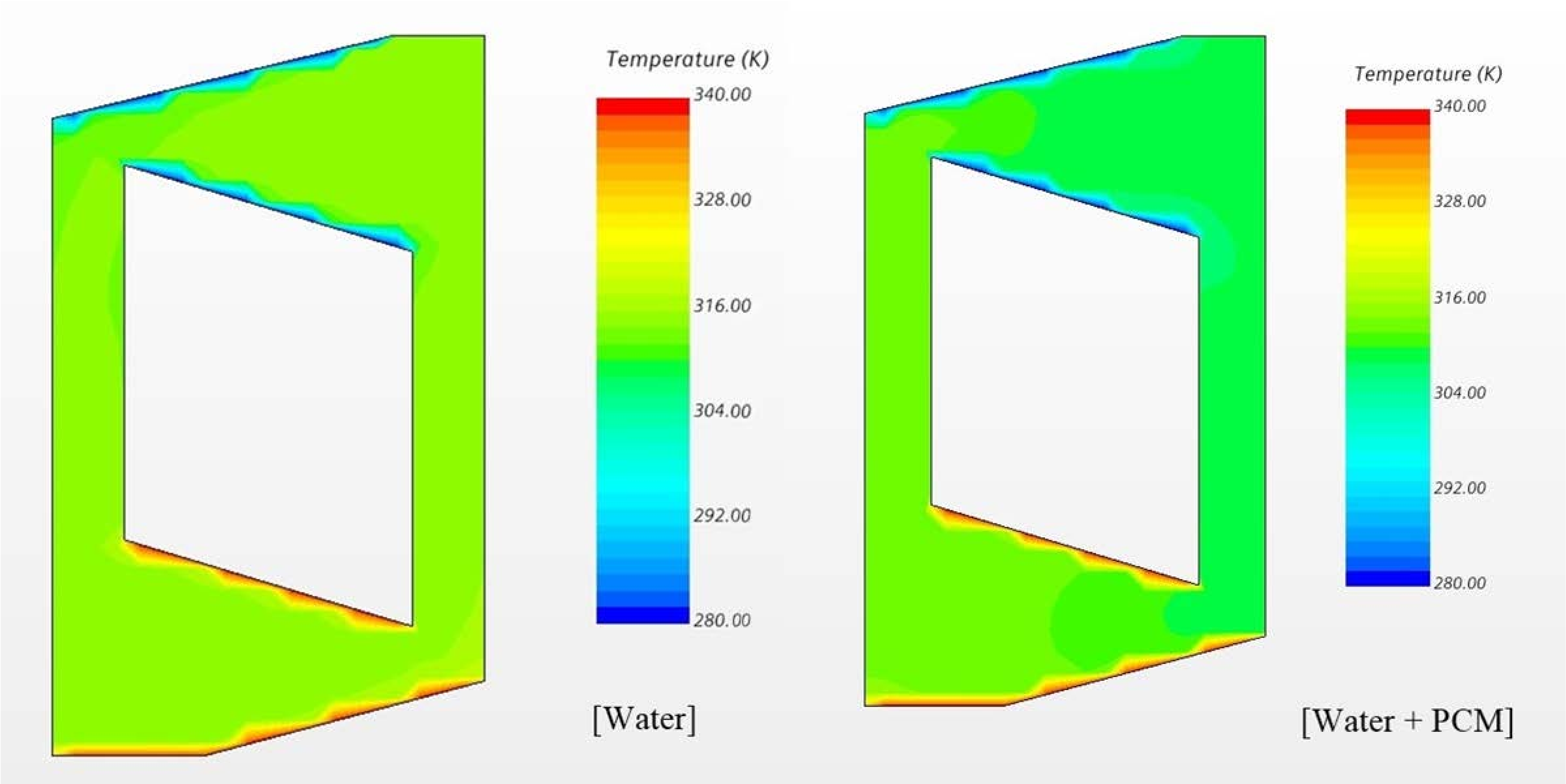
Reduction of temperature rise in water around the heat source $\rightarrow \Delta T$ increase ↑→ $\dot{Q}_{Convection}$ increase ↑

- **Heat Sink**

$$\dot{Q}_{Convection} = hA(T_{cool} - T_{water})$$

Reduce the temperature drop of water around the Heat sink→ ΔT increase ↑ → $\dot{Q}_{Convection}$ increase ↑

Result Analysis



Conclusion

Conclusion

- 4K difference in average temperature of the system under the same conditions (in Quasi- steady state)
- When PCM capsules were inserted into a Loop-type passive cooling system with 1.35% mass fraction, they delivered about 5 times more heat transfer under the same conditions and improved internal flow rates by 50%.
- PCM capsules have the potential to be used to improve heat removal capability in a passive cooling system in the form of a loop.

Application Plan

- **In the event of a Total loss of power accident, it is used to cool down areas, Such as MCR, Vital area, etc. where computer equipment is needed to be cooled.**
- **PCCS tank depletion protection/ cool the tank for delay in depletion time**
- **Can be used in various fields (required server rooms, etc.)**

Future Works & Supplement point

Future Works

Passive cooling system geometry

Working Fluid

PCM Property, Mass fraction

Working temperature

Supplement Point

PCM capsule integrity

Radiation stability

Performance

Differences between CFD and real-world experiments

감사합니다

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