

A STUDY ON HEAT AND FLUID FLOW IN PHASE CHANGE MATERIAL ASSISTED WITH HIGH CONDUCTIVE CONSOLIDATED POROUS MEDIA

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THESIS

A STUDY ON HEAT AND FLUID FLOW
IN PHASE CHANGE MATERIAL ASSISTED
WITH HIGH CONDUCTIVE
CONSOLIDATED POROUS MEDIA

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TABLE OF CONTENTS

ABSTRACT.....	V
LIST OF FIGURES.....	VII
LIST OF TABLES.....	XIII
NOMENCLATURE.....	XIV
 CHAPTER 1. INTRODUCTION.....	 1
1.1 Thermal energy storage.....	1
1.2 Heat transfer enhancement in solid/liquid phase change.....	3
1.3 Heat and fluid flow in porous media.....	5
1.3.1 Pore scale and volume average methods.....	6
1.3.2 Local thermal equilibrium/ Local thermal non-equilibrium.....	6
1.4 The aim of study.....	7
1.4 The outline of thesis.....	8
 CHAPTER 2. LITERATURE SURVEY.....	 10
2.1 Classification of the studies respect to materials.....	10
2.2 Classification respect to numerical and experimental studies.....	14
2.3 Classification respect to pore scale and volume average methods.....	15
2.4 Classification respect to local thermal equilibrium/ local thermal non-equilibrium.....	15
2.5 Classification respect to the range of porosity.....	16
 CHAPTER 3. CONSIDERED PROBLEM.....	 33
3.1 Studied problem 1.....	33
3.2 Studied problem 2.....	34
3.3 Studied problem 3.....	34
 CHAPTER 4. GENERAL FORM OF GOVERNING EQUATIONS FOR STUDIED PROBLEMS.....	 37

4.1 Single phase flow in porous media.....	37
4.1.1 Pore scale governing equations.....	37
4.1.2 Volume average governing equations.....	38
4.2 Solid/liquid phase change.....	40
4.2.1 Pore scale governing equations.....	40
4.2.2 Volume average governing equations.....	41
CHAPTER 5. SIMPLIFICATION AND NON-DIMENSIONLIZATION OF GOVERNING EQUATIONS FOR STUDIED PROBLEMS.....	44
5.1 Simplified dimensionless form of the governing equations for Problem 1	
5.1.1 Pore scale equations.....	44
5.1.2 Volume average equations.....	45
5.2 Simplified dimensionless form of the governing equations for Problem 2	
5.2.1 Pore scale equations.....	47
5.2.2 Volume average equations.....	49
5.3 Simplified dimensionless form of the governing equations for Problem 3	
5.3.1 Pore scale equations.....	51
5.3.2 Volume average equations.....	52
CHAPTER 6. COMPUTATIONAL DETAILS.....	53
6.1 The computational code.....	53
6.2 Computational determination of macroscopic parameters.....	56
6.2.1 Macroscopic parameters for Problem 1.....	56
6.2.2 Macroscopic parameters for Problem 2.....	57
6.2.3 Macroscopic parameters for Problem 3.....	58
6.3 Validation studies.....	60
6.3.1 The first validation study.....	61
6.3.2 The second validation study.....	62
6.3.3 The third validation study.....	63
6.3.4 The fourth Validation study.....	63
6.3.5 The fifth validation study.....	64
6.3.6 The sixth validation study.....	66

6.4 Grid Independency.....	67
6.4.1 Grid Independency for problem 1.....	67
6.4.2 Grid Independency for problem 2.....	67
6.4.3 Grid Independency for problem 3.....	68
CHAPTER 7. RESULT AND DISCUSSIONS.....	69
7.1 Result and discussions for problem 1.....	69
7.1.1 Results for the volume averaged parametric analysis.....	69
7.1.2 The pore scale and volume average results for real cases.....	73
7.1.2.1 Results for the porous media with water in cells.....	75
7.1.2.2 Results for porous media filled with air in cells.....	78
7.2 Result and discussions for Problem 2.....	79
7.2.1 Comparison of Pore scale and volume average results.....	81
7.2.2 Effective thermal conductivity and local Sparrow number.....	85
7.2.3 Analysis of local thermal equilibrium and non-equilibrium assumptions.....	88
7.2.4 Validation of the thermal equilibrium condition chart.....	91
7.3 Result and discussions Problem 3.....	92
7.3.1 Comparison of pore scale and volume average results.....	92
7.3.2 Determination of the volume average transport parameters using pore scale results.....	97
7.3.2.1 Permeability and inertia coefficient.....	98
7.3.2.2 Effective stagnant thermal conductivity of the solid and fluid phase.....	99
7.3.2.3 Interfacial heat transfer coefficient.....	99
7.3.3 Accuracy of the reported interfacial heat transfer correlations.....	102
CHAPTER 8. CONCLUSIONS.....	106
REFERENCES.....	111
VITA.....	124

Abstract

Heat and fluid flow for the phase change assisted with high thermal conductive porous media is studied, computationally. The study focuses on the validation of volume average governing equations and the separation of the local thermal equilibrium and local non-equilibrium problems. Two domains as 2D closed cell porous media and 3D open cell porous media whose voids filled with phase change material are studied. In the closed cell porous media, the PCM (phase change materials) in the voids is independent and fluid cannot move from one cell to other cells, while in the open cell porous media the flowing of PCM through cells is possible. In this study, the porous media is aluminum alloy and the water is used as the PCM.

In general, one surface of the considered domain is maintained at constant temperature which is greater than melting point while the other surfaces are insulated. The initial temperature is considered the same as the melting point temperature. The effect of gravity is taken into account in this study causing the natural convection, however, it is found that its effect for the problems of 2D closed cell porous media is negligible. That is why that the pore scale governing equations for the problems of 2D closed cell porous media are continuity, momentum and energy equations while in the volume averaged analysis the governing equations have only two heat conduction equations for the solid and fluid phase domains. In the study of 3D open cell porous media, the governing equations are continuity, momentum and energy equations for the pore scale analysis and volume averaged continuity, momentum and energy equations for the volume average analysis.

For the volume average analysis, the values of the effective thermal conductivity, convective heat transfer coefficient and permeability should be known, the commercial program COMSOL Multiphysics is used to calculate the governing equations and obtained the results of this study. The values of the effective thermal conductivity, interfacial heat transfer coefficient and permeability are calculated by numerical methods in COMSOL Multiphysics. In order to be ensure from the employed code and applied methods in the computational code, and validate our obtained results of this study, the results for 7 different studies reported in literature are obtained and compared with the reported results. Good agreement between the obtained results of this study and reported one were observed showing the correctness of the employed code and methods.

The comparison of the pore scale and volume average results for 2D and 3D studies showed that a good agreement between the volume average and pore scale results exists for different time steps and Rayleigh number. Hence volume average method can provide sufficient accurate results for the solid/liquid phase change problems. For local thermal non-equilibrium problems, the interfacial heat transfer coefficient should be calculated, otherwise the solution of volume average equations is impossible. The interfacial heat transfer coefficient is calculated from the pore scale results. It is observed that the interfacial heat transfer coefficient is not constant during melting process, it increases to a maximum value at the initial of melting process and then it reduces to value which is equal to the value of the interfacial heat transfer coefficient of natural convection for the single phase flow. However, the time and space average of the interfacial heat transfer coefficient for the entire domain provides sufficiently accurate volume average results. Furthermore, it is found that Sparrow number is an effective number to distinguish the local thermal equilibrium problem from that of the local thermal non-equilibrium. Sparrow number shows the convection heat transfer to the conduction heat transfer through the cavity. Hence for the large value of Sparrow number, the propagation of heat by convection is strong referring to the possibility of local thermal equilibrium between the solid and fluid, while for low values of Sparrow number the propagation of heat by conduction is strong referring to the possibility of local thermal non-equilibrium between the solid and fluid. It is proved that Sparrow number is a governing parameter of the phase change problem in porous media and it is possible to make charts or diagrams for distinguishing of local thermal equilibrium and local thermal non-equilibrium state. To the best of our knowledge, these charts are reported into literature for the first time and it may take attentions of researchers to provide the same graphs for other configuration of the porous media. For the closed cell porous media these charts are established and presented.

LIST OF FIGURES

Figure number and caption	Page
Fig.1.1 The schematic view of the orbit of satellite.....	2
Fig.1.2 The classification of thermal energy storage.....	3
Fig. 1.3 Three main methods for heat transfer enhancement of PCM (a)by using fins (Rozenfeld et al. (2015)) (b)by using Nano metal particles (Munyalo et al. (2018)) (c)by using high thermal conductive metal foam (Yao et al. (2018)).....	5
Fig. 2.1 The employed PCM materials.....	11
Fig. 2.2 Two views of two different researchers used paraffin as PCM and copper foam as porous media for heat transfer enhancement, a) Mancin et al. (2015), b) Jin et al. (2017).....	11
Fig. 2.3 The employed porous media.....	12
Fig.2.4 Three metal foams with different material and Pore Per Inch (PPM) (Yao et al. 2018).....	13
Fig. 2.5 The employed porous media and PCM materials	13
Fig. 2.6 The number of experimental and numerical studies.....	14
Fig. 2.7 The number of pore scale vs volume average studies.....	14
Fig. 2.8 The number of Equilibrium and non-equilibrium studies.....	16
Fig. 2.9 The roughness of the four porous materials based on the measured porosity of the uncompressed metal samples.....	17
Fig. 2.10 The range of porosity.....	17
Fig. 3.1.1 The schematic view of the considered study (a) pore scale domain (b) volume averaged domain.....	34
Fig. 3.2.1 The schematic view of the considered study (a) pore scale domain (b) volume averaged domain.....	35

Fig. 3.3.1 The 3D schematic view of the studied domain, a) the employed 3D LMF for heat transfer enhancement, b) the considered porous cavity in which voids are filled PCM.....	36
Fig.4.1.1 The schematic view of the pore scale domain.....	38
Fig.4.1.2 The schematic view of the volume average domain.....	38
Fig.4.1.3 The schematic view of the volume average domains for fluid flow.....	39
Fig.4.2.1 The schematic view of the entire domain.....	40
Fig.4.2.2 The schematic view of the fluid and solid domains.....	42
Fig 6.1.1 Flow chart for pore scale study in Comsol.....	54
Fig 6.1.2 Flow chart for volume average study in Comsol.....	55
Fig.6.2.1 Temperature distribution and boundary conditions for a cell of pore scale domain for determination of the effective thermal conductivity.....	58
Fig. 6.2.2 Temperature distribution in the representative cell for determination of k_{eff}	59
Fig. 6.3.1 (a) Temperature distribution (b)Effective thermal conductivity changing by solid thermal conductivity.....	61
Fig. 6.3.2 Illustration of melting in a semi–infinite slab with initial temperature of T_m	62
Fig. 6.3.3 Validation studies, comparison of the present study results with the reported studies for pure analytical solution (Carslaw and Jaeger (1959)).....	62
Fig. 6.3.4. Validation studies, comparison of the present study results with the reported studies for Beckermann and Viskanta (1988).....	63
Fig. 6.3.5 The comparison between our results and the results of Huber et al. (2008).....	64
Fig. 6.3.6 Illustration of melting in a semi–infinite slab with initial temperature of T_i ($T_i < T_m$).....	64

Fig. 6.3.7 Comparison of the numerical results with the results of the analytical solution by Alexiades and Solomon (1993) for 1D melting process.....	65
Fig. 6.3.8 Comparison between the present numerical results and the reported results in literature (Li et al. (2017)) when $Ste = 0.4$, $Ra = 2.5 \times 10^4$, $Pr = 10$	66
Fig. 6.4.1 The changes of pore scale temperature in the pore scale domain with number of mesh with $\tau = 0.0016$ and $Ra_{l-max} = 10^5$, $\varepsilon = 0.9$	67
Fig. 6.4.2 A sample of grid independency for a closed cell cavity with $\varepsilon = 0.9$, $Ra_f = 10^3$ and $Ste = 1$	68
Fig. 6.4.3 A sample of grid independency for the melting fraction with $\varepsilon = 0.9$, $Ra_f = 10^6$ and $Ste = 0.6$	68
Fig. 7.1.1 The change of dimensionless mean temperatures of solid and fluid and the difference between them with dimensionless time when $\Gamma_s = 1$, $\Omega_s = 0.01$ (a) $Sp = 50$ (b) $Sp = 250$ (c) $Sp = 1000$ (d) σ value fo $Sp = 50, 100, 250, \text{ and } 1000$	70
Fig. 7.1.2 The variation of dimensionless mean temperatures of solid and fluid phases and the difference between them with dimensionless time when $\Gamma_s = 0.5$, $\Omega_s = 0.01$ (a) $Sp = 50$ (b) $Sp = 250$ (c) $Sp = 1000$ (d) σ value for $Sp = 50, 100, 250, \text{ and } 1000$	71
Fig. 7.1.3 The variation of dimensionless mean temperatures of solid and fluid phases with dimensionless time when $\Gamma_s = 0.01$, $\Omega_s = 0.01$ for $Sp = 50, 250 \text{ and } 1000$ (two curves overlap).....	72
Fig. 7.1.4 Occurrence of local thermal equilibrium for the studied cases (a) local thermal equilibrium map according to Ω_s and Γ_s (assumption for the local thermal equilibrium is $\sigma \leq 0.05$) (b) the variation of thermal diffusivity ratio (α_s^* / α_f^*) with respect to Ω_s and Γ_s	74
Fig. 7.1.5 The temperature and velocity distributions of the water in the cells of domain with $Ra_f = 10^5$ and the same domain for volume averaged when $\Omega_s = 0.068$, $\Gamma_s = 1.06$ and $Sp = 46.7$ for three different time steps (a) $\tau = 0.0320$ (b) $\tau = 0.1602$ (c) $\tau = 0.3205$	77

Fig. 7.1.6 The comparison of pore scale and volume averaged results for the centerline of the porous media in which voids filled with water for $\Omega_s = 0.068$, $\Gamma_s = 1.06$ (a) $Sp = 39.2$ (for $Ra_f = 10^2$) (b) $Sp = 46.7$ (for $Ra_f = 10^5$).....	78
Fig. 7.1.7 The temperature and velocity distributions of air in the cells of domain with $Ra_f = 10^5$ and for the same domain for volume averaged when $\Omega_s = 1.11$, $\Gamma_s = 1.08$ and $Sp = 1.91$ for three different time steps (a) $\tau = 0.0510$ (b) $\tau = 0.1275$ (c) $\tau = 0.2550$	80
Fig. 7.1.8 The comparison of pore scale and volume averaged results for the centerline of the porous media in which voids filled with air for $\Omega_s = 1.11$, $\Gamma_s = 1.08$ (a) $Sp = 1.74$ (for $Ra_f = 10^2$) (b) $Sp = 1.91$ (for $Ra_f = 10^5$).....	80
Fig. 7.2.1 Domination of heat conduction for the phase change in a closed cell porous medium (a) Temperature and velocity distributions for $Ra_f = 10^3$ in cavity with $\varepsilon = 0.9$. (b) The temperature profile in the center line of the second row of cavity for four different values of Ra number at $F_o = 0.67$	82
Fig. 7.2.2 The comparisons of the pore scale and volume average temperatures of solid and fluid phases at different time steps with $\varepsilon = 0.9$ and $Ste = 1$ for the pore scale equations and $Sp = 35$, $\alpha_r = 668$ and $Ste = 1$ for the volume average equations.....	83
Fig. 7.2.3 The comparisons of the pore scale and volume average temperatures of solid and fluid phases at different time steps for $\varepsilon = 0.7$ and $Ste = 1$ for pore scale equations, and $Sp = 17$, $\alpha_r = 668$ and $Ste = 1$ for the volume average equations...	85
Fig. 7.2.4 Comparisons of the melting fraction between the pore scale and volume average results for three different porosities as $\varepsilon = 0.7, 0.8, 0.9$ when $Ste = 1$	85
Fig. 7.2.5 The change of effective thermal conductivity and effective porosity with the different porosity for ice and water.....	86
Fig. 7.2.6 The change of local heat transfer coefficient and Sparrow number for five different columns of the pore scale cavity when $Ste = 1$ and $\alpha_r = 668$	87
Fig. 7.2.7 The change of the solid and fluid volume average temperatures and σ for different values of Sparrow number when $\alpha_r = 500$ and $Ste = 1$	90

Fig. 7.2.8 Local thermal equilibrium condition in terms of different values of Sparrow number and thermal diffusivity ratio when $Ste = 1$	91
Fig. 7.2.9 Temperature distribution and temperature profile at $Y^* = 0.5$, (a) Case 1, $F_o = 0.15$ (b) Case 2, $F_o = 0.36$	93
Fig. 7.3.1 The comparison of temperature distributions between the pore scale and volume average results when $Ra = 1$ at three different melting fractions.....	95
Fig. 7.3.2 The comparison of temperature profile between the pore scale and volume average approaches at $Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$ when $Ra = 1$	95
Fig. 7.3.3 The pore scale velocity and temperature distributions of the cavity with $Ra = 10^6$ at three different melting fractions.....	96
Fig. 7.3.4 The comparison of temperature profiles between the pore scale and volume average when $Ra = 10^6$ at the center line of cavity ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$).....	97
Fig. 7.3.5 The comparison of temperature distributions between pore scale and volume average when $Ra = 10^6$ at the top row of cavity ($Y^* = 0.9$, $Z^* = 0.5$, $0 \leq X^* \leq 1$).....	98
Fig. 7.3.6 The change of dimensionless pressure with pore scale Reynolds number for a unit cell of 3D LMF.....	98
Fig. 7.3.7 The change of k_{eff} / k_f and ε^* with porosity for the studied 3D LMF	99
Fig.7.3.8 The change of volume average temperature difference, interfacial heat rate and local instant Nusselt number in the center cell of cavity during melting process when $Ra = 1$, a) volume average temperature difference and heat transfer rate assisted with temperature distributions in the center cell, b) local instant interfacial Nusselt number.....	100
Fig. 7.3.9 The change of volume average temperature difference, interfacial heat rate and local instant Nusselt number in the center cell of the cavity during melting process when $Ra = 10^6$, a) volume average temperature difference and heat transfer rate assisted with temperature distributions in the center cell, b) local instant interfacial Nusselt number.....	101

Fig. 7.3.10 The comparison of local instant Nusselt number obtained in the present study with correlations in literature for the center cell during the melting process, a) $Ra = 1$, b) $Ra = 10^6$	104
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Fig. 7.3.11 The comparison of temperature profile between our results and correlation results at the middle row of cavity ($Y^* = 0.5, Z^* = 0.5, 0 \leq X^* \leq 1$), a) $Ra = 1$, b) $Ra = 10^6$	105
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LIST OF TABLES

Tables number and caption	Page
Table 1.1 A list of some PCMs and their thermal conductivity and diffusivity values.....	4
Table 2.1 The list of literature survey.....	18
Table 3.1 Thermophysical properties of PCM and frame material.....	35
Table 7.1. Thermophysical properties and dimensionless governing parameters for water and air in the pore scale and volume averaged studies.....	75
Table 7.2 The thermophysical parameters of the porous media for Case 1 and 2	93
Table 7.3 The interfacial Nusselt number used by researchers.....	103

NOMENCLATURE

A	Heat transfer area, m ²
C	Thermal capacitance , J/ m ³ K
C _p	Specific heat capacity, J/ kg K
Fo	Fourier number
h	Interfacial heat transfer coefficient, W/m ² K
K	Permeability, m ²
k	Thermal conductivity, W/mK
L	Length of cavity, m
LTNE	Local thermal non-equilibrium
LTE	Local thermal equilibrium
l	Length of cell, m
n	Normal direction to the surface
P	Pressure, N/m ²
Pr	Prantl number
q"	Heat flux, W·m ⁻²
Ra	Rayleigh number
r	Diameter, m
Sp	Sparrow number
T	Temperature, K
t	Time, s
V	Velocity vector, m/s
x, y	Cartesian coordinates, m
α	Thermal diffusivity, m ² /s
β	Thermal expansion coefficient, 1/K
σ	Function for the level of non-equilibrium condition
ε	Porosity
φ	Any dependent parameter
κ	Thermal conductivity in equilibrium state
μ	Dynamic viscosity, Pa.s
ν	Kinematic viscosity, m ² /s
θ	Dimensionless temperature
ρ	Density, kg/m ³
ξ	Ratio between the characteristic lengths

τ	Dimensionless time
ψ	Thermal diffusivity ratio between fluid and solid
Γ	Dimensionless thermal conductivity
Ω	Dimensionless thermal capacitance

Subscripts and superscripts

c	Cold
cr	Cross section
e	Equilibrium
eff	Effective
f	Fluid
h	Hot, Hydraulic
i	Initial
int	Interface
ref	Reference
s	Solid
v	Volumetric
x	Solid or fluid phase

Chapter 1

Introduction

1.1 Thermal energy storage

By continuous increasing of the greenhouse gas emissions and demand of energy, the problem of energy becomes an important issue threatening our world. Therefore, renewable energy sources become attractive, finding the methods for the utilization of renewable energy sources becomes a hot research topic, recently.

One of the most important topics in analyzing of renewable energy sources is Thermal Energy Storage (TES). Many renewable energy sources such as solar energy or wind energy are intermittent. Hence the energy should be saved when the renewable energy sources exists and it should be consumed when renewable energy sources are not available. For example, if solar energy is request to be used for a 24 hours' process, since the solar energy during the night is not available, it should be saved during the daytime and then consumed during the night to provide continuity of the process. Hence some innovative devices are required to store energy and provide its usage later.

Thermal Energy Storage can play an important role in utilization of waste heat. Every day, a lot of gas and liquid with high temperature is thrown away in industry. All of us see many chimneys in which the hot gas is thrown to environment for many times in our life. The energy of those waste heat can be saved and transferred to another place where thermal energy is required. For example, in winter the heat of power plant can be saved and then carried to a big meeting hall in which HVAC system is not sufficient. Those kinds of applications are widely studied in these days.

Even in space technology, thermal energy storage can be used. As it can be seen in Fig.1.1, when the satellite is in sunlight period it is imposed under high thermal radiation but in eclipse suddenly the temperature decreases dramatically and this high temperature difference may destroy some of electronic equipment in the satellite. Therefore, some methods are required to prevent the sharp change of temperature and

TES (Thermal Energy Storage) can be one of them. Thermal Energy Storage can store sun radiation and prevent its transfer to electronic equipment during sunlight period and can release it when the satellite is in the eclipse period. By this way, the temperature of electronic equipment remains in the operation range.

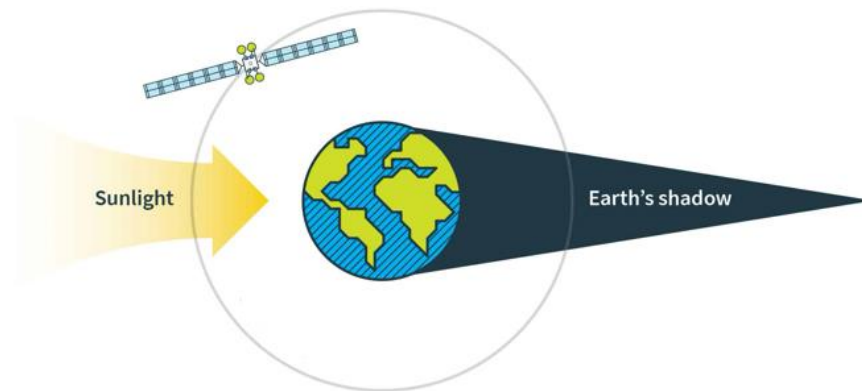


Fig.1.1 The schematic view of the orbit of satellite

<https://corpblog.viasat.com/how-satellites-are-affected-by-the-spring-and-autumn-equinoxes/>

There are many applications of thermal energy storage such as seasonal heating and cooling, balance of temperature of electronic equipment etc.

Thermal energy storage can be classified to three parts as sensible, latent and thermochemical storage which is seen in Fig.1.2. All of them have advantages and disadvantages. For instance, the thermal storage power of sensible storage is not high but the design of those systems is very easy. Thermochemical energy storage is also attractive and have high thermal storage power but their design is difficult and many problems were reported for these systems (Demir et al. (2008)).

Advantages of the solid/liquid thermal storage can be described as

- Among different methods, the application and practical use of latent heat storage especially solid/liquid storage make them attractive.
- They can store or release huge energy in a limited volume during the melting or

solidification period.

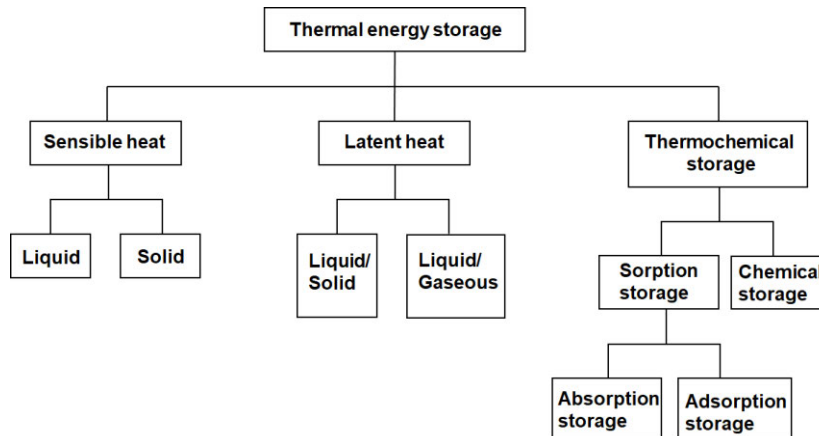


Fig.1.2 The classification of thermal energy storage

- They can allow the equipment working in any required temperature range to improve the performance.
- The principle working of solid/liquid thermal storage system is very simple and cheap compared to the chemical thermal storage. It does not have any moving part and have a very long working life time.

The disadvantages of the solid/liquid thermal storage can be described as

- The thermal conductivity and thermal diffusivities of PCM are low and some methods are required to improve their thermal conductivity.
- The performance of the thermal energy storage is not constant for entire process, it is very high at the beginning and then decreases by time.

1.2 Heat transfer enhancement in solid/liquid phase change

One of difficulties of solid/liquid phase change is the low thermal conductivity of PCM. Table 1.1 shows a list of some PCMs and their thermal conductivity and diffusivity values. As it can be seen, these values are very low for many phase change materials. The

definition of the energy storage is a device which can produce the energy at one time and use the energy for another later time. Thermal storage power depends on two parameters as solid/liquid latent heat and melting and freezing time. Latent heat of solid/liquid phase change of material is almost fix and it is not easy to change it while the time of the process can be changed. If the processing time is reduced, the power will increase.

Table 1.1 A list of some PCMs and their thermal conductivity and diffusivity values

PCM materials	Thermal conductivity (W / mK)	Thermal diffusivity (m^2 / s)
Docosane (Feng et al. (2015))	0.4	1.76×10^{-7}
Sodium nitrate (Yang et al. (2015))	0.514	1.63×10^{-7}
Paraffin RT35 (Esapour et al. (2018))	0.2	1.3×10^{-7}
Binary carbonate (Xu et al.(2018))	0.6	1.88×10^{-7}
Succinonitrile (Zhao et al. (2016))	0.223	1.15×10^{-7}
Lauric acid (Deng et al. (2017))	0.22	1.15×10^{-7}
Water (Li et al.(2018))	0.6	1.44×10^{-7}

In order to decrease the processing time, the thermal conductivity and thermal diffusivity of the PCM should be increased. Literature survey shows that the enhancement of heat transfer can be done by thee methods as using fin, nanoparticle and high conducive porous media (see Fig. 1.3). Many studies in literature on these methods have been done and reported. Each method has advantages and disadvantages. For instance, fin enhances heat transfer in PCM just for specific region, in other words heat transfer is enhanced only in the region around the fins. However, it is very simple and cheap method. Nanoparticle technology which is a new technology may be also attractive, but particles are not connected to each other and this reduces the heat transfer enhancement. That is why, the best method for enhancing of heat transfer might be consolidated porous media having high porosity and high thermal conductivity.

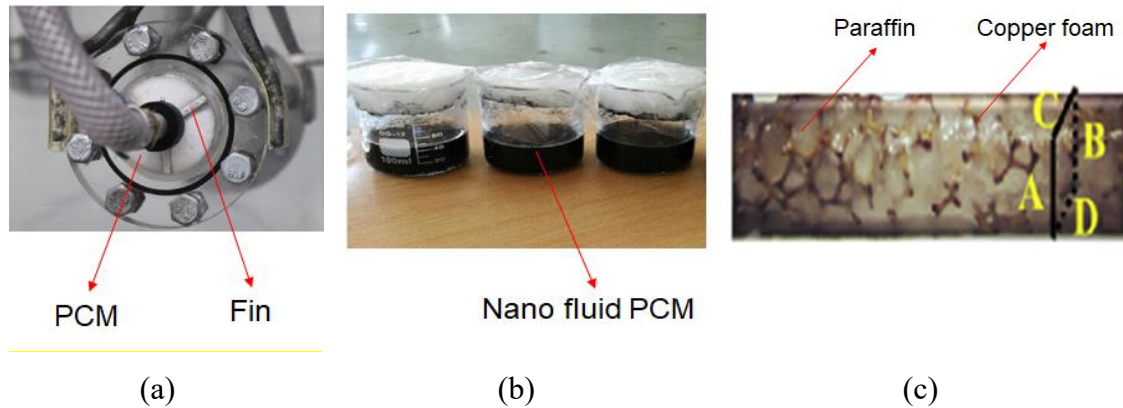


Fig. 1.3 Three main methods for heat transfer enhancement of PCM (a)by using fins (Rozenfeld et al. (2015)) (b)by using Nano metal particles (Munyalo et al. (2018)) (c)by using high thermal conductive metal foam (Yao et al. (2018))

Consolidated high conductive porous media has many advantages such as:

- Increasing thermal conductivity and diffusivity in the entire domain
- Increasing the interface area between the solid and PCM
- Recent technologies (laser printer) helps designer to produce 3D printer based on the requirement.

Based on these advantages, recently a lot of studies have been done to enhance heat transfer in PCM by using porous media. The performed studies on this topic is discussed in Chapter 2.

1.3 Heat and fluid flow in porous media

A porous medium is a composite material containing voids and solid phase. The voids can be interconnected (open pore) or unconnected (closed pore, isolated pore). In the heat and fluid flow area, porous media can be used in many areas such as thermal insulation, heat transfer enhancement, biology material, underground water flowing and so on.

There are two kinds of analyzing of heat and fluid flow in porous media as Pore Scale and Volume Average Method. Furthermore, an important assumption in heat and fluid flow in porous media is local thermal equilibrium assumption. Discussion about Pore Scale and Volume Average and also Local Thermal Equilibrium and Non-equilibrium are

done in this section.

1.3.1 Pore scale and volume average methods

There are two main approaches which can be used to find temperature distribution and consequently heat transfer rate through a porous medium. The first one is called as Pore Scale Method (PSM) in which the governing equations for the solid or fluid are solved directly. The velocity, temperature and pressure fields are obtained precisely. Practically, the application of PSM is difficult due to the large numbers of pores in a porous medium. Volume Averaged Method (VAM) can overcome this difficulty. The governing equations can be integrated over a representative volume of porous media and the volume averaged governing equations (i.e., macroscopic governing equations) can be obtained. Consequently, the discontinuity of phases can be removed. The solution of volume averaged governing equations requires the knowledge of volume averaged transport properties of porous media. The volume average transport properties for heat and fluid flow are permeability, inertia coefficient, effective thermal conductivity for the solid and fluid phases and interfacial heat transfer coefficient. These parameters can be calculated experimentally or computationally. The computational determination of these parameters are described in the studies of (Celik et al, 2019, 2020). In this study, computational method is used to calculate thermal conductivity of the PCM assisted porous media and permeability through the porous media.

1.3.2 Local thermal equilibrium/ Local thermal non-equilibrium

There are also two main methods for the analysis of solid/liquid phase change in a porous medium as local thermal equilibrium and local thermal non-equilibrium approaches. In the local thermal equilibrium, it is assumed that the difference of pore scale temperature between the solid and fluid is considerably smaller than macroscopic temperature difference, hence one heat transfer equation can be used to calculate temperature distribution in the entire domain. As it will be shown in literature survey, although the local thermal equilibrium assumption was widely used in literature, the obtained results may be questionable since the solid/liquid phase change is a transient heat transfer process in which the speed of heat propagation in the porous media and PCM may be considerable different.

There are difficulties in the volume average local thermal non-equilibrium approach such as determination of the effective thermal conductivities of the solid and fluid phases, interfacial heat transfer coefficient, thermal dispersion, porosity and inertia coefficient that should be known precisely. Although literature survey indicates that the use of volume average method for the phase change in a high conductive porous medium has many advantages, the accuracy of the results may be questionable since the results strongly depend on the volume average transport parameters. Hence, further studies are required to find out the mechanism of heat and fluid flow during phase change in a porous medium in order to obtain accurate results

Two important volume average parameters for heat and fluid flow are effective thermal conductivity and interfacial heat transfer coefficient. Both of them can be calculated numerically and experimentally, however experimental determination of these parameters are very difficult, that's why computational studies are used widely. These days, by development of computer technology and also computational methods, it is possible to calculate these parameters computationally.

1.4 The aim of study

Many studies have been performed on the solid/liquid phase change in porous media. A list of studies will be given in Chapter 2. Many reported studies are done by using the pore scale and volume average methods, but to the best of our knowledge *no serious research on the validation of the results of volume average*. Furthermore, the local thermal equilibrium and local thermal non-equilibrium approaches are used widely in the studies on the solid/liquid phase change in porous media, but *again to the best of our knowledge no study explained how to separate the local thermal equilibrium and local thermal non-equilibrium problem*. If a wrong approach is used in a research study, the obtained results may be questionable. The convection interfacial heat transfer coefficient is an important parameter in the local thermal non-equilibrium approach. Most of the studies used single phase convective heat transfer correlation in porous media for determination of interfacial heat transfer coefficient, *however to the best of our knowledge again no study has searched about the validity of these correlations or at least to analyze which one gives more accurate results*.

As can be seen from the above paragraph, there are some gaps in the field of enhancement of heat transfer by using high conductive porous media. The aim of this study is to fill those gaps for the future researchers and to provide more accurate results for the optimization or innovative design of solid/liquid heat exchangers. Therefore, the aim of this study can be expressed as:

- (a) to compare the pore scale and volume averaged approaches in phase change problems in order to prove that the volume averaged method is an appropriate technique for solving solid/liquid phase change assisted with metal foam.
- (b) to prove Sparrow number is a governing parameter, and establish a new chart for the separation of local thermal equilibrium from non-equilibrium by using governing parameters.
- (c) to determine the change of interfacial heat transfer coefficient through the process and then compare with correlations reported in literature and discuss their accuracy.

Based on those aims, this study has been done.

1.5 The outline of thesis

The thesis consists of 8 chapters. In the first chapter which is Introduction, the background and importance of the topic and the aim of study are explained. In the second chapter, some literature studies will be given in details. The chapter 3 is considered problem, the three considered problems will be explained. The thermo-physical properties of considered domain and materials are clarified in detail. In chapter 4, the general form of the governing equations for finding the velocity, pressure and temperature in 2D closed cell porous media and 3D cubic lattice metal frame are given. Assumptions for the problem is also given in the same chapter. The initial and boundary conditions and heat transfer between the solid and liquid phase also are discussed in this chapter. The dimensionless governing equations for the single phase flow and the problem of solid/liquid phase change are given for the closed and open cell porous media in chapter 5. These equations are pore scale and volume average equations which are explained in

this chapter. All dimensionless parameters are presented and physical meaning of these parameters describe in the same section. Computational details and grid independency are given in chapter 6. Determination of effective thermal conductivity and porosity for the studied porous media are described. The solution method and mesh grid for slurry region both are also explained in this section. Then the results and discussion of this study will be shown in chapter 7. All results are supported by graphs and it has been tried to find concrete and usable results. Based on the performed 3 studies the conclusion is presented in chapter 8.

Chapter 2

Literature survey

There are many studies referring to the solid/liquid phase change in porous media in literature. Around 60 papers about the melting in the porous media were found. It is tried to classify them and discuss them. Table 2.1 shows the list of the found papers. In the first column, the name of researchers and publication year are written. As it was mentioned in the introduction part, there is an important assumption for researches who study on the phase change in porous media as local thermal equilibrium or local thermal non-equilibrium. In the second column the employed assumption in the study is written. In the third column, the porous media and PCM material are written. The type of study (numerical or experimental) is described in column 4. Porosity is an important issue, that is why it is also found in the studies and mention in column 5. Finally, the solution method and a view if the studied domain is added in column 6 and 7 respectively. Based on the number of studies, diagrams are plotted and discussed.

2.1 Classification of the studies respect to materials

Fig. 2.1 shows the number of study employed PCM materials. As it can be seen, the paraffin wax is popular to be used as PCM. For instance, Mancin et al. (2015) did an experimental analysis of phase change phenomenon of paraffin waxes embedded in copper foams. A picture of their experiment is shown in Fig. 2.2. Jin et al. (2017) did a visualized study at the pore-scale carried out to explore the pore size effects on melting heat transfer of a paraffin wax saturated in a copper foam and used. Buonomo et al. (2017) performed a numerical study on the thermal behaviors of two-dimensional latent thermal energy storage with PCM and aluminum foam and used Paraffin (paraffin RT58) as PCM. Zhao et al. (2010) did an experimental investigation on the solid/liquid phase change (melting and solidification) processes and Paraffin wax RT58 was used as PCM. Other studies can be found from the Table 2.1 and literature. Paraffin wax is a good PCM because it has wide range of freezing and meting temperature generally above the $0\text{ }^{\circ}\text{C}$ (environment temperature). It can be used for solar application, air conditioning etc.

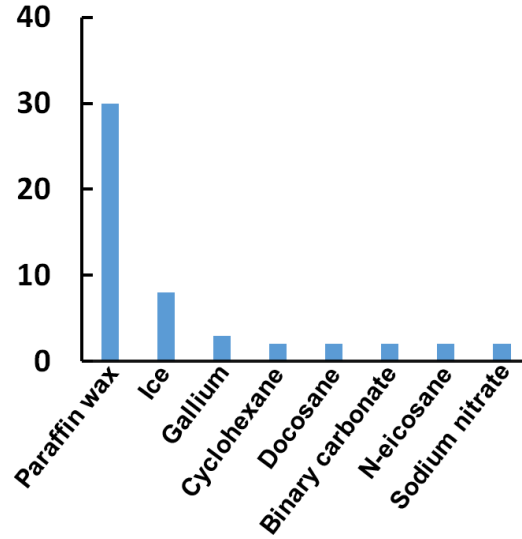


Fig. 2.1 The employed PCM materials

It is a safe material and cheap. Paraffin can be frozen without super cooling. For example, the paraffin wax RT35H, its latent heat is around 240 kJ/kg which is not bad value and the melting point temperature changes between 34 and 36°C . Ice is the second material used in the studies. The problem of ice is the melting (or freezing point is low) and it can be used for the specific application. Gallium is another PCM candidate because of its excellent thermal properties such as the low melting point, high thermal conductivity, large specific heat and small volume change. Cyclohexane, docosane, binary carbonate, n-eicosane and sodium nitrate are the other materials used in reported the studies.

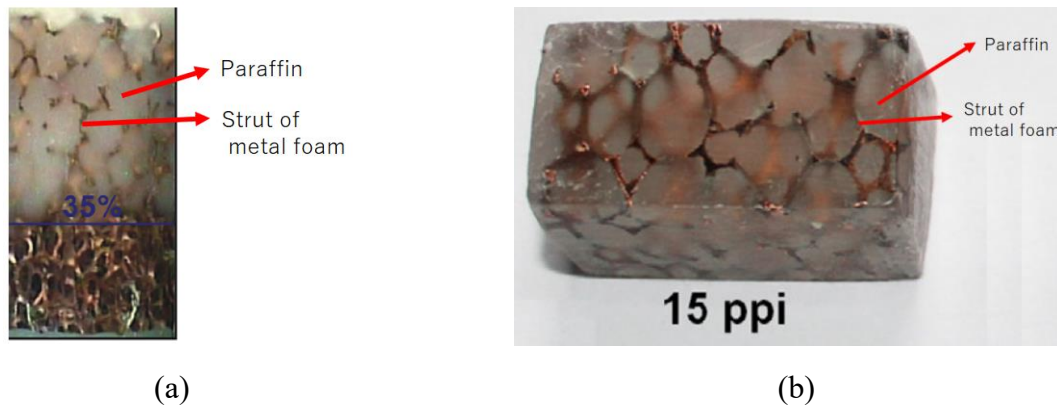


Fig. 2.2 Two views of two different researchers used paraffin as PCM and copper foam as porous media for heat transfer enhancement, a) Mancin et al. (2015), b) Jin et al. (2017)

Fig. 2.3 shows the number of studies employed different porous materials. The Aluminum foam and Copper foam are used commonly since they have the high thermal conductivity which can accelerate the phase change process. For example, Yao et al. (2018) in Fig. 2.4 performed a direct numerical simulation of interfacial heat transfer coefficient between paraffin and high porosity open cell metal foam which is copper foam.

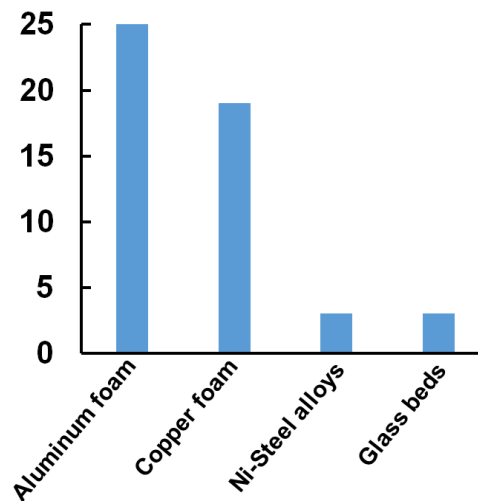


Fig. 2.3 The employed porous media

Feng et al. (2015) did a numerical work on Pore-scale and volume-averaged numerical simulations of melting phase change heat transfer in finned metal foam. They used Aluminum metal foam - Docosane as porous media and PCM, respectively. Li et al. (2012) did an experimental and numerical studies on melting phase change heat transfer in open-cell metallic foams filled with paraffin. The material of open cell metal foam was copper. Wang et al. (2020) studied on the numerical study on acceleration of melting process under forced convection by using high thermal conductive porous media and used aluminum foam –water in their studies. Jourabian et al. (2016) studied heat transfer enhancement of PCM melting in 2D horizontal elliptical tube using metallic porous matrix which was Nickel steel open foam. They performed their studies both numerically and experimentally. Other studies can be seen from Table 2.1.

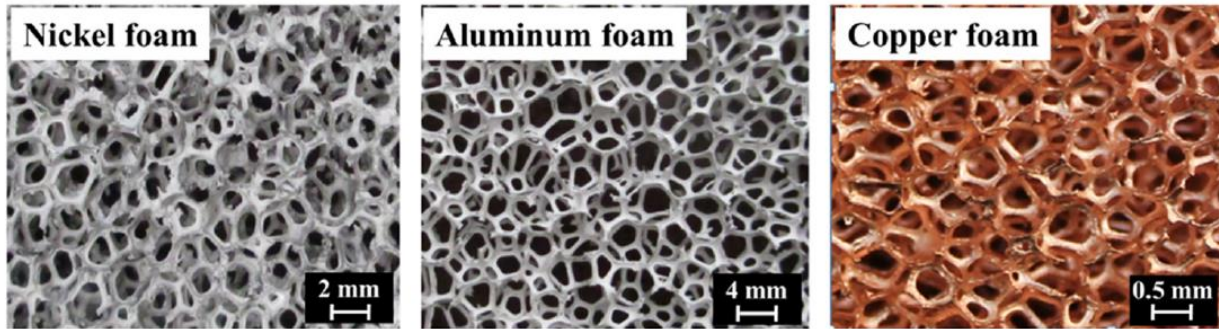


Fig.2.4 Three metal foams with different material and Pore Per Inch (PPM) (Yao et al. 2018)

The number of studies by using Aluminum foam is more than that of Copper foam, probably due to the price of copper that is more expensive compared to aluminum. Besides, Ni-steel alloys and glass beds also are the options used as porous media material.

In Fig. 2.5, the number of study employed the pair of porous media and PCM materials in literature is presented. As seen from this figure, the people preferred to use Paraffin wax /Aluminum foam and Paraffin wax /Copper foam in their studies. As we discussed before, the Paraffin wax is safety, cheap and easy to control during the phase change process. Furthermore, the Aluminum foam and Copper foam have the high thermal conductivity which can accelerate the phase change process. That is why, the couple of Paraffin wax /Aluminum foam and Paraffin wax /Copper foam are widely used for research.

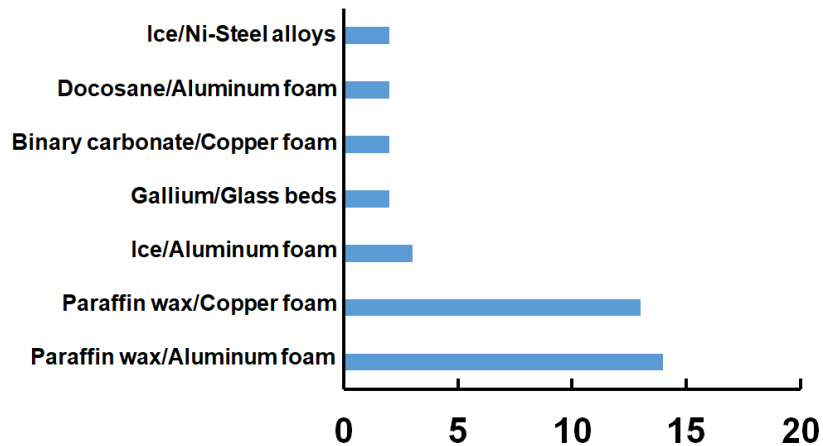


Fig. 2.5 The employed porous media and PCM materials

2.2 Classification respect to numerical and experimental studies

The number of experimental and numerical studies are shown in Fig. 2.6. For instance, Gao et al. (2017) performed a numerical study and proposed a modified lattice Boltzmann (LB) model for simulating melting of phase change materials in porous media with a conducting fin. Hu et al. (2015) investigated a numerical study of heat transfer in open cell micro foam with phase change material. Liu and He (2015) did a study on a double multiple relaxation time lattice Boltzmann model for solid/liquid phase change with natural convection in porous media numerically. Mancin et al. (2015) presented an experimental study of the solid/liquid phase change process of three natural paraffin waxes.

As can be seen, the number of numerical studies are higher than experimental studies. The number of studies that used both numerical and experimental works are also limited. The reason for this trend of studies type is difficulties in experimental studies. The change of density by melting or freezing and consequently leakage problem is one of them. Due to observation in the domain, boundary conditions change since the sight glass part cannot be insulated. Furthermore, it is not easy to measure temperature inside the domain since thermocouples should be inserted and this make leakage problem. Although, the numerical studies seem easy, but finding accurate result is not easy and required to discuss many assumptions. As it was mentioned before, this is one of the aims this study.

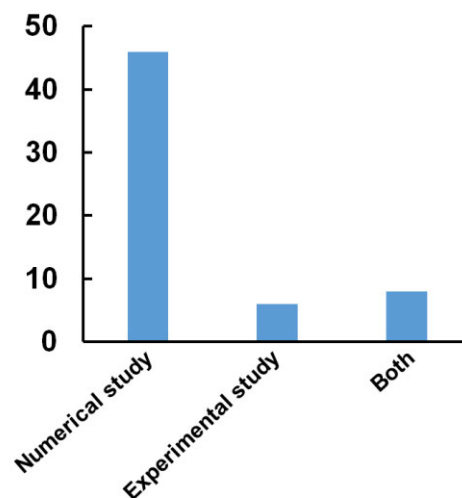


Fig. 2.6 The number of experimental and numerical studies

2.3 Classification respect to pore scale and volume average methods

There are commonly two methods to solve the problem of solid /liquid phase change in porous media which are pore scale and volume average methods. Just for example, for the pore scale study of Li et al. (2018) who did a pore scale investigation of gravity effects on phase change heat transfer characteristics using lattice Boltzmann method. For the volume average studies such as Buonomo et al. (2019) preformed a numerical study on latent thermal energy storage systems with aluminum foam by using the volume average method. Chen et al. (2010) also used the volume average method to do a heat transfer performance analysis of a solar flat-plate collector with an integrated metal foam porous structure filled with paraffin.

In Fig.2.7, based on the literature survey we found, the number of volume average study is around 5 times greater than pore scale study, which means the volume average method is more popular than pore scale method. Even though the pore scale method can provide the accurate result, when the size of domain is large, the use of pore scale approach is difficult and the volume average method is employed, that's why that the volume average method is applied in many research studies.

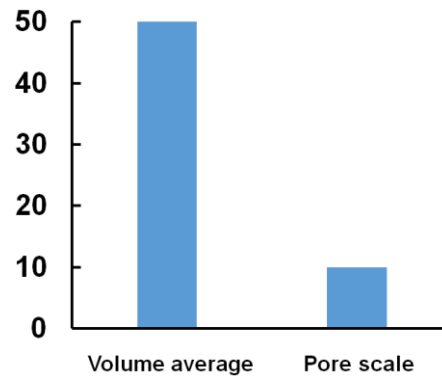


Fig. 2.7 The number of pore scale vs volume average studies

2.4 Classification respect to local thermal equilibrium and local thermal non-equilibrium

As it was mentioned in the introduction chapter, one of main assumption used in the heat and fluid flow in porous media is the assumption of local thermal equilibrium. In the study of Wu et al. (2017), they applied a local thermal equilibrium assumption for the phase change with convection heat transfer in porous media. Gopalan and Eswaran (2016) investigated the thermal performance

of PCM using porous media by applying a local thermal equilibrium assumption. There are also some studies which applied the local thermal non-equilibrium assumption. For instance, a local thermal non-equilibrium assumption is applied in the study of Li et al. (2017) who investigated the supergravity effects on charging process. Joshi and Rathod (2019) performed a study on Thermal performance augmentation of metal foam infused phase change material using a partial filling strategy by using a local thermal non-equilibrium assumption. Fig. 2.8 shows number of studies who used local thermal equilibrium and local thermal non-equilibrium. As is seen, almost half of the researchers were used local thermal equilibrium without proving that local thermal equilibrium exists in their studies. As the result, the correctness of the results for that case may be questionable. One of the aim of this study is to find a parameter or parameters to understands local thermal equilibrium or non-equilibrium at the beginning.

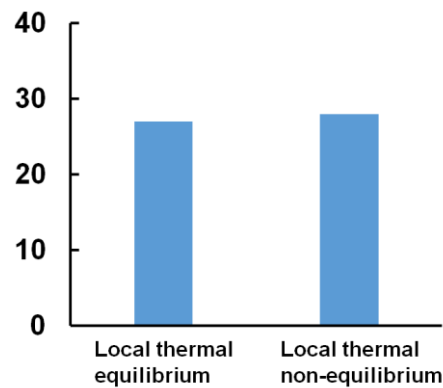


Fig. 2.8 The number of Equilibrium and non-equilibrium studies

2.5 Classification respect to the range of porosity

Porosity is one important parameter in porous media. There is no doubt by decreasing of porosity, the amount of the PCM decreases and consequently the storage power decreases. Fig. 2.9 is adapted from the study of Ali et al. (2018), as it can be seen by changing of the porosity the permeability value is also changed for metal foam. For the high values of porosity (92%), the large voids exist and the fluid flows freely while for the low values of porosity (76%), the amount of metal is high and permeability becomes smaller.

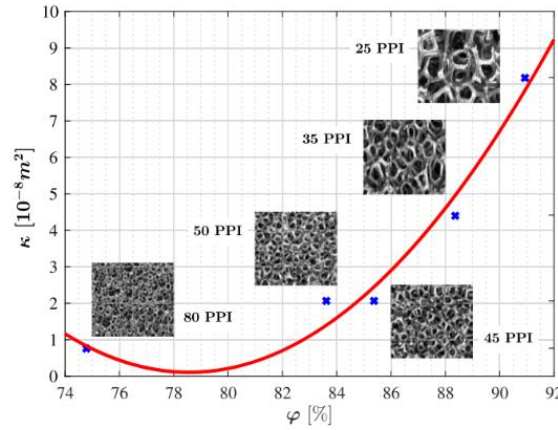


Fig. 2.9 The roughness of the four porous materials based on the measured porosity of the uncompressed metal samples

That is why many studies have been done for high values of porosity between 0.8 to 1.0 as can be seen in Fig.2.10. For instance, copper foam with a high porosity of 0.974 is used as porous media in the study of Yao et al. (2018), and the copper foam also is adopted in the experimental study of Guo et al. (2018), and the porosity of copper foam is 0.96. Studies on low porosity were done on special cases such as to develop mathematical formulations. For example, the study of Beckermann and Viskanta (1988) who did an experimental and numerical study of solid/liquid phase change in porous media with natural convection and used the gallium and glass beds as the fluid and porous matrix whose porosity is 0.385. Also in the study of Change and Yang (1996), they investigated the transient behavior and heat transfer for the melting of ice in porous media within a rectangular enclosure. The constant porosity of porous media is used by 0.4.

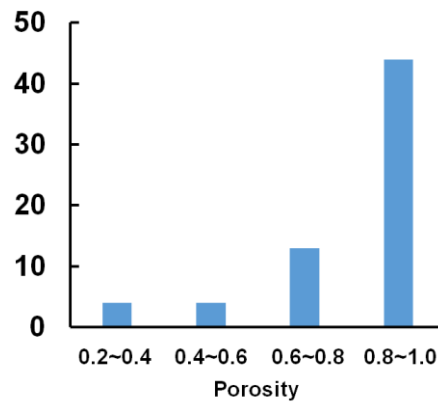
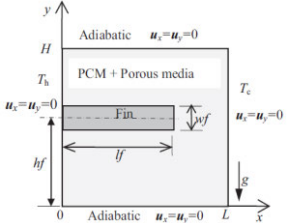
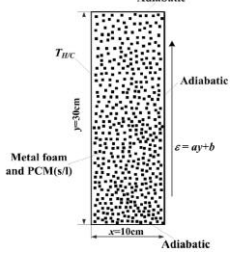
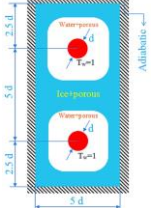
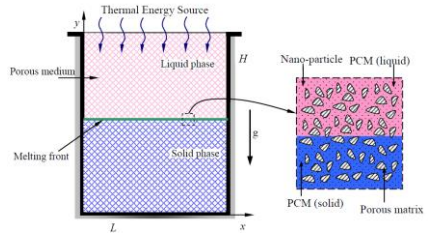
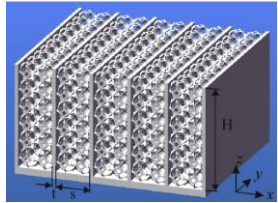
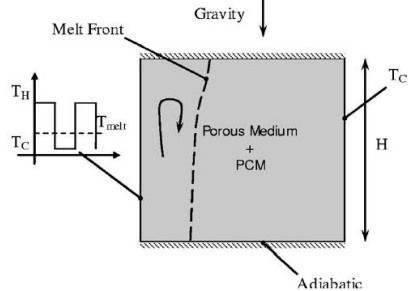
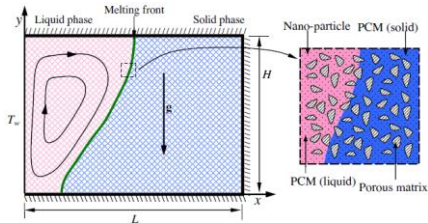


Fig. 2.10 The range of porosity

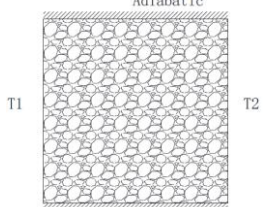
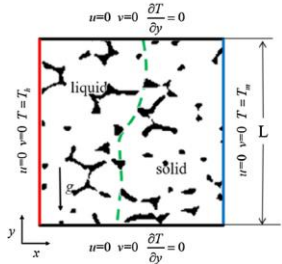
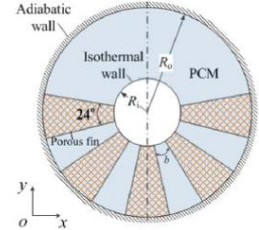
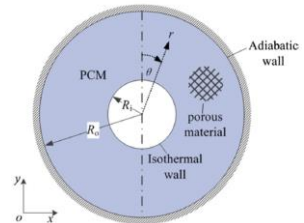
Table 2.1 The list of literature survey

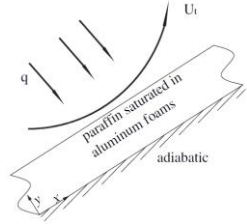
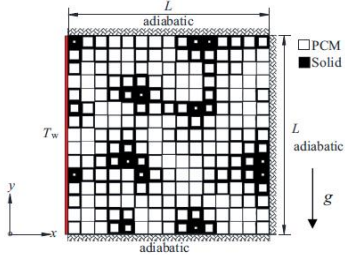
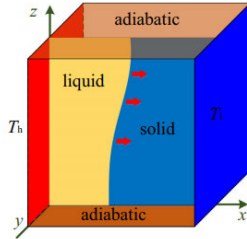
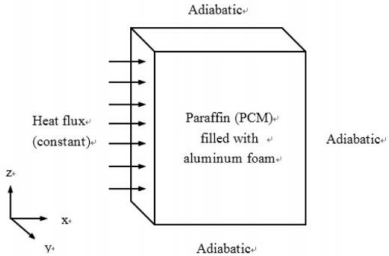
Name of researchers and publications year	Equilibrium / Non-equilibrium	Phase change / Porous media materials	Numerical / Experimental	Porosity	Solution method	Considered domain
Buonomo et al. (2016)	Non-equilibrium	Paraffin wax / Aluminum foam	Numerical	0.8 and 0.9 with 20 PPI	Enthalpy-porosity method	
Gao et al. (2017)	Equilibrium	---	Numerical	0.9	Enthalpy-based lattice Boltzmann method	
Yang et al. (2015)	Equilibrium	Sodium nitrate / Copper foam	Numerical	0.9, 0.92 and 0.88	Enthalpy-porosity method	
Jourabian et al. (2018a)	Equilibrium	Ice / Ni-Steel alloys porous matrix	Numerical	0.6-0.8	Enthalpy-based lattice Boltzmann method	

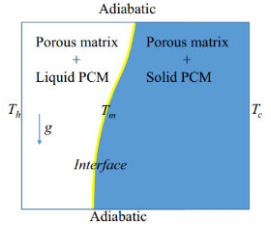
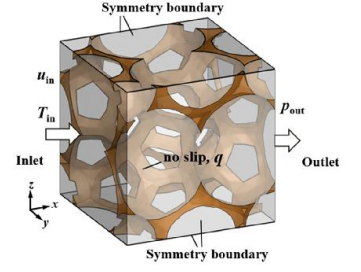
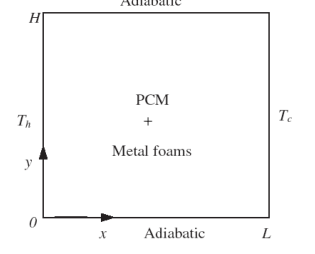
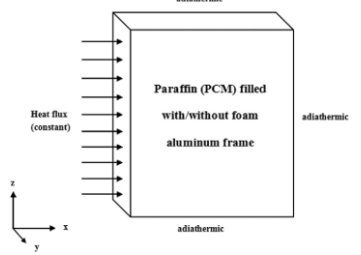
Jourabian et al. (2018b)	Equilibrium	Ice / Nickel-Steel alloys porous matrix	Numerical	0.9 and 0.95	Enthalpy- based lattice Boltzmann method	
Al-Jethelah et al. (2016)	Equilibrium	Al2O3 nanoparticles- Water/ Aluminum foam	Numerical	0.98	---	
Mesalhy et al. (2005)	Non- equilibrium	---	Numerical	0.95, 0.9 and 0.85	Enthalpy- porosity method	
Liu and He (2015)	Equilibrium	---	Numerical	---	Enthalpy- based method	

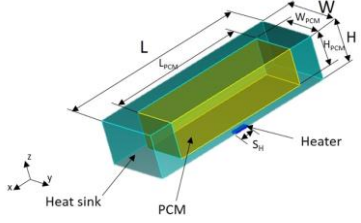
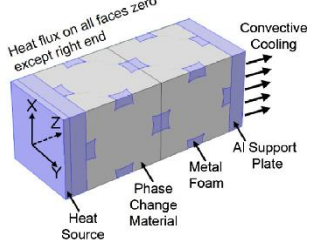
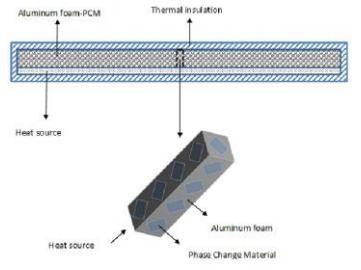
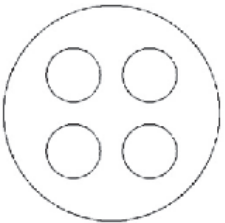
Hossain et al. (2015)	Equilibrium	Cyclohexane + CuO nanoparticle/ Aluminum solid matrix	Numerical	0.95 and 0.85	---	
Feng et al. (2015)	Non-equilibrium	Docosane/ Aluminum foam	Numerical	0.97	Enthalpy-porosity method	
Krishnan et al. (2007)	Non-equilibrium	---	Numerical	0.8	Enthalpy method	
Tasnim et al. (2015)	Equilibrium	Cyclohexane +CuO nanoparticle/ Aluminum solid matrix	Numerical	0.9	---	

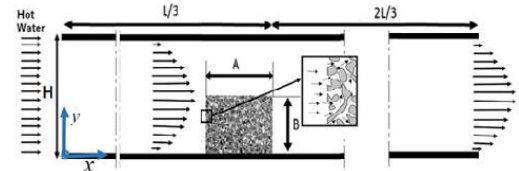
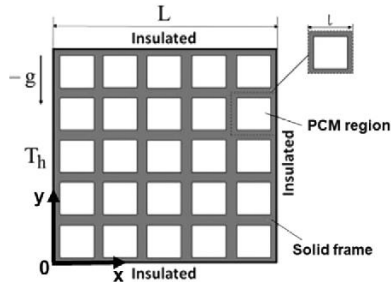
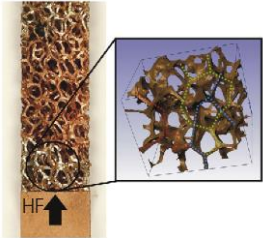
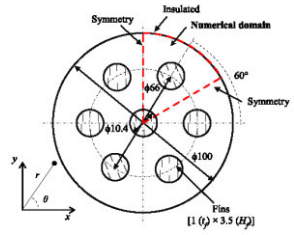
Taghilou et al. (2018)	Equilibrium	RT28HC and RT35/ Aluminum foam	Numerical	0.8	Enthalpy- porosity method	
Zhao et al.(2010)	Non- equilibrium	Paraffin wax RT58/Copper foam	Both	0.95	Enthalpy method	
Li et al. (2012)	Non- equilibrium	Paraffin wax /Copper foam	Both	0.9, 0.95 and 0.98	Enthalpy- porosity method	
Hu et al. (2015)	Non- equilibrium	Docosane/ Aluminum foam	Numerical	0.757	Enthalpy- porosity method	

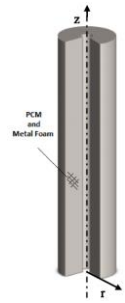
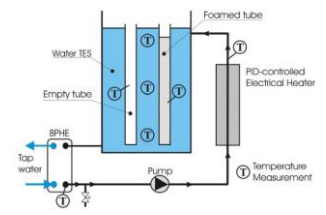
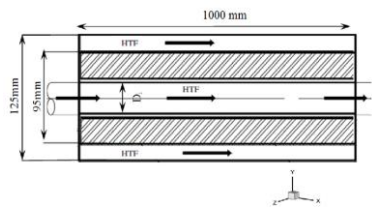
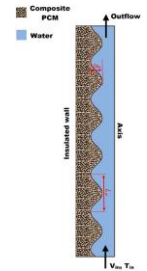
Huang et al. (2016)	Non-equilibrium	Paraffin wax / Aluminum foam	Numerical	0.522 and 0.778	Enthalpy method	
Li et al. (2018)	Non-equilibrium	Water/metal foam	Numerical	0.9	Enthalpy-based method	
Xu et al. (2018)	Equilibrium	Binary carbonate/ Copper foam	Numerical	0.95 with 10PPI	Enthalpy method	
Xu et al. (2017)	Equilibrium	Binary carbonate/ Cu, SiC, Ni, Al ₂ O ₃ metal foam	Numerical	0.9486 with 10PPI	Enthalpy method	

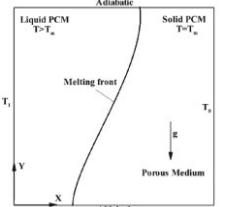
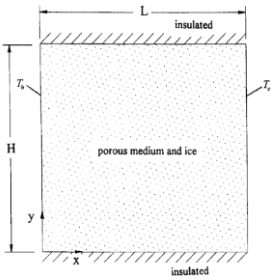
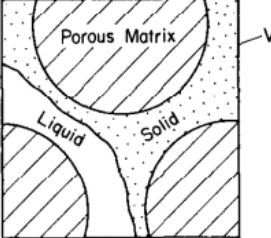
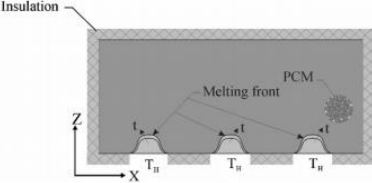
Chen et al. (2010)	Non-equilibrium	Paraffin wax / Aluminum foam	Numerical	0.9	Apparent heat capacity method	
Deng et al. (2017)	Equilibrium	Lauric acid/ Aluminum	Both	0.6, 0.7 and 0.75	Enthalpy-porosity method	
Li et al. (2017)	Equilibrium	---	Numerical	---	Enthalpy method	
Zhang and He (2017)	Non-equilibrium	Paraffin wax / Aluminum foam	Both	0.966, 0.934 and 0.884	Enthalpy method	

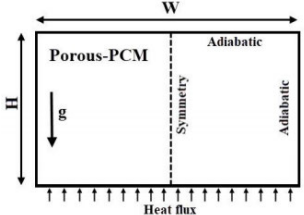
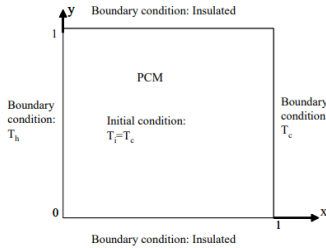
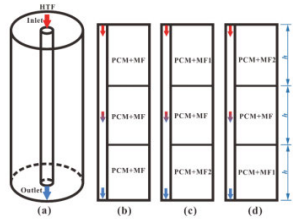
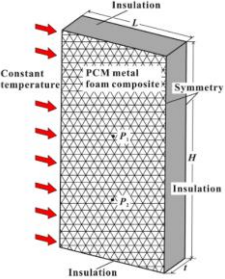
Wu et al. (2017)	Equilibrium	---	Numerical	---	---	
Yao et al. (2018a)	Non-equilibrium	Paraffin /metal foam	Numerical	0.929 and 0.974	Enthalpy method	
Chen et al. (2014)	Equilibrium	Paraffin /metal foam	Both	0.9	Enthalpy-based method	
Zhang et al.(2017)	Non-equilibrium	Paraffin wax / Aluminum foam	Both	0.9	Enthalpy method	

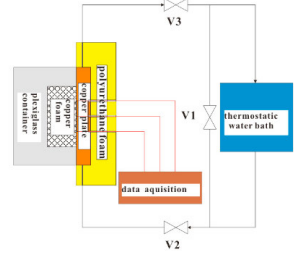
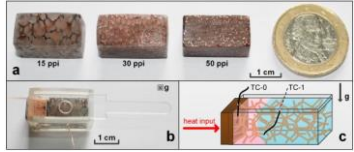
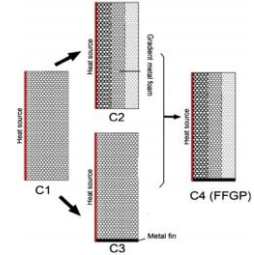
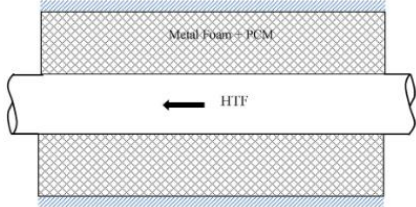
Gopalan and Eswaran (2016)	Equilibrium	N-eicosane/ Aluminum foam	Numerical	0.85, 0.9 and 0.95	Enthalpy- porosity method	
Sundarram and Li (2014)	Equilibrium	Paraffin wax / Aluminum foam	Numerical	0.75, 0.8, 0.84, 0.88 and 0.94	---	
Zhang et al.(2015)	---	Paraffin wax / Aluminum foam	Numerical	0.65, 0.7 and 0.75	---	
Pourakabar and Darzi (2019)	Non-equilibrium	N-eicosane/ Copper foam	Numerical	0.7	Enthalpy- porosity method	

Wang et al.(2020)	Equilibrium	Ice/ Aluminum foam	Numerical	0.9	Enthalpy method	
Wang and Mobedi (2020)	Non-equilibrium	Ice/ Aluminum metal frame	Numerical	0.7 and 0.9	Enthalpy method	
Mancin et al.(2015)	---	Paraffin wax / Copper foam	Experimental	0.95	---	
Kumar and Saha (2016)	Non-equilibrium	Organic material A164/Stainless steel	Numerical	0.85, 0.9, 0.95 and 0.97	Enthalpy method	

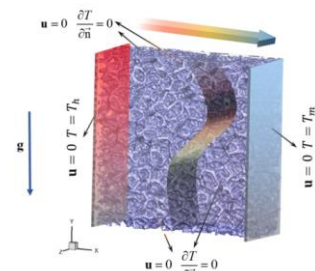
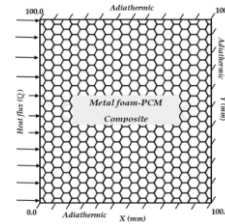
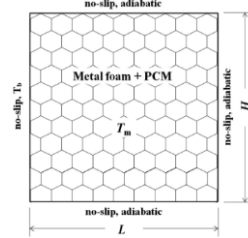
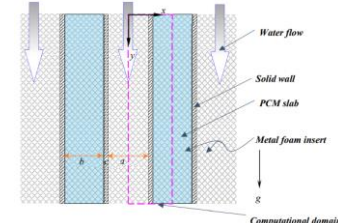
Buonomo et al.(2019)	Equilibrium	Paraffin RT58/ Aluminum foam	Numerical	0.80, 0.85, 0.90, 0.95, 0.97 and 0.99	Enthalpy- porosity method	
Righetti et al.(2019)	---	Paraffin wax / Aluminum foam	Experimental	0.92	---	
Esapour et al.(2018)	Non-equilibrium	Paraffin wax RT35 / Aluminum foam	Numerical	0.7and 0.9	Enthalpy- porosity method	
Shahsavari et al.(2019)	Equilibrium	Paraffin wax RT35 / Copper foam	Numerical	0.95	Enthalpy- porosity method	

Jourabian et al. (2016)	Equilibrium	Paraffin wax/ Nickel steel porous matrix	Numerical	0.85 and 0.95	Enthalpy method	
Change and Yang (1996)	Equilibrium	Ice/Porous media	Numerical	0.4	---	
Beckermann and Viskanta(1988)	Equilibrium	Gallium/glass beds	Both	0.385	Enthalpy- porosity method	
Rattanadecho(2006)	Equilibrium	Ice/glass beds	Numerical	0.38	---	

Sardari et al.(2019)	Equilibrium	Paraffin wax RT58 / Copper foam	Numerical	0.95	Enthalpy- porosity method	
Damronglerd and Zhang(2010)	Equilibrium	Gallium/glass beds	Numerical	0.385	---	
Wei et al.(2019)	---	Paraffin wax RT35 / Copper foam	Numerical	0.9, 0.94 and 0.98	---	
Yang et al.(2018)	Non- equilibrium	Paraffin wax / Aluminum foam	Numerical	0.9	---	

Guo et al.(2018)	Non-equilibrium	Paraffin wax / Copper foam	Experimental	0.96	---	
Jin et al.(2017)	Non-equilibrium	Paraffin wax / Copper foam	Experimental	0.95	---	
Zhu et al.(2017)	Non-equilibrium	Sodium acetate/ Aluminum foam	Numerical	---	Lattice Boltzmann method	
Mahdi and Nsofor (2018)	Equilibrium	Paraffin wax RT55 / Aluminum foam	Numerical	0.95	Enthalpy-porosity method	

Yao et al. (2018b)	Non-equilibrium	Paraffin wax / Copper foam	Experimental	0.974	---	
Han et al. (2012)	Non-equilibrium	Paraffin wax / Copper foam	Numerical	0.95	---	
Giorgio et al. (2016)	Non-equilibrium	Paraffin wax / Aluminum foam	Both	0.85 and 0.95	---	
Hussain and Jasim (2017)	---	Paraffin wax RT58 / Copper foam	Experimental	0.9	---	

Li et al. (2019)	Non-equilibrium	Gallium/ Copper foam	Numerical	0.88	Enthalpy method	
Joshi and Rathod (2019)	Non-equilibrium	Paraffin wax / Copper foam	Numerical	0.9, 0.92, 0.95 and 0.97	Enthalpy-porosity method	
Zhao et al. (2016)	Non-equilibrium	Succinonitrile/Copper foam	Numerical	0.9	Enthalpy method	
Chen et al. (2019)	Non-equilibrium	Paraffin wax RT58 / Copper foam	Numerical	0.9	Enthalpy-porosity method	

Chapter 3

The considered problems

As it was mentioned before, in this thesis four problems were studied. These problems are explained in this chapter separately. The explanation for each problem is supported with schematic view.

3.1 Studied problem 1

The schematic views of the considered pore scale domain and volume averaged domain for the problem 1 are shown in Fig. 3.1.1. Both the pore scale and volume average domains are described below. Pore scale domain: The porous media is a square domain with length of L . The details of closed cells can be seen in the Fig. 3.1.1 (a). It consists of 25 square closed cells with the length of l . The cells are not connected to each other while the solid phase (i.e. aluminum frame) interconnected in the entire domain. The top and bottom surfaces of the porous media are insulated and the left and right vertical surfaces are maintained at constant temperature of T_h and T_c , respectively. The gravity affects in $-y$ direction and the radiation heat transfer is neglected. The working fluids are water and air and their thermal properties are given in the Table 1. The density, specific heat capacity and thermal conductivity of the solid phase, which is aluminum alloy, are $2700(\text{kg/m}^3)$, $900(\text{J/kg K})$ and $203(\text{W/m K})$, respectively. Based on the thermophysical properties and the geometry of the studied domain, the value of dimensionless parameters such as Pr_f , Ra_f and ψ are calculated for the studied cases with air and water and given in Table 1. Volume averaged domain: The volume averaged domain is also shown in Fig. 3.1.1 (b). A continuous domain exists for the volume averaged equations since the governing equations are volumetrically integrated. No velocity field exists in the volume averaged domain and the conduction heat transfer is the only mechanism of heat transfer. Volume averaged domain: The volume averaged domain is also shown in Fig. 3.1.1 (b). A continuous domain exists for the volume averaged equations since the governing equations are volumetrically integrated. No velocity field exists in the volume averaged domain and the conduction heat transfer is the only mechanism of heat transfer. The

volume averaged governing equations are non-dimensionalized and a parametric study is performed by changing the dimensionless governing parameters in the range of $0.01 < \Omega_s < 1$, $0.01 < \Gamma_s < 1$ and $1 < Sp < 1000$.

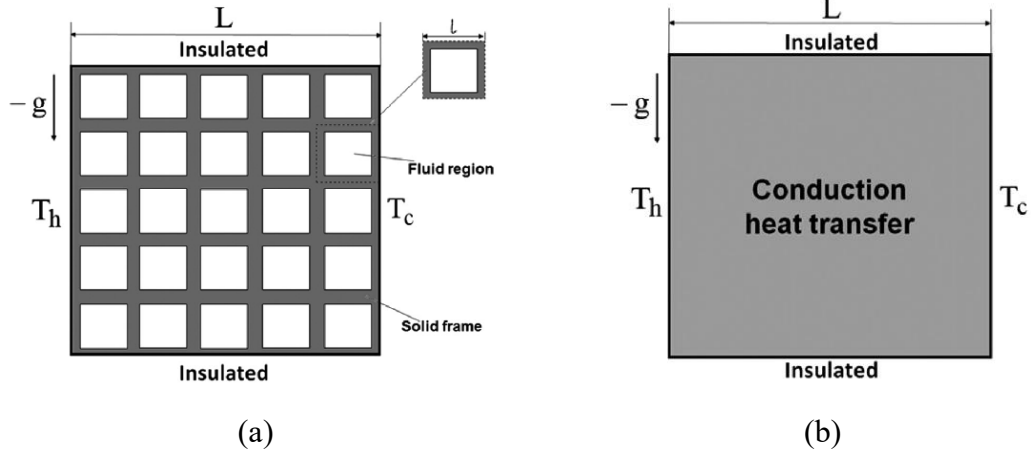


Fig. 3.1.1 The schematic view of the considered study (a) pore scale domain (b) volume averaged domain

3.2 Studied Problem 2

The schematic views of studied pore scale and volume average domains are shown in Fig. 3.2.1 (a). The pore scale domain consists of 25 square closed cells in which PCM exists. All surfaces of the cavity are insulated, except the left vertical surface maintaining at the constant temperature. The gravity affects in $-y$ direction and its effect is included in the pore scale study. The effect of radiation is neglected. The working fluid is water and the solid frame is aluminum with thermal conductivity of 237 W/mK . The occurrence of maximum density of water at 4°C is not include in the formulation. Fig. 3.2.1 (b) shows the volume average domain for the solid and fluid phase, the domain is continuous since the independent parameters are integrated over the entire domain. The study is limited to $Ra_f \leq 10^4$.

3.3 Studied Problem 3

Fig.3.3.1 shows the 3D schematic views of studied porous media and the computational domain. The porous media is a 3D cubic Lattice Metal Frame consisting of the 125 cells. The struts are perpendicular to each other and having the same size for all cells. The voids

of 3D cubic LMF are filled with PCM and the porosity of the porous media is 0.9 . The length of the cavity is 18.7 mm , while the pore size and the strut size are 3 mm and 0.74 mm , respectively.

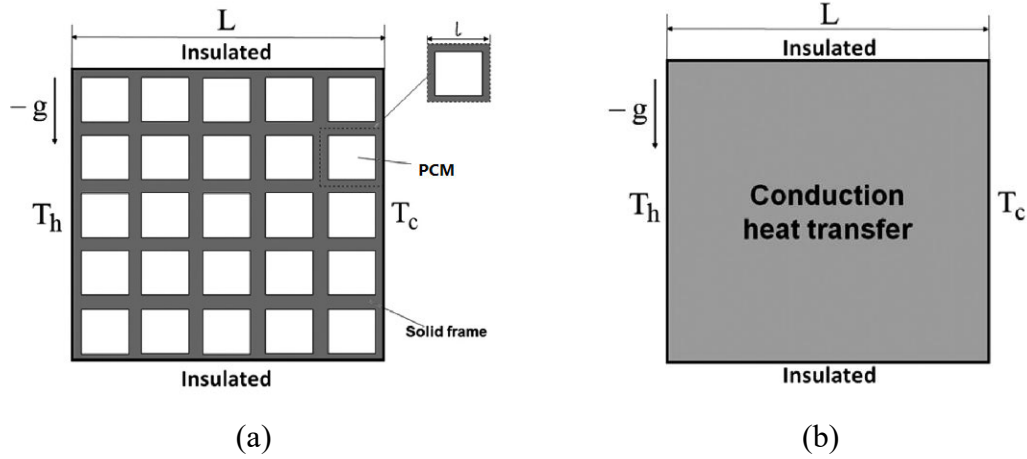


Fig. 3.2.1 The schematic view of the considered study (a) pore scale domain (b) volume averaged domain

The PCM is water and the LMF material is aluminum. The thermophysical properties of frame, water (liquid PCM) and ice (solid PCM) are given in Table 3.1. It is assumed that melting occurs between 273.15 K and 274.15 K . The Stefan number is 0.6 for the entire study and Rayleigh number is changed from 1 to 10^6 .

Table 3.1 Thermophysical properties of PCM and frame material

Parameters	Aluminum	Water	Ice
$\rho\text{ (Kg/m}^3\text{)}$	2700	1000	1000
$k\text{ (W/m K)}$	237	0.61	2.2
$C_p\text{ (J/kg K)}$	900	4180	2000

All surfaces of the porous cavity are thermally insulated, except one surface ($x = 0$) maintained at the constant temperature. For the volume average study, two volume averaged domain exist, one refers to the solid region while the other one belongs to the fluid region. The volume averaged domain is continuous for both solid and fluid temperatures due to the application of the space volume average into the pore scale governing equations. The gravity affects in $-y$ direction and its effect is included into both

the pore scale and volume averaged momentum equations.

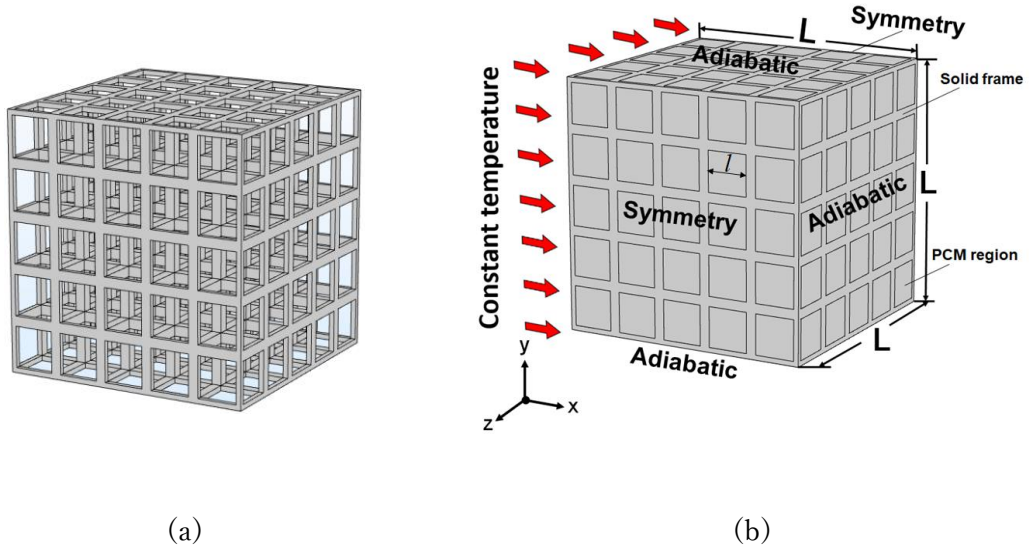


Fig. 3.3.1 The 3D schematic view of the studied domain, a) the employed 3D LMF for heat transfer enhancement, b) the considered porous cavity in which voids are filled PCM

Chapter 4

General form of governing equations for studied problems

In this chapter, the dimensional governing equations for the single phase heat and fluid flow for the porous media and dimensional solid/liquid phase change are given for the porous media. These equations can be classified into two groups as pore scale and volume average equations.

4.1 Single phase flow in porous media

4.1.1 Pore scale governing equations

For the pore scale analysis, the continuity and momentum equations are solved to find the velocity and pressure distributions for fluid moving in the space between solid as shown in Fig. 4.1.1, while the energy equations for the solid and fluid phases are solved to find the temperature distributions for the entire domain. The dimensional form of the pore scale governing equations when the gravity also affect the flow can be written as follows:

$$\vec{\nabla} \cdot \vec{V} = 0 \quad (4.1)$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \vec{\nabla}) \vec{V} = -\frac{1}{\rho_f} \vec{\nabla} p + \nu_f(T) \vec{\nabla}^2 \cdot \vec{V} + g\beta(T - T_{ref}) \vec{j} \quad (4.2)$$

$$(\rho C_p)_f \left(\frac{\partial T_f}{\partial t} + \vec{V} \cdot \vec{\nabla} T_f \right) = k_f(T) \vec{\nabla}^2 T_f \quad (4.3)$$

$$(\rho C_p)_s \frac{\partial T_s}{\partial t} = k_s \vec{\nabla}^2 T_s \quad (4.4)$$

where β and T_{ref} are the volumetric thermal expansion coefficient of working fluid and reference temperature, respectively. The last term in Eq. (4.2) shows the effect of the gravity on flow when the density of the fluid changes by temperature. It is written based on the Boussinesq approximation. In the above equations, it is assumed that thermophysical properties of the fluid does not change by temperature (except density),

the fluid is Newtonian and incompressible.

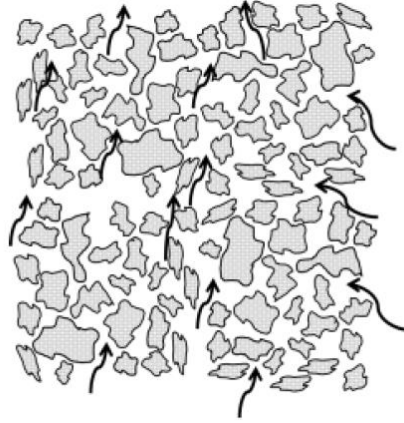


Fig.4.1.1 The schematic view of the pore scale domain

4.1.2 Volume average governing equations

The pore scale analysis provides accurate results for heat and fluid flow in porous media. However, when the size of porous media is large, the use of the pore scale analysis becomes troublesome. That is why, researchers use Volume Average Method for analyzing heat and fluid flow in many porous media problems. For the volume average method, a scalar or vector quantity can be integrated in a representative discontinues space and consequently the continuity of that space can be provided as shown in Fig. 4.1.2.

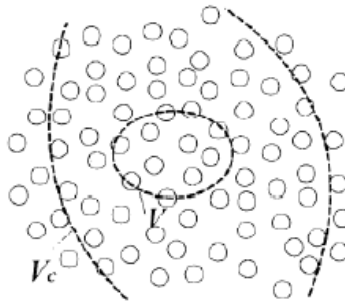


Fig.4.1.2 The schematic view of the volume average domain

Since two phases as solid and fluid exist in the porous media, two volume averaged quantities can be defined:

$$\langle \phi \rangle = \frac{1}{V} \int_V \phi dV \quad (4.5)$$

$$\langle \phi \rangle^x = \frac{1}{V_x} \int_{V_x} \phi dV \quad (4.6)$$

which are called as the volume averaged and intrinsic volume averaged of ϕ quantities, respectively. V and V_x are the total volume and corresponding volume of solid or fluid phase. The schematic view of the volume average domains for fluid flow is shown in Fig.4.1.3.

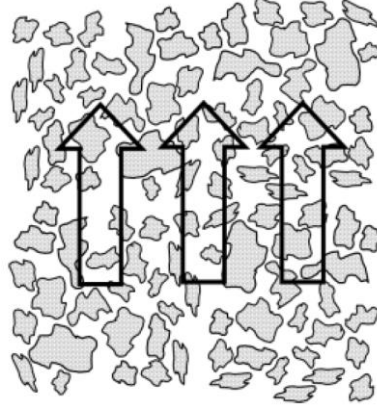


Fig.4.1.3 The schematic view of the volume average domains for fluid flow

Taking volume average of the dimensional pore scale governing equations Eqs. (4.1- 4.4) yields the dimensional volume averaged governing equations. When the thermophysical properties of the fluid does not change by temperature (except density), the fluid is Newtonian and incompressible, the volume average transport equations for heat and fluid flow in porous media can be written as;

$$\vec{\nabla} \cdot \langle \vec{V} \rangle = 0 \quad (4.7)$$

$$\begin{aligned} \frac{\rho_f}{\varepsilon} \frac{\partial \langle \vec{V} \rangle^f}{\partial t} + \frac{\rho_f}{\varepsilon^2} (\langle \vec{V} \rangle^f \cdot \vec{\nabla}) \langle \vec{V} \rangle^f = -\vec{\nabla} \langle P \rangle^f + \frac{\mu_f}{\varepsilon} \vec{\nabla}^2 \langle \vec{V} \rangle^f - \frac{\mu_f}{K} \langle \vec{V} \rangle^f \\ - \rho_f \frac{C_F}{\sqrt{K}} \left| \langle \vec{V} \rangle^f \right| \langle \vec{V} \rangle^f + \rho_f g \beta (T - T_{ref}) \vec{j} \end{aligned} \quad (4.8)$$

$$\varepsilon (\rho C_p)_f \frac{\partial \langle T \rangle^f}{\partial t} + (\rho C_p)_f \langle \vec{V} \rangle^f \cdot \vec{\nabla} \langle T \rangle^f = k_{eff,f}(T) \vec{\nabla}^2 \langle T \rangle^f + h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (4.9)$$

$$(1 - \varepsilon) (\rho C_p)_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \vec{\nabla}^2 \langle T \rangle^s - h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (4.10)$$

where ε , K and C_F shows porosity, permeability and inertia coefficient of the porous media. The third term in right hand side of Eq. (4.8) is Darcy term while the fourth term shows the effect of inertia. It is clear that the fifth term is Buoyancy term due to gravity and change of density with temperature. h_v is the volumetric interfacial heat transfer coefficient, $k_{eff,s}$ and $k_{eff,f}$ are the solid and fluid effective thermal conductivities, respectively. The effect of the heat transfer between the solid and fluid phases are shown by terms in Eqs. (4.9) and (4.10). $k_{eff,s}$ and $k_{eff,f}$ can be defined as,

$$\begin{aligned} k_{eff,s} &= (1 - \varepsilon^*) k_s \\ k_{eff,f} &= \varepsilon^* k_f \end{aligned} \quad (4.11)$$

The ε^* is the effective porosity and it can be found from following equation.

$$k_{eff} = \varepsilon^* k_f + (1 - \varepsilon^*) k_s \quad (4.12)$$

k_{eff} can be calculated numerically.

4.2 Solid/liquid phase change

4.2.1 Pore scale governing equations

The governing equations for the solid/liquid phase change under gravity are again continuity, momentum and energy equations. There are many approximations for solving solid/liquid phase change however the following equations are used in this study. Actually, in a solid/liquid phase change in a cavity there are three regions as fully melted region, slurry region and unmelted regions as shown in Fig. 4.2.1.

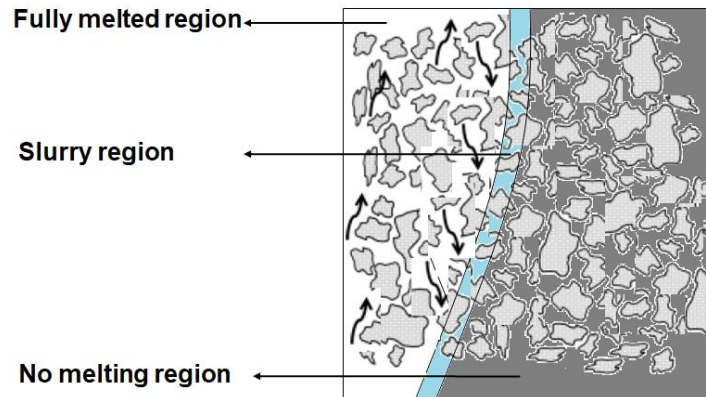


Fig.4.2.1 The schematic view of the entire domain

The following equations are valid for entire domain including melted and unmelted region.

$$\vec{\nabla} \cdot \vec{V} = 0 \quad (4.13)$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \vec{\nabla}) \vec{V} = -\frac{1}{\rho_f} \vec{\nabla} p + \nu_f(T) \vec{\nabla}^2 \cdot \vec{V} + g\beta(T - T_{ref}) \vec{j} \quad (4.14)$$

$$(\rho C_p)_f \left(\frac{\partial T_f}{\partial t} + \vec{V} \cdot \vec{\nabla} T_f \right) = k_f(T) \vec{\nabla}^2 T_f - \rho_f \frac{\partial \omega}{\partial t} \Delta H \quad (4.15)$$

$$(\rho C_p)_s \frac{\partial T_s}{\partial t} = k_s \vec{\nabla}^2 T_s \quad (4.16)$$

It should be mentioned that the density and specific heat (ρ and C_p) for fluid and frozen PCM and also for solid particles (porous media) are constant. But for the fluid PCM, the properties such as the kinematic viscosity and thermal conductivity change by temperature due to phase change during the melting process. The details of those valuables will be discussed in Chapter 5. For instance, when the governing equations are solved for the fully melted region, the value of kinematic viscosity and thermal conductivity of PCM are the real values of melted PCM. However, if the governing equations are solved for the solid region, the kinematic viscosity is very high value such as 10^8 to eliminate the effect of continuity and momentum equations, consequently energy equations for the frozen PCM and particles (porous media) are solved. In the slurry region, the values of kinematic viscosity and thermal conductivity change linearly between the solid and fluid PCM.

In the Eqs. (4.13-4.16), ω is the liquid fraction and its value changes from 0 (no melted) to 1 (fully melted). ΔH , β and T_{ref} are the latent heat, volumetric thermal expansion coefficient of working fluid and reference temperature, respectively. The values of viscosity and thermal conductivity of the PCM depend on the temperature and their variations are discussed in the next section. The reference temperature is the initial temperature in this study.

4.2.2 Volume average governing equations

Similarly, the volume average governing equations for the solid/liquid phase change

under gravity also include the continuity, momentum and energy equations. There are two domains in the volume average method as solid (particle or metal foam) and PCM (frozen or melted PCM) as can be seen in Fig. 4.2.2.

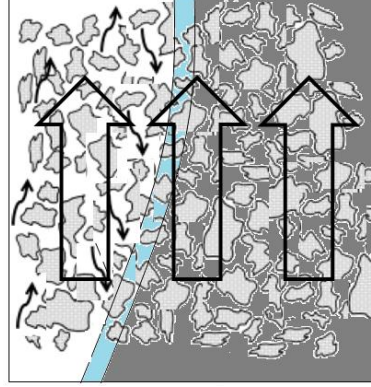


Fig.4.2.2 The schematic view of the fluid and solid domains

If a local thermal non-equilibrium assumption is used, there are two energy equations for fluid and solid phases.

$$\vec{\nabla} \cdot \langle \vec{V} \rangle = 0 \quad (4.17)$$

$$\begin{aligned} \frac{\rho_f}{\varepsilon} \frac{\partial \langle \vec{V} \rangle^f}{\partial t} + \frac{\rho_f}{\varepsilon^2} (\langle \vec{V} \rangle^f \cdot \vec{\nabla}) \langle \vec{V} \rangle^f = & -\vec{\nabla} \langle P \rangle^f + \frac{\mu_f(T)}{\varepsilon} \vec{\nabla}^2 \langle \vec{V} \rangle^f - \frac{\mu_f(T)}{K} \langle \vec{V} \rangle^f \\ & - \rho_f \frac{C_F}{\sqrt{K}} \left| \langle \vec{V} \rangle^f \right| \langle \vec{V} \rangle^f + \rho_f g \beta (T - T_{ref}) \vec{j} \end{aligned} \quad (4.18)$$

$$\begin{aligned} \varepsilon (\rho C_p)_f \frac{\partial \langle T \rangle^f}{\partial t} + (\rho C_p)_f \langle \vec{V} \rangle^f \cdot \vec{\nabla} \langle T \rangle^f = & k_{eff,f}(T) \vec{\nabla}^2 \langle T \rangle^f + h_v (\langle T \rangle^s - \langle T \rangle^f) \\ & - \varepsilon \rho_f \frac{\partial \omega}{\partial t} \Delta H \end{aligned} \quad (4.19)$$

$$(1 - \varepsilon) (\rho C_p)_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \vec{\nabla}^2 \langle T \rangle^s - h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (4.20)$$

Again the ω is the liquid fraction and its value changes from 0 (no melted) to 1 (fully melted). ΔH , β and T_{ref} are the latent heat, volumetric thermal expansion coefficient of working fluid and reference temperature, respectively. The value of $k_{eff,s}$ and $k_{eff,f}$ can be calculated by Eq. 4.11. ΔH , β and T_{ref} are the latent heat, volumetric thermal

expansion coefficient of working fluid and reference temperature and h_v is the volumetric interfacial heat transfer coefficient.

In the above equations (Eqs. (4.17-4.20)), dynamic viscosity and effective thermal conductivity for the solid and fluids are function of temperature. They are calculated similar to what are explained in previous section. For instance, when the above volume average governing equations are solved for the frozen fluid the value of kinematic viscosity is very high (such as 10^8) providing a solid region but when they are solved for the fluid region, the value of μ is the value of the fluid PCM.

If the volume average temperature of the solid and fluids ($\langle T \rangle^s$ and $\langle T \rangle^f$) are close to each other and if we add Eq. (4.19) to Eq. (4.20), the following energy equation is obtained,

$$\varepsilon(\rho C_p)_{eff} \frac{\partial \langle T \rangle}{\partial t} + (\rho C_p)_{eff} \langle \vec{V} \rangle \cdot \vec{\nabla} \langle T \rangle = k_{eff}(T) \vec{\nabla}^2 \langle T \rangle - \varepsilon \rho \frac{\partial \omega}{\partial t} \Delta H \quad (4.21)$$

The above equation is valid for a local thermal equilibrium. And there is only one energy equation which should be considered.

It might be useful to mention that Eqs. (4.17-4.20) and Eq. (4.21) is valid for the PCM which are Newtonian, constant density and specific heat capacity. And many reported studies are applied the local thermal equilibrium, however, some studies may not be suitable to use the local thermal equilibrium.

Chapter 5

Simplification and non-dimensionalization of governing equations for studied problems

In this chapter, the dimensionless governing equations for the single phase flow and the problem of solid/liquid phase change are given for the closed and open cell porous media. These equations are pore scale and volume average equations which are explained in this section.

5.1 Simplified dimensionless form of the governing equations for Problem 1

The continuity and momentum equations are solved to find velocity and pressure distributions and the energy equations for fluid and solid phases are solved to obtain the solid and fluid temperatures. The equivalent thermal diffusivity can be employed to make the above equations dimensionless.

5.1.1 Pore scale equations

The pore scale equations include the continuity and momentum equations and energy equations for solid and fluid phases and they are given with Eqs. (4.1-4.4) in Chapter 4. If the equilibrium thermal diffusivity is employed for non-dimensionalization of those equations. The above governing equations can be written in dimensionless form as follows,

$$\vec{\nabla}^* \cdot \vec{V}^* = 0 \quad (5.1)$$

$$\frac{\partial \vec{V}^*}{\partial \tau} + (\vec{V}^* \cdot \vec{\nabla}^*) \vec{V}^* = -\vec{\nabla}^* P^* + Pr_e \vec{\nabla}^{*2} \vec{V}^* + Ra_e \xi^3 Pr_e \theta_f \vec{j} \quad (5.2)$$

$$\frac{\partial \theta_f}{\partial \tau} + \vec{V}^* \cdot \vec{\nabla}^* \theta_f = \psi_f \vec{\nabla}^{*2} \theta_f \quad (5.3)$$

$$\frac{\partial \theta_s}{\partial \tau} = \psi_s \vec{\nabla}^{*2} \theta_s \quad (5.4)$$

where $\vec{V}^*$, P^* , θ_f and θ_s represent the dimensionless velocity vector, pressure and temperatures of the solid and fluid phases. The length of cavity and cells are L and l , separately. τ , Ra_e and Pr_e are the dimensionless time, Rayleigh number and Prandtl

number based on the equivalent thermal diffusivity, respectively. The sub index of “e” is very important in this study and it shows equivalent. ψ is the thermal diffusivity ratio for the fluid or solid phase with equivalent one. The employed dimensionless parameters can be mathematically expressed as,

$$\bar{\nabla}^* = \frac{\bar{\nabla}}{L}, \quad \bar{V}^* = \frac{\bar{V}L}{\alpha_e}, \quad \xi = \frac{L}{l}, \quad \tau = \frac{t\alpha_e}{L^2}, \quad P^* = \frac{PL^2}{\rho_f \alpha_e^2}, \quad Pr_e = \frac{\nu_f}{\alpha_e}, \quad (5.5)$$

$$Ra_e = \frac{\rho_f g \beta (T_h - T_c) l^3}{\alpha_e \nu_f}, \quad \theta = \frac{T - T_c}{T_h - T_c}, \quad \psi_f = \frac{\alpha_f}{\alpha_e}, \quad \psi_s = \frac{\alpha_s}{\alpha_e}$$

where $\alpha_e = k_e / (\rho C_p)_e$ is the equivalent thermal diffusivity. It is defined as:

$$\alpha_e = \frac{k_e}{(\rho C_p)_e} = \frac{\varepsilon k_f + (1 - \varepsilon)k_s}{\varepsilon(\rho C_p)_f + (1 - \varepsilon)(\rho C_p)_s} \quad (5.6)$$

It should be mentioned that the following relations are valid for the Prandtl and Rayleigh numbers,

$$Pr_f = Pr_e \frac{\alpha_e}{\alpha_f}, \quad Ra_f = Ra_e \frac{\alpha_e}{\alpha_f} \quad (5.7)$$

Where Pr_f and Ra_f are Prandtl and Rayleigh numbers based on the fluid thermal diffusivity.

5.1.2 Volume average equations

The volume average governing equations of Problem 1 are the same with Eqs. (4.7-4.10) given in Chapter 4, however, since the volume averaged velocity for the closed cell porous media is zero, the continuity and momentum Eqs.(4.7-4.8) disappear automatically.

$$\langle \bar{V}^* \rangle^f = \frac{1}{V_f} \int_{V_f} \bar{V}^* dV_f = 0 \quad (5.8)$$

That's why there are only the energy equations of solid and fluid phases for the volume average equations in the closed cell porous media. Therefore, the dimension form of the volume average governing equations for Problem 1 can be written by.

$$\varepsilon C_f \frac{\partial \langle T \rangle^f}{\partial t} = k_{eff,f} \bar{\nabla}^{*2} \langle T \rangle^f + h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (5.9)$$

$$(1 - \varepsilon)C_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \bar{\nabla}^{*2} \langle T \rangle^s - h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (5.10)$$

As it can be seen from the above equations, the heat conduction equations for the solid and fluid phases are the only equations for the volume average approach in the closed cell porous media. h_v which is the volumetric interfacial heat transfer coefficient and it can be defined as $h_v = h_s A_v$, where h_s (W / m² K) is the surface interfacial heat transfer coefficient and A_v (m² / m³) is the volumetric heat transfer area. It is possible to write the volumetric heat transfer area as $A_v = \varepsilon / r_h$, where r_h is hydraulic diameter of the fluid phase. It can be defined as $r_h = V_f / A_{int}$ where A_{int} is the interface heat transfer area in the fluid volume of V_f . Then, the Eqs. (5.9) and (5.10) become as:

$$\varepsilon C_f \frac{\partial \langle T \rangle^f}{\partial t} = k_{eff,f} \bar{\nabla}^{*2} \langle T \rangle^f + \frac{h_s \varepsilon}{r_h} (\langle T \rangle^s - \langle T \rangle^f) \quad (5.11)$$

$$(1 - \varepsilon)C_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \bar{\nabla}^{*2} \langle T \rangle^s - \frac{h_s \varepsilon}{r_h} (\langle T \rangle^s - \langle T \rangle^f) \quad (5.12)$$

The above equations can be non-dimensionalized by using dimensionless variables of Eq. (5.15) and the new parameter as Sparrow appears automatically in the following equations.

$$\Omega_f \frac{\partial \langle \theta \rangle^f}{\partial \tau_e} = \Gamma_f \bar{\nabla}^{*2} \langle \theta \rangle^f + Sp (\langle \theta \rangle^s - \langle \theta \rangle^f) \quad (5.13)$$

$$\Omega_s \frac{\partial \langle \theta \rangle^s}{\partial \tau_e} = \Gamma_s \bar{\nabla}^{*2} \langle \theta \rangle^s - Sp (\langle \theta \rangle^s - \langle \theta \rangle^f) \quad (5.14)$$

Γ , Ω are the dimensionless thermal conductivity and thermal capacitance, respectively, and Sp is the Sparrow number. The employed dimensionless parameters can be defined mathematically as

$$\Omega_s = \frac{C_s(1 - \varepsilon)}{\varepsilon C_e}, \quad \Omega_f = \frac{C_f}{C_e}, \quad \Gamma_s = \frac{k_{eff,s}}{\varepsilon k_e}, \quad \Gamma_f = \frac{k_{eff,f}}{\varepsilon k_e}, \quad Sp = \frac{h_s L^2}{k_e r_h} \quad (5.15)$$

where τ_e is the dimensionless time for porous media, C_e and Γ_e are the thermal capacitance and thermal conductivity based on thermal equivalent properties. $k_{eff,f} / k_e$ and $k_{eff,s} / k_e$ are the thermal conductivity ratios for the volume average domain of fluid and solid phases with equivalent thermal conductivity. The parameter of Ω is the

thermal capacitance ratio between fluid and solid with equivalent thermal capacitance. The values of $k_{eff,f}$ and $k_{eff,s}$ must be known to find out the solution. Discussion on the Sparrow number will be done later in Chapter 7. Both the solid and fluid phases are made in dimensionless form based on the equivalent thermal diffusivity which a value between the solid and fluid thermal diffusivities. The number of the governing parameters is 5 which are $\Gamma_s, \Gamma_f, \Omega_s, \Omega_f$ and Sp . It is possible to add two equations more and reduces the number of the governing parameters to 3. These equations are,

$$\Omega_s + \Omega_f = \frac{1}{\varepsilon} \quad (5.16)$$

$$\Gamma_s + \Gamma_f \approx \frac{1}{\varepsilon} \quad (5.17)$$

If the Eqs. (5.13) and (5.14) are considered with Eqs. (5.16) and (5.17), it is seen that the number of governing parameters decreases to four as solid (or fluid) dimensionless thermal conductivity and thermal capacitance, Sparrow number and porosity. In this study, the values of Γ_f and Ω_f are written in terms of Γ_s and Ω_s . Hence the dimensionless governing parameters are Γ_s, Ω_s and Sp while porosity is constant as 0.9. Furthermore, for the thermal equilibrium case, $\langle \theta \rangle_s$ and $\langle \theta \rangle_f$ are close to each other ($\langle \theta \rangle \approx \langle \theta \rangle_s \approx \langle \theta \rangle_f$), therefore Eqs. (5.13) and (5.14) take the following form,

$$\frac{\partial \langle \theta \rangle}{\partial \tau_e} = \bar{\nabla}^{*2} \langle \theta \rangle \quad (5.18)$$

The above equation is valid for a local thermal equilibrium condition. Sparrow number plays an important role on the results of the governing equations, the details of Sparrow number will be discussed in Chapter 7.

5.2 Simplified dimensionless form of the governing equations for Problem 2

5.2.1 Pore scale equations

For the pore scale study of Problem 2, the governing equations for the solid/liquid phase change under gravity include continuity and momentum equations are solved to find the velocity and pressure distributions and the energy equations for fluid phase and solid phase are solved to obtain the solid and fluid temperature distribution. These equations were given in Chapter 4 by Eqs. (4.17-4.20).

Again if the equilibrium thermal diffusivity is used in those governing equations, the above governing equation can be written in dimensionless form as follows,

$$\frac{\partial \vec{V}^*}{\partial F_o} + (\vec{V}^* \cdot \vec{\nabla}^*) \vec{V}^* = -\vec{\nabla}^* P^* + M(\theta) Pr_e \vec{\nabla}^{*2} \vec{V}^* + Ra_e Pr_e \theta_f \vec{j} \quad (5.19)$$

$$\Lambda(\theta) \frac{\partial \theta_f}{\partial F_o} + \vec{V}^* \cdot \vec{\nabla}^* \theta_f = \Pi(\theta) \psi_f \vec{\nabla}^{*2} \theta_f - \frac{\partial \omega}{\partial F_o} \frac{1}{Ste} \quad (5.20)$$

$$\frac{\partial \theta_s}{\partial F_o} = \psi_s \vec{\nabla}^{*2} \theta_s \quad (5.21)$$

where $\vec{V}^*$ and P^* are the dimensionless velocity vector and pressure. The dimensionless temperatures of solid and fluid phases are given by θ_f and θ_s , respectively. F_o , Ra_e and Pr_e are the Fourier number, Rayleigh number and Prandtl number based on the equilibrium thermal diffusivity, respectively. ψ is the thermal diffusivity ratio between the fluid or solid phase and equilibrium thermal diffusivity. The governing dimensionless parameters can be mathematically expressed as,

$$\begin{aligned} \vec{\nabla}^* &= \frac{\vec{\nabla}}{L}, \quad \vec{V}^* = \frac{V L}{\alpha_f}, \quad \xi = \frac{L}{l}, \quad \tau = \frac{t \alpha_f}{L^2}, \quad P^* = \frac{P L^2}{\rho \alpha_f^2}, \quad Pr = \frac{\nu_f}{\alpha_f}, \\ Ra_{l-max} &= \frac{\rho g \beta (T_h - T_c) l^3}{\alpha_f \nu_f}, \quad \theta = \frac{T - T_c}{T_h - T_c}, \quad \psi = \frac{\alpha_s}{\alpha_f} \end{aligned} \quad (5.22)$$

The values of functions of $M(\theta)$, $\Lambda(\theta)$ and $\Pi(\theta)$ change by temperature, they are the necessary coefficients to describe PCM properties from frozen to melted state and defined as:

$$M(\theta) = \frac{\nu(T)}{\nu_f}, \quad \Lambda(\theta) = \frac{Cp(T)}{Cp_f}, \quad \Pi(\theta) = \frac{k(T)}{k_f} \quad (5.23)$$

It should be mentioned that the following relations for the Prandtl and Rayleigh numbers exist.

$$Pr_f = Pr_e \frac{\alpha_e}{\alpha_f}, \quad Ra_f = Ra_e \frac{\alpha_e}{\alpha_f} \quad (5.24)$$

5.2.2 Volume average equations

Similarly, the volume average equations of problem 2 are same with the governing

equations for the solid/liquid phase change given by Eqs. (4.13-4.16) in Chapter 4. It should be mentioned that the volume averaged velocity in a cell is zero as shown by Eq. (4.5-4.6). Hence, no continuity and momentum equations exist for the volume averaged domain. The volume averaged heat conduction equations should only be applied to the solid and fluid volume averaged domains. The dimensional form of the equations for a closed cell porous medium are given as,

$$\varepsilon C_f(T) \frac{\partial \langle T \rangle^f}{\partial t} = k_{eff,f}(T) \vec{\nabla}^2 \langle T \rangle^f + h_v (\langle T \rangle^s - \langle T \rangle^f) - \rho_f \varepsilon \frac{\partial \omega}{\partial t} \Delta H \quad (5.25)$$

$$(1 - \varepsilon) C_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \vec{\nabla}^2 \langle T \rangle^s - h_v (\langle T \rangle^s - \langle T \rangle^f) \quad (5.26)$$

The same as the volume average equations of problem 1, the heat conduction equations for the solid and fluid phases are the only equations for the volume average approach in the closed cell porous media. h_v which is the volumetric interfacial heat transfer coefficient can be defined as $h_v = h_s A_v$, where h_s (W / m² K) is the surface interfacial heat transfer coefficient and A_v (m² / m³) is the volumetric heat transfer area. It is possible to write the volumetric heat transfer area as $A_v = \varepsilon / r_h A$, where r_h is hydraulic diameter of the fluid phase. It can be defined as $r_h = V_f / A_{int} r$ where A_{int} is the interface heat transfer area in the fluid volume of V_f .

Then, the Eqs. (5.25) and (5.26) become as:

$$\varepsilon C_f(T) \frac{\partial \langle T \rangle^f}{\partial t} = k_{eff,f}(T) \vec{\nabla}^2 \langle T \rangle^f + \frac{h_s \varepsilon}{r_h} (\langle T \rangle^s - \langle T \rangle^f) - \rho_f \varepsilon \frac{\partial \omega}{\partial t} \Delta H \quad (5.27)$$

$$(1 - \varepsilon) C_s \frac{\partial \langle T \rangle^s}{\partial t} = k_{eff,s} \vec{\nabla}^2 \langle T \rangle^s - \frac{h_s \varepsilon}{r_h} (\langle T \rangle^s - \langle T \rangle^f) \quad (5.28)$$

The above equations can be non-dimensionalized based on the dimensionless parameters of Eq. (5.31):

$$\Lambda(\theta) \Omega_f \frac{\partial \langle \theta \rangle^f}{\partial F_o} = N(\theta) \Gamma_f \vec{\nabla}^{*2} \langle \theta \rangle^f + Sp(\langle \theta \rangle^s - \langle \theta \rangle^f) - \Omega_f \frac{1}{Ste} \frac{\partial \omega}{\partial F_o} \quad (5.29)$$

$$\Omega_s \frac{\partial \langle \theta \rangle^s}{\partial F_o} = \Gamma_s \vec{\nabla}^{*2} \langle \theta \rangle^s - Sp(\langle \theta \rangle^s - \langle \theta \rangle^f) \quad (5.30)$$

Γ and Ω are the dimensionless thermal conductivity and thermal capacitance, respectively, and Sp is the Sparrow number. The employed dimensionless parameters can be defined mathematically as

$$\Omega_s = \frac{C_s(1-\varepsilon)}{\varepsilon C_e}, \quad \Omega_f = \frac{C_f}{C_e}, \quad N(\theta) = \frac{k_{eff,f}(\theta)}{k_{eff,f}}, \quad \Gamma_s = \frac{k_{eff,s}}{\varepsilon k_e}, \quad \Gamma_f = \frac{k_{eff,f}}{\varepsilon k_e}, \quad (5.31)$$

$$Sp = \frac{h_s L^2}{k_e r_h}$$

C_e and Γ_e are the equilibrium thermal capacitance and thermal conductivity and they can be written as:

$$C_e = (1-\varepsilon)C_s + \varepsilon C_f \quad (5.32)$$

$$\Gamma_e = \Gamma_s + \Gamma_f \quad (5.33)$$

The values of $\Lambda(\theta)$ and $N(\theta)$ adjust thermal properties from the frozen to melted state and their values do not play important roles compared to other dimensionless parameters. For many PCMs, $k_f|_{frozen} \sim k_f|_{melted}$ and $C_f|_{frozen} \sim C_f|_{melted}$ hence

$N(\theta) \approx 1$ and $\Lambda(\theta) \approx 1$ leading Eq. (5-29) and (5-30) into:

$$\Omega_f \frac{\partial \langle \theta \rangle^f}{\partial F_o} = \Gamma_f \bar{\nabla}^{*2} \langle \theta \rangle^f + Sp(\langle \theta \rangle^s - \langle \theta \rangle^f) - \Omega_f \frac{1}{Ste} \frac{\partial \omega}{\partial F_o} \quad (5.34)$$

$$\Omega_s \frac{\partial \langle \theta \rangle^s}{\partial F_o} = \Gamma_s \bar{\nabla}^{*2} \langle \theta \rangle^s - Sp(\langle \theta \rangle^s - \langle \theta \rangle^f) \quad (5.35)$$

Therefore, the dominant dimensionless parameters for the present study are Ω_s , Ω_f , Γ_s , Γ_f , Ste and Sp . Our numerical experience shows that it is possible to combine four coefficients as Ω_s , Ω_f , Γ_s , Γ_f by defining thermal diffusivity ratio as

$$\alpha_r = \frac{\Gamma_s / \Omega_s}{\Gamma_f / \Omega_f} = \frac{(1-\varepsilon^*)\varepsilon}{\varepsilon^*(1-\varepsilon)} \frac{\alpha_s}{\alpha_f} \approx \frac{\alpha_s}{\alpha_f} \quad (5.36)$$

Hence, the results of Eqs. (5.34) and (5.35) are controlled by three parameters which are α_r , Ste and Sp .

5.3 Simplified dimensionless form of the equations for Problem 3

5.3.1 Pore scale equations

For the pore scale analysis, the heat and fluid flow for the entire domain including phase change in the cells and 3D Lattice Metal Frame is considered. The effect of gravity is taken into account and the buoyancy effect is involved by using Boussinesq approximation. The dimensional form of the pore scale governing equations for problem 3 are described in Chapter 4 by Eqs. (4.13-4.16). The above governing equations can be written in the dimensionless form as follows,

$$\vec{\nabla}^* \cdot \vec{V}^* = 0 \quad (5.37)$$

$$\frac{\partial \vec{V}^*}{\partial Fo} + \vec{V}^* (\vec{\nabla}^* \cdot \vec{V}^*) = -\vec{\nabla}^* P^* + \Gamma(\theta) Pr (\vec{\nabla}^{*2} \cdot \vec{V}^*) + Ra Pr \theta_f \vec{j} \quad (5.38)$$

$$\frac{\partial \theta_f}{\partial Fo} + \vec{V}^* (\vec{\nabla}^* \theta_f) = \Pi(\theta) \vec{\nabla}^{*2} \theta_f - \frac{1}{Ste} \frac{\partial \omega}{\partial Fo} \quad (5.39)$$

$$\frac{\partial \theta_s}{\partial Fo} = \Lambda \vec{\nabla}^{*2} \theta_s \quad (5.40)$$

where $\vec{V}^*$ and P^* are the dimensionless velocity vector and pressure. The dimensionless temperatures of solid and fluid phases are shown by θ_f and θ_s , respectively. $\Gamma(\theta)$ and $\Pi(\theta)$ are the dimensionless functions for viscosity and thermal conductivity ratio during the melting period and Λ is the thermal diffusivity ration between solid and fluid, they are given as below,

$$\Gamma(\theta) = \frac{\nu(T)}{\nu_f}, \quad \Pi(\theta) = \frac{k(T)}{k_f}, \quad \Lambda = \frac{\alpha_s}{\alpha_f} \quad (5.41)$$

These functions are discussed in the next section. The dimensionless governing parameters are,

$$V^* = \frac{VL}{\alpha_f}, \quad \theta = \frac{T - T_i}{T_h - T_i}, \quad Ra = \frac{\rho_f g \beta (T_h - T_i) L^3}{\alpha_f \nu_f}, \quad Ste = \frac{C_{p,f} (T_h - T_i)}{\Delta H},$$

$$Pr = \frac{\nu_f}{\alpha_f}, \quad P^* = \frac{PL^2}{\rho_f \alpha_f^2}, \quad Fo = \frac{\alpha_f t}{L^2} \quad (5.42)$$

where Ra , Fo and Ste represent Rayleigh, Fourier and Stefan numbers.

5.3.2 Volume average equations

The dimensional form of volume average governing equations for the solid and fluid phases are the volume averaged continuity, momentum and energy equations for the fluid phase and energy equation for the solid phase. Compared with the Problem 2 which is closed cell porous media, the problem 3 is open cell porous media. That's why that the problem of 3D lattice metal frame includes the continuity and momentum equations while Problem 2 does not include. The dimensional form of volume average governing equations for Problem 3 are given in Chapter 4 as Eqs. (4.17-4.20). The above equations can be non-dimensionalized based on the dimensionless parameters in Eq. (5.42).

$$\bar{\nabla}^* \cdot \langle \vec{V}^* \rangle^f = 0 \quad (5.43)$$

$$\begin{aligned} \frac{l}{\varepsilon} \frac{\partial \langle \vec{V}^* \rangle^f}{\partial Fo} + \frac{l}{\varepsilon^2} \langle \vec{V}^* \rangle^f \bar{\nabla}^* \cdot \langle \vec{V}^* \rangle^f = -\bar{\nabla}^* P^* + \frac{l}{\varepsilon} \Gamma(\theta) Pr_f \bar{\nabla}^{*2} \cdot \langle \vec{V}^* \rangle^f \\ - \Gamma(\theta) \frac{Pr_f}{Da} \langle \vec{V}^* \rangle^f - \frac{C_F}{\sqrt{Da}} \left| \langle \vec{V}^* \rangle^f \right| \left| \langle \vec{V}^* \rangle^f \right| + Ra_f Pr_f \theta_f \vec{j} \end{aligned} \quad (5.44)$$

$$\varepsilon \frac{\partial \langle \theta \rangle^f}{\partial Fo} + \langle \vec{V}^* \rangle^f \bar{\nabla}^* \cdot \langle \theta \rangle^f = N(\theta) \bar{\nabla}^{*2} \langle \theta \rangle^f + \bar{Nu}_v \left(\langle \theta \rangle^s - \langle \theta \rangle^f \right) \xi^2 - \varepsilon \frac{l}{Ste} \frac{\partial \omega}{\partial Fo} \quad (5.45)$$

$$(1 - \varepsilon) \frac{\partial \langle \theta \rangle^s}{\partial Fo} = \Psi \bar{\nabla}^{*2} \langle \theta \rangle^s - \Omega \bar{Nu}_v \left(\langle \theta \rangle^s - \langle \theta \rangle^f \right) \xi^2 \quad (5.46)$$

ξ is the ratio between the characteristic length of a representative cell and porous media.

The dimensionless parameters of $N(\theta)$, Ψ and Ω are defined as,

$$N(\theta) = \frac{k_{eff,f}(T)}{k_f}, \quad \Psi = \frac{\alpha_{eff,s}}{\alpha_f}, \quad \Omega = \frac{(\rho C_p)_f}{(\rho C_p)_s} \quad (5.47)$$

For the volume averaged equations, the effective thermal diffusivities for the fluid and solid phases, and Nusselt number are,

$$\alpha_{eff,f} = \frac{\varepsilon^* k_f}{(\rho C_p)_f}, \quad \alpha_{eff,s} = \frac{(1 - \varepsilon^*) k_s}{(\rho C_p)_s}, \quad \bar{Nu}_v = \frac{h_v l^2}{k_f}, \quad \xi = \frac{L}{l} \quad (5.48)$$

where l is the pore size.

Chapter 6

Computational details

In this chapter, the solution method and grid independency are explained. The commercial program COMSOL 5.3a is used to solve all the governing equations in this study simultaneously. The validation studies of three problems are also shown.

6.1 The computational code

For the pore scale and volume average studies, a commercial software, COMSOL Multiphysics (V5.3a COMSOL Multiphysics), based on the finite element method is used to solve the coupled heat and fluid flow equations.

For the pore scale domain, the Multiphysics module used to solve motion equation is “Laminar flow”, while for solving heat transfer equations for the solid and fluid the Multiphysics module of the “Heat transfer in fluids” is used. In the momentum equations, the buoyancy term is added due to gravity. Fig. 6.1.1 shows the flow chart for pore scale analysis. As it can be seen, first the model is generated by the Comsol program, then the mesh is generated. In the most of cases a Custom mesh is generated in this study. After that, the necessary modules (explained before) is downloaded from the Multiphysics module. The necessary thermophysical properties of the solid and fluids such as thermal conductivity of the solid and fluid, viscosity of the fluid are assigned. The next step is that to assign boundary and initial conditions. For the problem 1 all thermophysical properties are constant while for the Problem 2 and 3, functions for the variation of viscosity and thermal conductivity are defined. Furthermore, the buoyancy term and also the heat source term due to the enthalpy of the phase change is added to the momentum and energy equations, respectively. The solution method is selected and tolerance is assigned to the program. The program starts to run and for each time step some iterations are done. The number of iteration for each time step is decided by the program. After finishing the assigned process time, the program stops and necessary post processing works can be done.

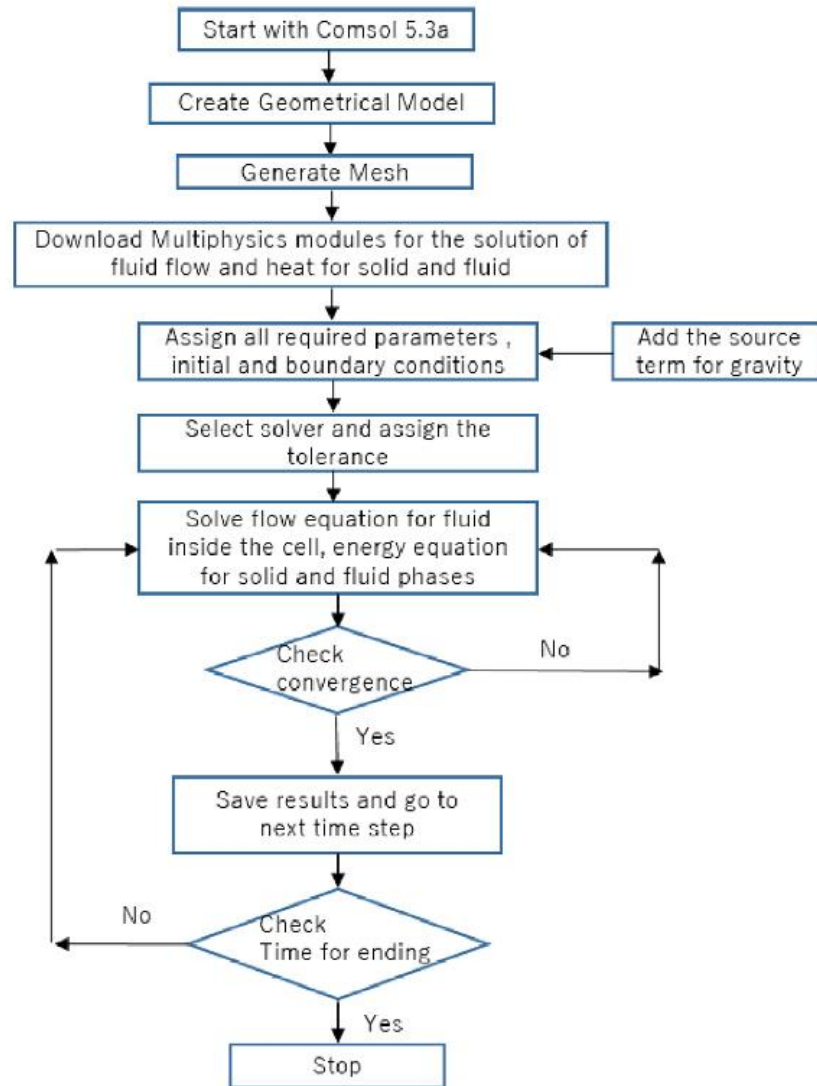


Fig 6.1.1 Flow chart for pore scale study in Comsol

For the volume average domain, since the cavity for the problem 1 and 2 are the closed cell porous media, the module of “Heat transfer in fluids and solid” is used only for solving heat transfer equations in solid and fluid, and meanwhile the “local thermal non-equilibrium” module is applied. In the problem 3, the Multiphysics module used to solve motion equation which is “Laminar flow” is added. And the of Multiphysics module of the “Heat transfer in fluids and solid” solved heat transfer equations for the solid and fluid.

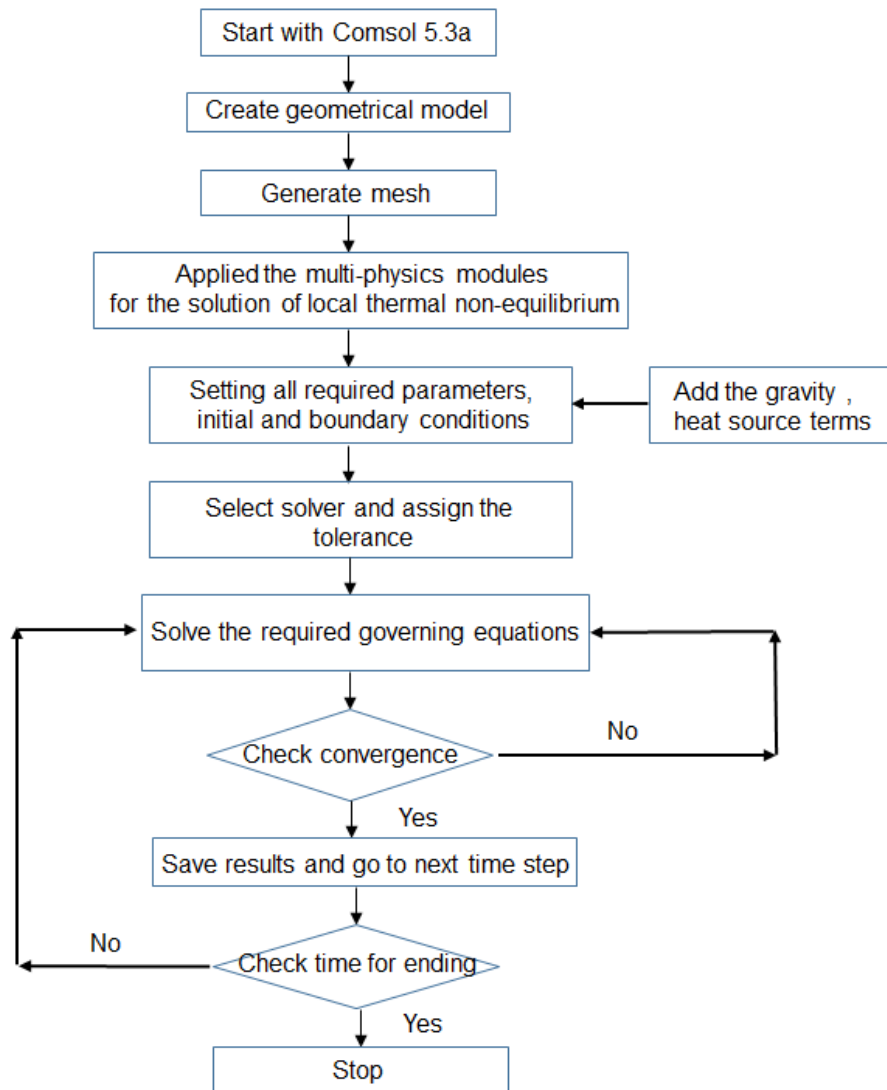


Fig 6.1.2 Flow chart for volume average study in Comsol

Similarly, in the momentum equations, the buoyancy term is added due to the effect of gravity. The flow chart for pore scale analysis can be seen in Fig. 6.1.2. Similar to the pore scale study, the first model is generated by the Comsol program, then the mesh is generated. After that, the necessary thermophysical properties of the solid and fluids such as thermal conductivity of the solid and fluid, viscosity of the fluid, initial and boundary conditions are assigned, at last the program start running. One point should be mentioned that in the problem 3 the heat generation term should be added in the energy equation of fluid phase due to the phase change.

The software was run in a workstation with Intel(R) Xeon(R) CPU E5-2630 v3, 32G

RAM. Commonly, for the problem 1 and 2, each run takes around 8 hours and for the problem 3, the running time is almost 2 days due to the 3D melting problem. Besides, during the computational period, there are some difficulties to converged. Maybe the reasons are the number of mesh, unavailable initial and boundary conditions or others. It always takes long time to solve those difficulties. So the Comsol is a not easy program to catch the results we need.

6.2 Computational determination of macroscopic parameters

6.2.1 Macroscopic parameters for Problem 1

The solution of the volume averaged heat conduction equations for the solid and fluid Eqs. (5.13 and 5.14) requires to know the value of Sp (consequently, $\bar{h}_v$ should be known). Unfortunately, no study relating to the transient value of the interfacial heat transfer coefficient for the closed pores of porous media could be found. In this study, the value of interfacial heat transfer coefficient is obtained from the pore scale study. The employed definition for determination of the average interfacial heat transfer coefficient is,

$$\bar{h}_v = \frac{I}{A_{int} \Delta t} \frac{\int_0^{\Delta t} \frac{\iint A_{int} q''(t) dA}{\langle T \rangle^s - \langle T \rangle^f} dt}{\langle T \rangle^s - \langle T \rangle^f} \quad (6.1)$$

q'' is the heat flux between solid and fluid phases at any point of the interface and at any instant such as t , and A_{int} is the total interfacial heat transfer area. Δt is the required time for the system to become steady state ($\langle T \rangle^s - \langle T \rangle^f < 0.05$ is the condition for the steady state in this study). As it can be seen from Eq. (6.2), the average of interfacial heat transfer coefficient is obtained by integration of the local interfacial heat transfer coefficient both in time and space. The average of the solid and fluid temperatures of the entire domain for the solid and fluid phases are found at any time step to compare the solid and fluid phase temperatures.

$$\langle \theta \rangle_m^f(\tau) = \frac{\iint_{v_f} \langle \theta \rangle^f(\tau) dv}{\iint_{v_f} dv} \quad \langle \theta \rangle_m^s(\tau) = \frac{\iint_{v_s} \langle \theta \rangle^s(\tau) dv}{\iint_{v_s} dv} \quad (6.2)$$

where $\langle \theta \rangle_m^f(\tau)$ and $\langle \theta \rangle_m^s(\tau)$ are the solid and fluid phase mean (i.e., surface average for the entire domain) temperatures. Finally, in order to understand the order of local thermal non-equilibrium, the parameters of σ is defined as following:

$$\sigma = \left| \langle \theta \rangle_m^s(\tau) - \langle \theta \rangle_m^f(\tau) \right| \quad (6.3)$$

The above equation shows that the temperature difference between the mean solid and fluid phases for the whole domain during the entire heat transfer process.

6.2.2 Macroscopic parameters for Problem 2

As it was mentioned before, in order to handle the slurry region, the values of viscosity, thermal conductivity and thermal capacitance changed from solid to fluid by using the following formula,

$$\phi(T) = \phi_{solid} + \left(\frac{T - T_m}{\Delta T} \right) (\phi_{fluid} - \phi_{solid}) \quad (6.4)$$

T_m is the melting point and ΔT is the phase change temperature range. In this study, these values are $T_m = 273.15K$ and $\Delta T = 1K$. The parameter of $\phi(T)$ can be thermal conductivity, thermal capacitance or dynamics viscosity whose values changes in the phase change temperature range.

One of the important parameters influences the volume average results is the effective thermal conductivities of the solid and fluid phases (i.e., $k_{eff,f}, k_{eff,s}$). In order to obtain the effective thermal conductivities, a representative cell of pore scale domain is considered. The representative cell is shown in Fig. 6.2.1. A temperature gradient is imposed horizontally while other surfaces are insulated. Pure heat conduction equations are solved for the cases of ice and water (without phase change) and effective thermal conductivity (i.e., ε^*) of the cell consisting of the solid and fluid phases are obtained. Then, by using Eq. (4.12) the value of ε^* is found and finally the values $k_{eff,f}, k_{eff,s}$ are calculated by using Eq. (4.11).

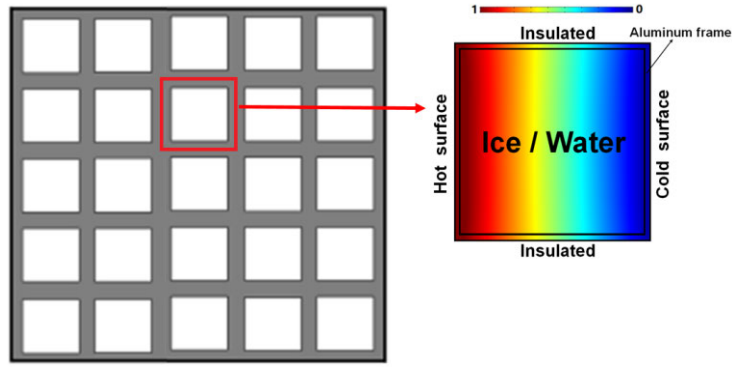


Fig.6.2.1 Temperature distribution and boundary conditions for a cell of pore scale domain for determination of the effective thermal conductivity

Many attempts are done in this study to find out a criterion for distinguishing of local thermal equilibrium from non-equilibrium. Our numerical results showed that actually, always there is a local thermal non-equilibrium at the beginning of the phase change process particularly in the region close to the hot surface (surface in which rapid temperature change occurs). However, for some cases this initial period of local thermal non-equilibrium is very short and almost the entire process is in local thermal equilibrium state, while for other cases the period of local thermal non-equilibrium is very long and those cases should be accepted as local thermal non-equilibrium. In this study the pore scale domain is divided into five equal columns and the first column touching the hot wall is excluded, and therefore the condition for the local thermal equilibrium can be assumed as

$$\left| \langle \theta \rangle^s - \langle \theta^f \rangle \right|_{x^* > 0.2, F_o > 0} < 0.1 \quad (6.5)$$

6.2.3 Macroscopic parameters for Problem 3

The method to handle the slurry region is very similar to what was used in Problem 2. The values of viscosity, thermal conductivity and thermal capacitance changed from solid to fluid by using (6.4). In order to calculate the value of effective thermal conductivities, a representative cell of pore scale domain (which is an isotropic domain) can be considered (Fig. 6.2.2). A temperature gradient is imposed in x direction and other surfaces are insulated.

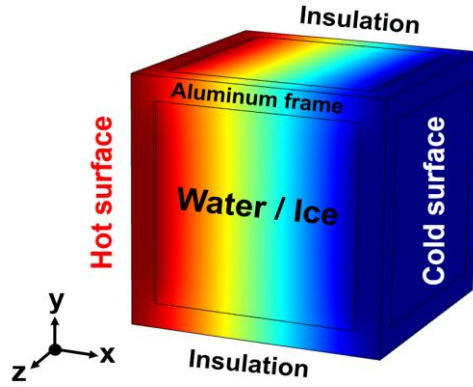


Fig. 6.2.2 Temperature distribution in the representative cell for determination of k_{eff}

The pure heat conduction equation is solved for the cases of ice and water separately (without any phase change) and the effective thermal conductivity of the studied 3D cubic LMF is obtained. Then, by using Eq. (4.12) the value of ε^* is found and finally the values of $k_{eff,s}$, $k_{eff,f}$ are calculated easily by using Eq. (4.11) (Wang and Mobedi (2019)).

The value of permeability and inertia coefficient are also required for calculation of the volume average temperature, pressure and velocity. Based on the methods described in the study of Ozgumus et al. (2014) and Celik et al. (2019), a uniform velocity is imposed at the inlet of the computational domain, the pore scale continuity and momentum equations are solved and the pressure drop through the 3D Lattice Cubic structure is obtained for the specified velocity (i.e., Reynolds number). The same computation is done for different inlet velocities. The change of the dimensionless pressure with pore scale Reynolds number is plotted and the value of permeability and inertia coefficient are obtained.

In general, the interfacial heat transfer coefficient can be obtained numerically or experimentally, however the recent developments in the computational technologies allow easier determination of the heat transfer coefficient. Details about the computational calculation of heat transfer coefficient can be found in the papers of Ozgumus and Mobedi (2015) and Celik et al. (2018). Briefly, the heat transfer rate between the solid and fluid phases can be calculated computationally, then it can be divided into the volume averaged temperature difference between the solid and fluid phases and also cell volume (or all cells) of the computational domain in order to

determine volumetric interfacial heat transfer coefficient. The local and instant interfacial heat transfer coefficient can be defined as,

$$h_v(t) = \frac{I}{V} \frac{\oint_A q''(t) dA}{(\langle T \rangle^s - \langle T \rangle^f)} \quad (6.6)$$

where A is the total interfacial area in the studied cell and V is the volume of the cell. $\langle T \rangle^s$ and $\langle T \rangle^f$ are the volume average solid and fluid temperatures of the cell. $q''(t)$ is the local heat flux between the solid and fluid phases at the interface at any time step (i.e., t). The average of $h_v(t)$, calculated for all cells in the domain, yields the average instant interfacial heat transfer coefficient:

$$\bar{h}_v(t) = \frac{I}{125} \sum_{n=1}^{125} h_v(t) \quad (6.7)$$

The time average of the instant interfacial heat transfer coefficient yields the average interfacial heat transfer coefficient of the porous media.

$$\bar{h}_v = \frac{I}{\Delta t} \int_t \bar{h}_v(t) dt \quad (6.8)$$

where Δt is the total melting period. Similarly, the local and instant Nusselt number, average instant Nusselt number and average interfacial Nusselt number can be defined as,

$$\begin{aligned} Nu_v(Fo) &= \frac{h_v(t) l^2}{k_f} \\ \bar{Nu}_v(Fo) &= \frac{\bar{h}_v(t) l^2}{k_f} \end{aligned} \quad (6.9)$$

$$\bar{Nu}_v = \frac{\bar{h}_v l^2}{k_f}$$

where l is the pore scale characteristic length, which is the cell size in this study. In this study, the melting fraction is also used to discuss the results. Melting fraction is defined as the volume of the melted PCM to the volume of the entire domain.

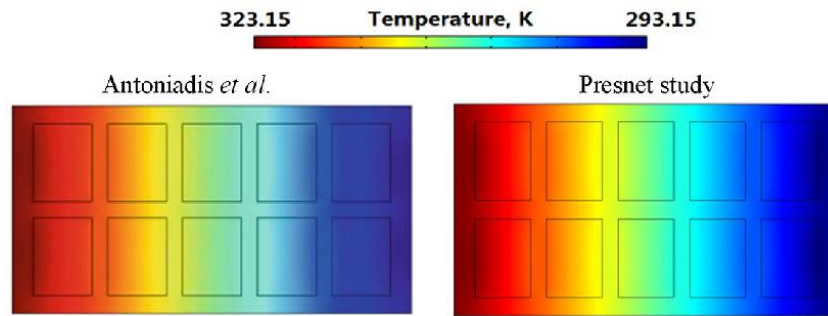
6.3 Validation studies

For the validation of the numerical results, 7 validation study were done and all of those studies proved that the employed method and performed computational studies are correct.

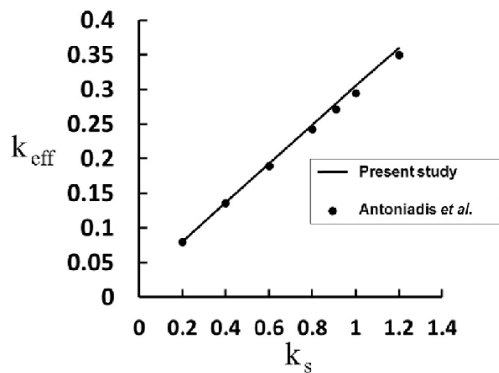
6.3.1 The first validation study

For validation of our numerical results, the study of Antoniadis et al. (2012) performed a wall with the hollow brick (two dimensional porous media with closed cell) was selected and done for different values of thermal conductivity ratio. The top and bottom sides are insulated and there is a temperature difference between the left and right walls. The thermal conductivity of the solid part of the clay brick is 0.91 W/mK , and the thermal conductivity value of air is 0.0255 W/mK . On the right-hand side of the brick, a boundary temperature of 293.15 K is considered, while on the left-hand side, a temperature of 323.15 K is imposed. The porosity of the domain is 0.55 .

Fig. 6.3.1 shows both sample of comparison of temperature distribution and the comparison of the change of effective thermal conductivity with solid thermal conductivity. As it can be seen, an excellent agreement (below 1 per cent absolute difference) exists between their results and our study.



(a)



(b)

Fig. 6.3.1 (a) Temperature distribution (b) Effective thermal conductivity changing by solid thermal conductivity

6.3.2 The second validation study

The second validation was done for one dimensional melting problem under pure condition heat transfer as shown in Fig. 6.3.2.

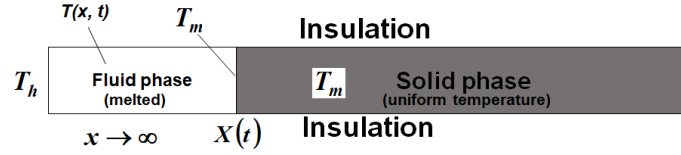


Fig. 6.3.2 Illustration of melting in a semi-infinite slab with initial temperature of

$$T_m$$

. The temperature for fluid phase can be found as Carslaw and Jaeger (1959):

$$\frac{T(x, t) - T_h}{T_m - T_h} = \frac{\text{erf}(x / 2\sqrt{\alpha t})}{\text{erf}(\beta)} \quad (6.10)$$

where α_f is the thermal diffusivity of fluid phase and the value of β can be found from following relation,

$$\beta e^{\beta^2} \text{erf}(\beta) = \frac{Ste}{\sqrt{\pi}} \quad (6.11)$$

It should be mentioned that the initial temperature in this problem is equal to melting temperature. The comparison of the results of present computational study and analytical solution is shown in Fig. 6.3.3 for water melting at $t = 900$ and $t = 2000$ sec. A good agreement between our computational study and analytical results is perfect for 1D melting problem.

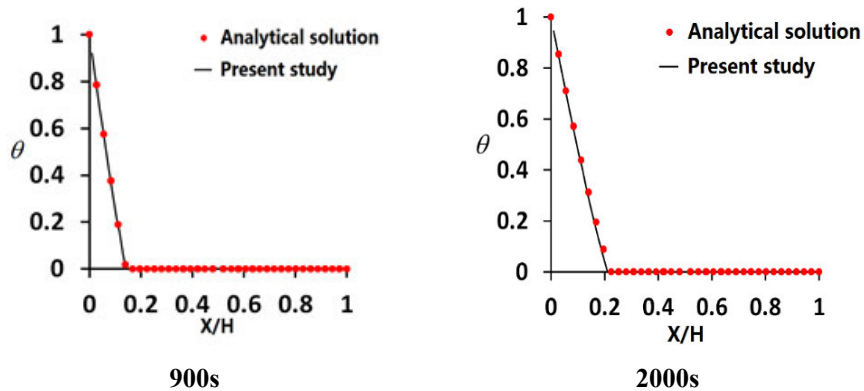


Fig. 6.3.3 Validation studies, comparison of the present study results with the reported studies for pure analytical solution (Carslaw and Jaeger (1959))

6.3.3 The third validation study

The third comparison was done between the results of our program and the results of Beckermann and Viskanta (1988) for the melting in a square cavity filled with porous media under natural convection.

The height of cavity is H and the length is L , the constant temperatures T_h and T_c are applied to the right and left wall of the cavity, and the top and bottom wall are insulated. The porous domain is saturated with a fluid. During the melting period, there are three regions as melt region, slurry region and solid region.

The Fig. 6.3.4 shows the comparison of melting interface positions for different dimensionless time step. A perfect agreement between our results and the results of Beckermann and Viskanta (1988) can be observed.

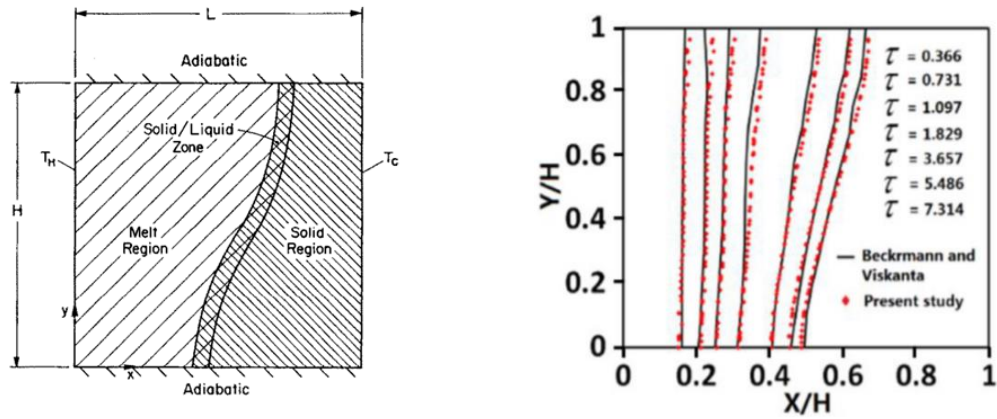


Fig. 6.3.4. Validation studies, comparison of the present study results with the reported studies for Beckermann and Viskanta (1988)

6.3.4 The fourth Validation study

A comparison between our results and the results of Huber et al. (2008) for the melting of clear ice without metal foam are done.

In the considered domain, the left vertical wall is maintained at constant temperature T_l and the initial temperature is equal to melting temperature T_m , other walls are adiabatic and no-slip.

An excellent agreement between our study and their reported study (below 7% difference for the third validation and below 1% for the fourth validation) was observed.

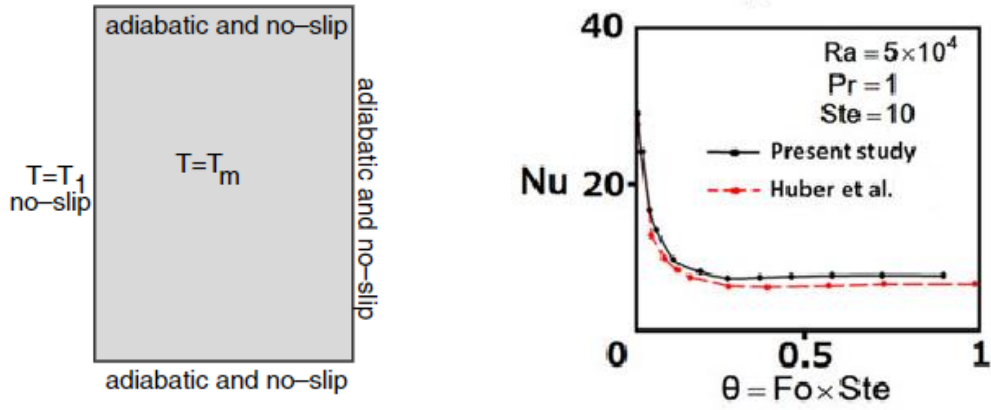


Fig. 6.3.5 The comparison between our results and the results of Huber et al. (2008)

6.3.5 The fifth validation study

The next validation study is similar to the second validation study, but initial temperature is less than melting temperature. That is why a heat transfer also exists in the solid phase and a temperature equation for the solid phase also exists. Analytical solution of 1D phase change and 3D melting in a cavity reported in literature are done. Fig. 6.3.6 shows 1D model of a melting process when the initial temperature of the solid is less than melting temperature. The governing equation and the analytical solution for this process are given by Alexiades and Solomon (1993).

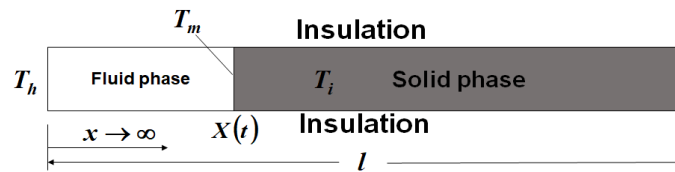


Fig. 6.3.6 Illustration of melting in a semi-infinite slab with initial temperature of T_i

$$(T_i < T_m)$$

Melting occurs in the x direction and the position of melting front and temperature of the solid and fluid can be obtained from the following equations.

$$X(t) = 2\lambda \sqrt{\alpha_f t} \quad (6.12)$$

$$T_f(x, t) = T_h - (T_h - T_m) \frac{\text{erf}\left(\frac{x}{2\sqrt{\alpha_f t}}\right)}{\text{erf}(\lambda)}, \quad 0 \leq x \leq X, \quad t > 0 \quad (6.13)$$

$$T_s(x,t) = T_{in} + (T_m - T_{in}) \frac{\operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha_s t}}\right)}{\operatorname{erfc}(\gamma\lambda)}, \quad x \geq X, \quad t > 0 \quad (6.14)$$

where $X(t)$ is the location of the solid-fluid interface, and γ is the square root of thermal diffusivity ratio of fluid and solid phases (i.e., $\gamma = \sqrt{\alpha_f / \alpha_s}$). The value of λ in the above equations can be determined by solving the following equations,

$$\frac{Ste_f}{\exp(\lambda^2) \operatorname{erf}(\lambda)} - \frac{Ste_s}{\gamma \exp(\gamma^2 \lambda^2) \operatorname{erfc}(\gamma\lambda)} = \lambda \sqrt{\pi} \quad (6.15)$$

Ste_f and Ste_s are the Stefan number of fluid and solid phases, respectively.

$$Ste_f = \frac{Cp_f (T_h - T_m)}{\Delta H}, \quad Ste_s = \frac{Cp_s (T_m - T_{in})}{\Delta H} \quad (6.16)$$

Cp_f and Cp_s represent the specific heat capacitance of fluid and solid phases, respectively. Fig. 6.3.7 shows the dimensionless temperature of the solid and fluid regions with dimensionless time obtained from the Eqs. (6.15) and (6.16) and our computational results. There is an excellent agreement between the analytical and numerical solution showing our established model in the employed software and computational results for the simulation of a melting process of a PCM is correct.

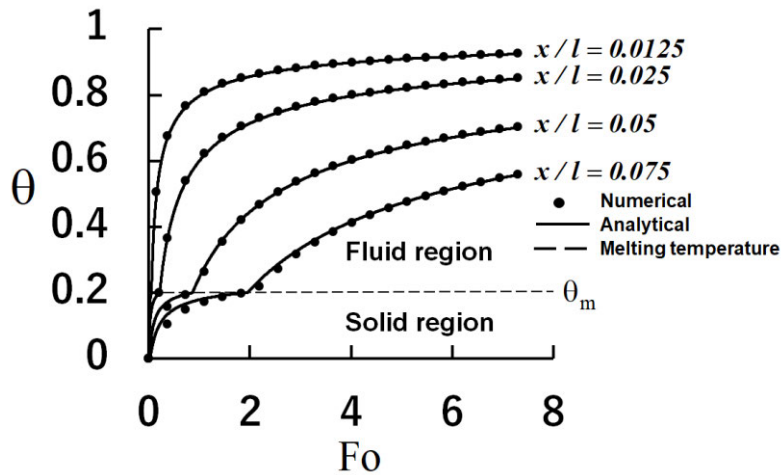


Fig. 6.3.7 Comparison of the numerical results with the results of the analytical solution by Alexiades and Solomon (1993) for 1D melting process

6.3.6 The sixth validation study

Furthermore, a comparison between the results of Li et al. (2017) and our obtained numerical results can be seen in Fig. 6.3.8. The problem is 3D melting of a PCM in a cavity whose upper and lower parts are insulated and left and right walls are at constant at different temperatures. The initial temperature is constant, which is equal to the melting temperature $T_m = 0$ and left wall temperature is also 0. The density, specific heat, and thermal conductivity of the solid phase and those of the liquid phase are equal. Similarly, an excellent agreement exists between our numerical results and the reported results.

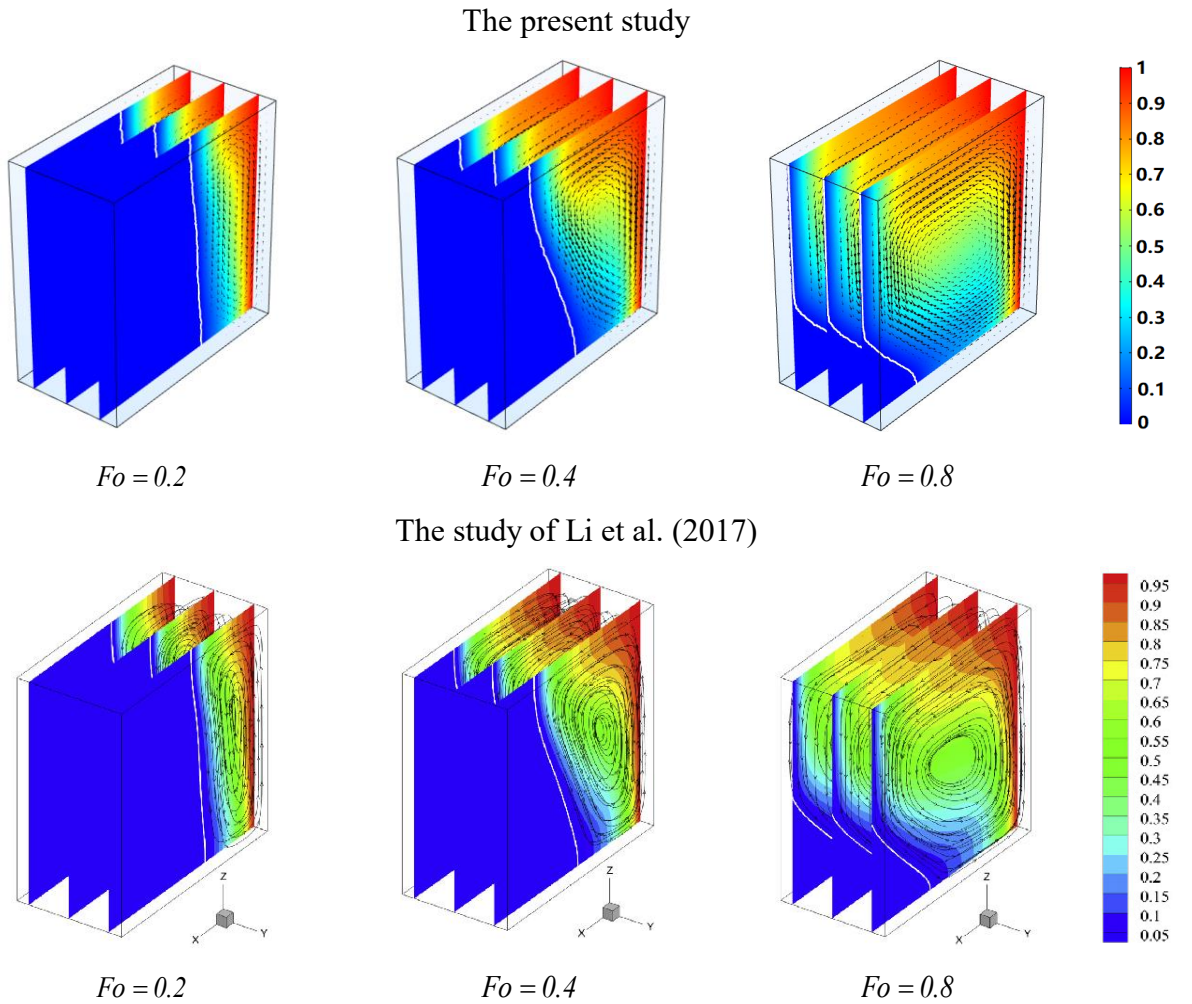


Fig. 6.3.8 Comparison between the present numerical results and the reported results in literature (Li et al. (2017)) when $Ste = 0.4, Ra = 2.5 \times 10^4, Pr = 10$

6.4 Grid Independency

6.4.1 Grid Independency for problem 1

Furthermore, the grid independency for the solution of both pore scale method and volume average method is done. Fig. 6.4.1 shows a sample of grid (element) refinement test for Problem 1. The change of temperature in the center line of the pore scale cavity for dimensionless time step of $\tau = 0.0016$ and $Ra_{l-max} = 10^5$, $\varepsilon = 0.9$ is shown. The number of mesh used in this study is 61,440, which is sufficient to obtain accurate result.

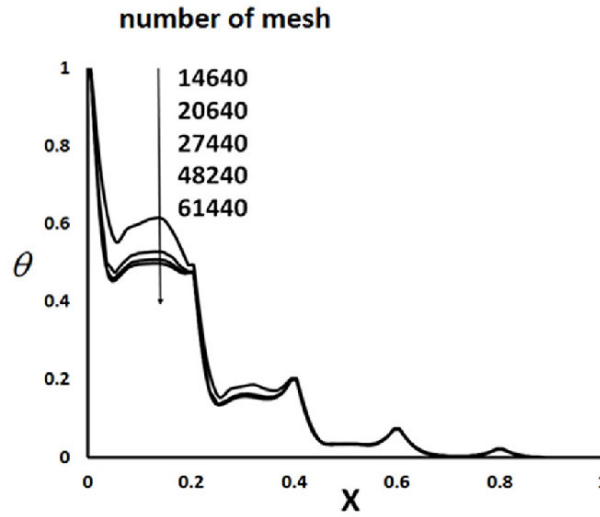


Fig. 6.4.1 The changes of pore scale temperature in the pore scale domain with number of mesh with $\tau = 0.0016$ and $Ra_{l-max} = 10^5$, $\varepsilon = 0.9$

6.4.2 Grid Independency for problem 2

A grid refinement analysis is done for Problem 2 and the results are shown in Fig. 6.4.2 in which the temperature at the horizontal center line ($Y^* = 0.5$) for the cavity with $\varepsilon = 0.9$, $Ra_f = 10^3$ and $Ste = 1$ is shown. The program did not converge for small number of element and that is why the mesh independency started from 17058 total elements. Hence, the results for different number of grids are close to each other. It is found that 41684 total elements (37708 number of domain elements (triangular), 3840 edge elements, and 136 vertex elements) are sufficient to obtain the accurate results for this problem.

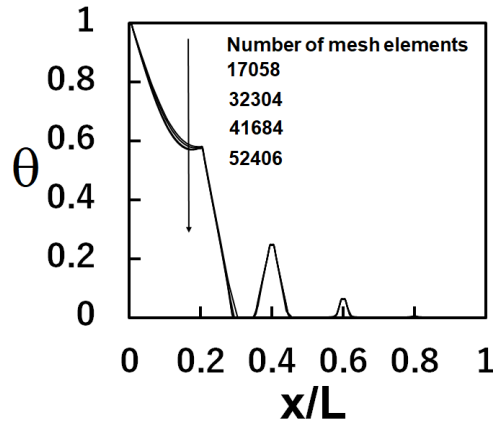


Fig. 6.4.2 A sample of grid independency for a closed cell cavity
with $\varepsilon = 0.9$, $Ra_f = 10^3$ and $Ste = 1$

6.4.3 Grid independency for Problem 3

The another grid refinement analysis for the Problem 3 was performed. The melting fraction in the cavity with Fourier number for $\varepsilon = 0.9$, $Ra_f = 10^6$ and $Ste = 0.6$ can be seen by using the 4 different mesh grid in Fig. 6.4.3. As it can be found that the larger number of mesh elements smoother curve can be obtained, and the result of 891850 total elements is very close to the 2492220 total elements. 891850 total elements are enough to catch the accurate results for this problem.

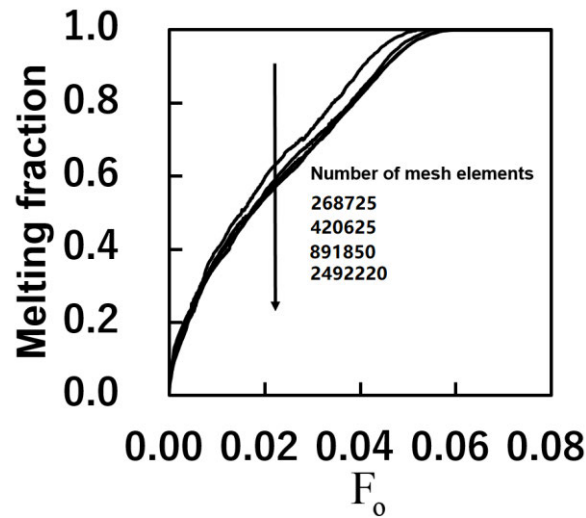


Fig. 6.4.3 A sample of grid independency for the melting fraction with $\varepsilon = 0.9$,
 $Ra_f = 10^6$ and $Ste = 0.6$

Chapter 7

Result and Discussions

In this chapter, the result and discussions of three problems will be explained. The volume average and pore scale methods will be used and the obtained results of two methods are compared for each problem.

7.1 Result and discussions for problem 1

7.1.1 Results for the volume averaged parametric analysis

A parametric study is performed to investigate the effects of dimensionless numbers as thermal conductivity ratio, thermal capacitance ratio and Sparrow number (Γ_s , Ω_s and Sp) on the temperatures of the solid and liquid phases. Since the transient behavior of temperature is important, the average of solid and fluid temperatures for the entire domain are calculated (i.e., Eq. (6.3)) and plotted.

Fig. 7.1.1 shows the change of mean temperature of solid and fluid for the case of $\Omega_s = 0.01$, $\Gamma_s = 1$, $Sp = 50, 250$ and 1000 . As it can be seen from Fig. 7.1.1 (a), there is an obvious temperature difference between the solid and fluid mean temperatures before they become steady state. Since the value of Sparrow number is low (referring to high convection thermal resistance), the heat exchange between the solid and fluid is weak and a non-equilibrium heat transfer in the porous media is expected. By increasing the Sparrow number from 50 to 250, the heat exchange between the solid and fluid phases increases and the temperatures of the solid and fluid phases approach to each other. Further increase in Sparrow number (from 250 to 1000) causes the fluid and solid phase mean temperatures become considerably close to each other and almost a local thermal equilibrium can be observed. The difference between the dimensionless temperature of solid and fluid (i.e., σ) can be a good parameter to show the magnitude of local thermal non-equilibrium. This difference for four Sparrow number is shown in Fig. 7.1.1 (d). As can be seen for $Sp = 1000$, the maximum temperature difference between the solid and liquid is 0.016 showing almost an equilibrium state, while the maximum value of σ for $Sp = 50$ is 0.13 indicating a local thermal non-equilibrium state.

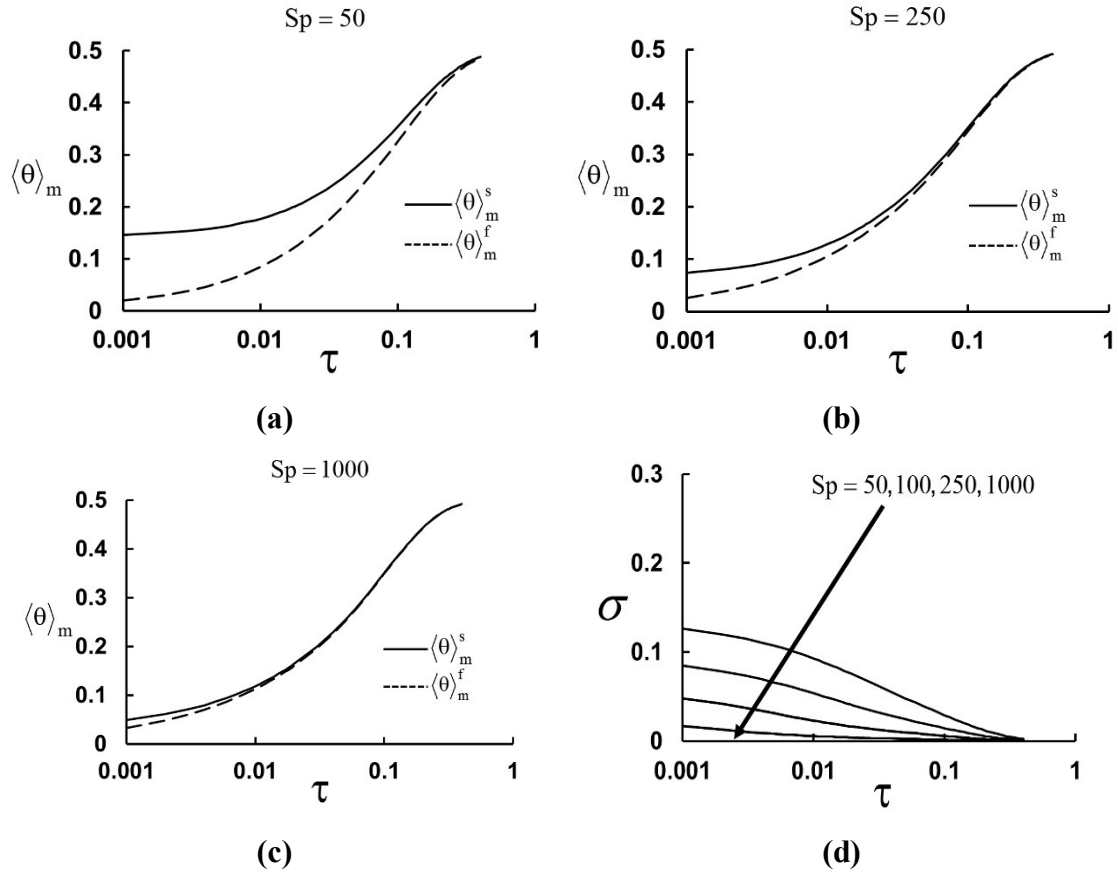


Fig. 7.1.1 The change of dimensionless mean temperatures of solid and fluid and the difference between them with dimensionless time when $\Gamma_s = 1$, $\Omega_s = 0.01$ (a)

$Sp = 50$ (b) $Sp = 250$ (c) $Sp = 1000$ (d) σ value for
 $Sp = 50, 100, 250, \text{ and } 1000$

The parameter values of Fig. 7.1.2 are the same with Fig. 7.1.1 except the solid dimensionless thermal conductivity $\Gamma_s = 0.5$. The values of α_s^* (i.e., $\alpha_s^* = \Gamma_s / \Omega_s$) and α_f^* (i.e., $\alpha_f^* = \Gamma_f / \Omega_f$) can be calculated by using Eqs. (5.15-5.17). By decreasing the solid dimensionless thermal conductivity from 1 to 0.5, the value of α_s^* / α_f^* decreases from 991 to 91 causing heat propagation in the solid and fluid phases becomes closer to each other and the temperature difference between the solid and fluid phases becomes smaller. This fact can be seen by the comparison of Figs. 7.1.1(a) and 7.1.2(a). Similar to the Fig. 7.1.1, by increasing Sp from 50 to 100, and from 100 to 1000, the solid and fluid dimensionless mean temperatures become closer due to the increase of heat exchange

between the solid and fluid phases. The temperature differences between the solid and fluid are shown in Fig. 7.1.2(d) to observe the magnitude of local thermal non-equilibrium. The comparison of 2(d) and 3(d) indicates the effect of Γ_s on the local thermal equilibrium condition. By decreasing the value of Γ_s from 1 to 0.5, the difference between the solid and fluid temperatures decreases.

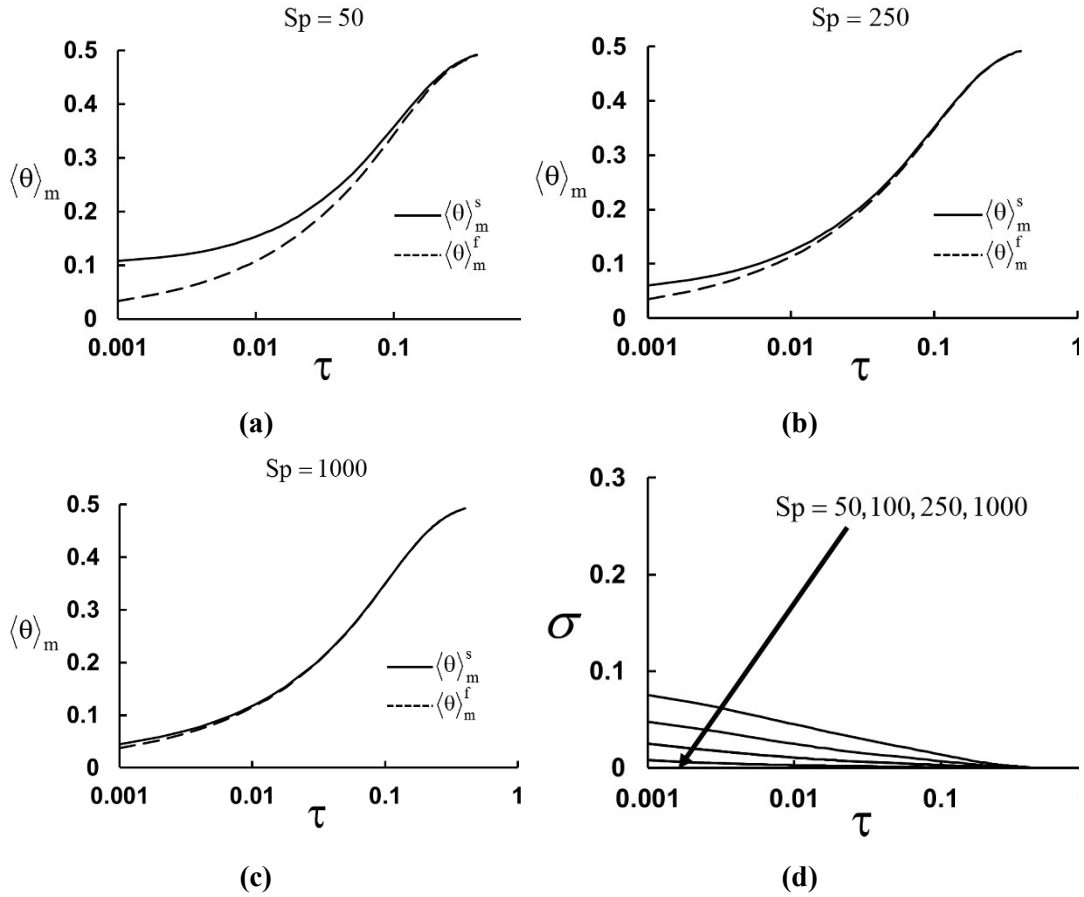


Fig. 7.1.2 The variation of dimensionless mean temperatures of solid and fluid phases and the difference between them with dimensionless time when $\Gamma_s = 0.5$,

$\Omega_s = 0.01$ (a) $Sp = 50$ (b) $Sp = 250$ (c) $Sp = 1000$ (d) σ value for $Sp = 50, 100, 250, \text{ and } 1000$

The change of solid and fluid phases temperature for further decrease of Γ_s from 0.5 to 0.01 is shown in Fig. 7.1.3. Further decrease in Γ_s from 0.5 to 0.01 causes the value of α_s^* / α_f^* decreases from 91 to 1. An equal heat propagation in the solid and fluid phases

exists for Fig.7.1.3. Therefore, for the all studied Sparrow number ($Sp = 50, 250, 1000$), a local thermal equilibrium can be observed. The results of Figs. 7.1.1, 7.1.2 and 7.1.3 clearly show that the heat exchange between the solid and fluid phases increases by increasing Sparrow number however, the critical Sparrow number (can be defined to distinguish the local thermal equilibrium from non-equilibrium) strongly depends on Γ_s .

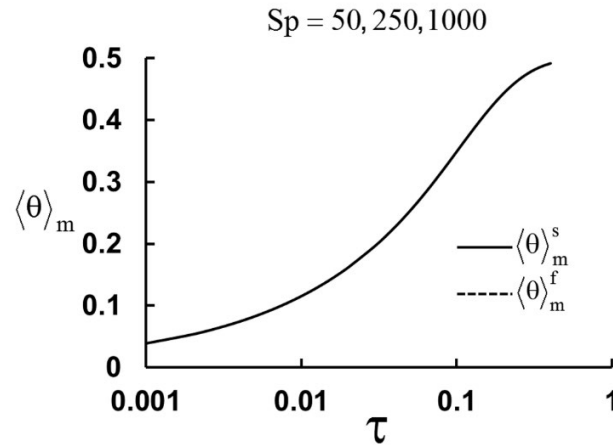


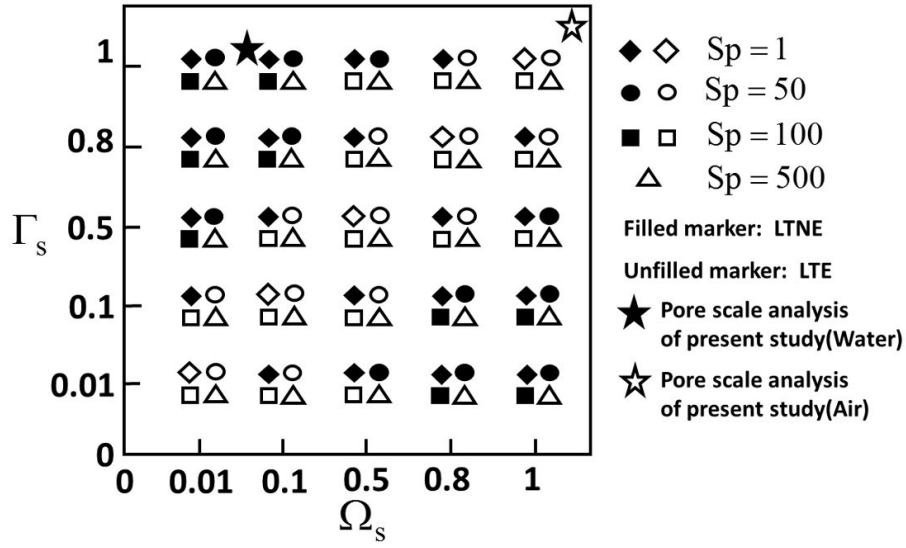
Fig. 7.1.3 The variation of dimensionless mean temperatures of solid and fluid phases with dimensionless time when $\Gamma_s = 0.01$, $\Omega_s = 0.01$ for $Sp = 50, 250$ and 1000 (two curves overlap)

A parametric study on the various values of Γ_s , Ω_s and Sp was done to separate the region of local thermal equilibrium from non-equilibrium. The results of the parametric study is shown in Fig. 7.1.4 for $Sp = 50, 100$ and 500 . The x axis of Fig. 7.1.4(a) shows Ω_s while the y axis refers to Γ_s . It is assumed that a local thermal equilibrium for the heat transfer in the closed cell porous media exists if $\sigma < 0.05$. This is the assumption of present study and it might be changed based on the application. Fig. 7.1.4(b) is presented in order to interpret the results of Fig. 7.1.4(a). It shows the value of α_s^* / α_f^* for the studied case of Fig. 7.1.4(a). For the studied cases of Fig. 7.1.4(a), the value of α_s^* / α_f^* changes from the large value of 991 to small value as 0.001 . Fig. 7.1.4 provides important information for the prediction of a local thermal non-equilibrium heat transfer process in a cavity with closed cell as follows;

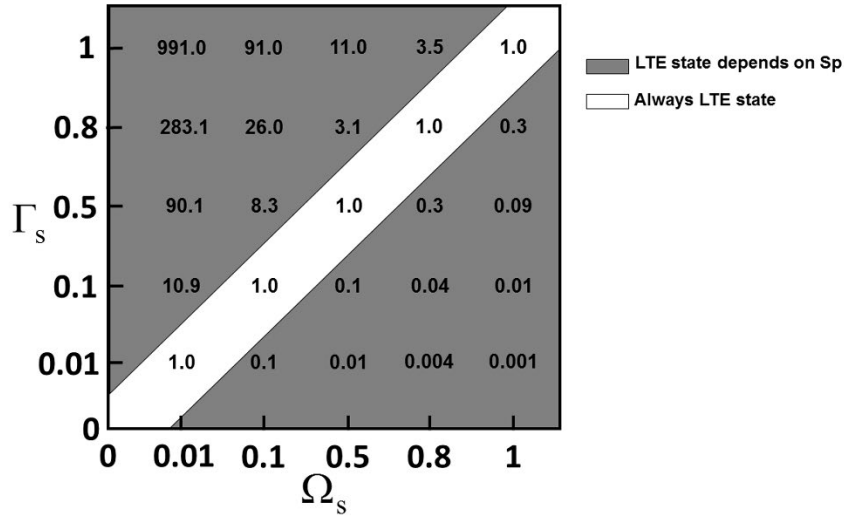
- For the value of $\alpha_s^* / \alpha_f^* = 1$, the propagation of heat in the solid and fluid is close to each other causing local thermal equilibrium state becomes independent of Sparrow number.
- Further increase or decrease in the value of α_s^* / α_f^* (such as 991 or 0.001), the possibility of local thermal non-equilibrium increases due to different speed of heat propagation in the solid and fluid phases. For instance, when $Sp = 50$, a local thermal non-equilibrium exists for the points of $\Omega_s = 0.01$ and $\Gamma_s = 1$ due the large difference in heat propagation of solid and fluid (Faster heat prorogation exists in the solid, $\alpha_s^* / \alpha_f^* = 991$).
- In addition to Ω_s and Γ_s , the Sparrow number plays an important role on the character of heat transfer through the closed cell porous media. By increasing the value of Sp , the source terms in qqs. (3)) and (31) becomes more active, and consequently the heat exchange between the solid and fluid increases. This increase of heat exchange increases the possibility of occurrence of local thermal equilibrium state. That is why, number of unfilled markers in the Fig. 7.1.4(a) for $Sp = 100$ is more than $Sp = 50$, or number of unfilled markers for $Sp = 500$ is greater than $Sp = 100$.
- For $Sp = 500$, all markers are unfilled showing considerable heat transfer between the solid and fluid phases despite of extremely high or low values of α_s^* / α_f^* (such as 991 or 0.001).
- It seems that α_s^* / α_f^* and Sp are two important parameters for the prediction of local thermal non-equilibrium for the onset of a heat transfer in closed cell of porous media. .

7.1.2 The pore scale and volume average results for real cases

A pore scale and a volume average study are done for a closed cell porous medium and the obtained results are used to support the comments of parametric study explained in previous section.



(a)



(b)

Fig. 7.1.4 Occurrence of local thermal equilibrium for the studied cases (a) local thermal equilibrium map according to Ω_s and Γ_s (assumption for the local thermal equilibrium is $\sigma \leq 0.05$) (b) the variation of thermal diffusivity ratio (α_s^* / α_f^*) with respect to Ω_s and Γ_s

7.1.2.1 Results for the porous media with water in cells

Fig. 7.1.5 shows the temperature and velocity distributions for both the pore scale and volume averaged domains when $\Omega_s = 0.068$, $\Gamma_s = 1.06$, $Sp = 46.7$ and $Ra_f = 10^5$, as given in Table 7. 1. The value of Sparrow number is calculated from the pore scale results when

$Ra_f = 10^5$. The values of fluid thermal capacitance and thermal conductivity are found as $\Omega_s = 0.068$ and $\Gamma_s = 1.06$, and the thermal diffusivity ratio is calculated as 300 (i.e. $\alpha_s^* / \alpha_f^* = 300$). This value of α_s^* / α_f^* is considerably larger than 1 and furthermore the Sparrow number is low ($Sp = 46.7$). Based on the previous section comments, the possibility of the existence of local thermal non-equilibrium under this condition is high and this fact is investigated below.

Table 7.1. Thermophysical properties and dimensionless governing parameters for water and air in the pore scale and volume averaged studies

Parameters	Water	Air
k (W/m K)	0.61	0.026
ρ (kg/m ³)	996	1.177
C_p (J/kg K)	4180	1005
μ (Pa.s)	8.544e-4	1.86e-5
$k_{eff,f}$ (W/m K)	0.58	0.025
Pr_f	5.85	0.71
Ra_f	$10^2, 10^5$	$10^2, 10^5$
Pr_e	0.30	0.34
Ra_e	5.066, 5065.9	48, 47996.1
ψ	28.88	1.82
α_s^*	15.60	0.98
Ω_s	0.068	1.11
α_f^*	0.053	0.50
Ω_f	1.04	0.0048
Sp	46.75 for $Ra_f = 10^5$ 39.28 for $Ra_f = 10^2$	1.91 for $Ra_f = 10^5$ 1.74 for $Ra_f = 10^2$

From Fig. 7.1.5(a), it is seen that the solid phase temperature is faster than the fluid phase due to the faster propagation of heat in the solid at the starting period ($\tau = 0.032$). By increasing the time to $\tau = 0.16$ and $\tau = 0.32$, the pore scale temperatures of both solid and fluid phases become closer to each other. The volume averaged temperatures (middle and bottom cavities of Fig. 7.1.5) also show the same behavior of the pore scale one. It should be mentioned that heat conduction equations for the solid and fluid phases are solved and that is why no velocity is seen in the results of the volume averaged domains.

Fig. 7.1.6 shows the comparison of solid and fluid dimensionless mean temperatures ($\langle \theta \rangle_m^s, \langle \theta \rangle_m^f$) obtained from the pore scale and volume averaged analysis for $Ra_f = 10^2$ and 10^5 , respectively.

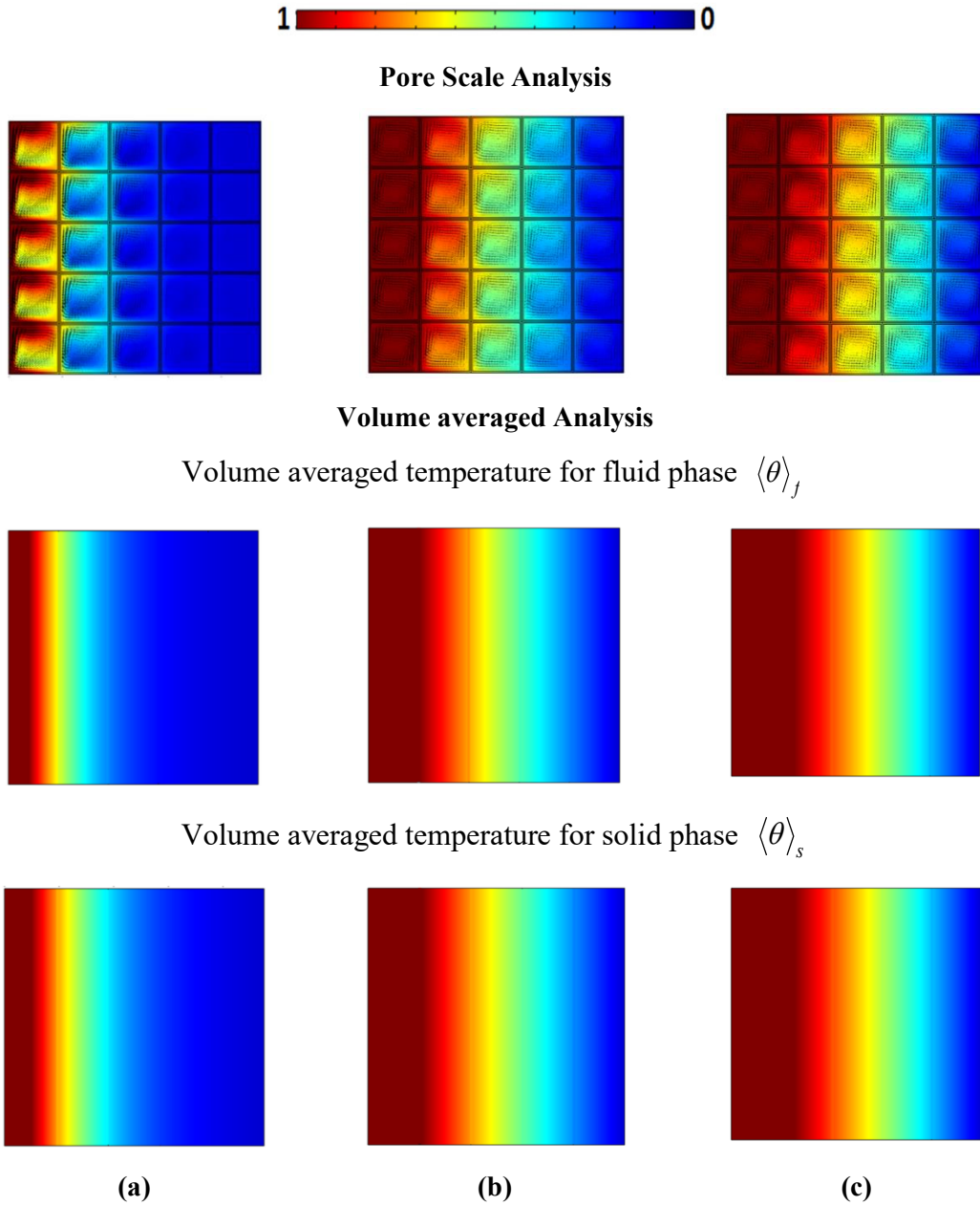


Fig. 7.1.5 The temperature and velocity distributions of the water in the cells of domain with $Ra_f = 10^5$ and the same domain for volume averaged when $\Omega_s = 0.068$,

$\Gamma_s = 1.06$ and $Sp = 46.7$ for three different time steps (a) $\tau = 0.0320$ (b) $\tau = 0.1602$
(c) $\tau = 0.3205$

A good agreement between the volume averaged and pore scale analysis can also be observed proving the correctness of our volume average study. The small differences between the pore scale and the volume averaged results may be due to the definition of interfacial heat transfer coefficient (Eq. (6.1)) in which the average of local heat transfer coefficient both in time and space was considered. A local thermal non-equilibrium for a large period at the beginning of the heat transfer process can be seen, supporting the comments of the parametric volume averaged study. Large difference in heat propagations due to the high value of α_s^* / α_f^* (i.e. 300) and weak heat exchange between the solid and fluid phases causes a local thermal non-equilibrium exist.

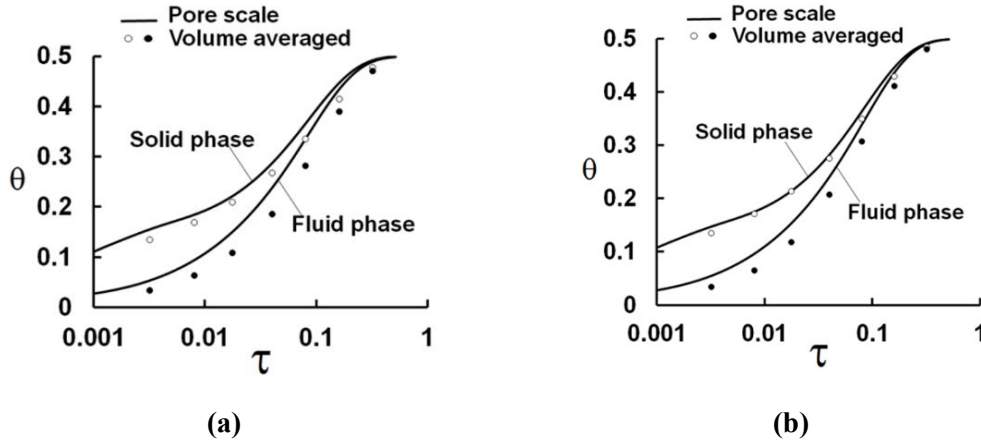


Fig. 7.1.6 The comparison of pore scale and volume averaged results for the centerline of the porous media in which voids filled with water for $\Omega_s = 0.068$,

$\Gamma_s = 1.06$ (a) $Sp = 39.2$ (for $Ra_f = 10^2$) (b) $Sp = 46.7$ (for $Ra_f = 10^5$)

7.1.2.2 Results for porous media filled with air in cells

Fig. 7.1.7 shows the temperature and velocity distributions of a closed cell porous media when the voids are filled with air for $\Omega_s = 1.11$, $\Gamma_s = 1.08$, $Sp = 1.91$ and $Ra_f = 10^5$, as given in Table 7.1. The value of thermal conductivity ratio (α_s^* / α_f^*) is calculated as 2.09. The value of thermal diffusivity ratio takes the attention since it is around 1. Although the

Sparrow number is extremely low, a local thermal equilibrium can be expected due to almost equal propagation of heat in the solid and fluid.

Fig. 7.1.7 indicates that the propagation of heat in the solid and fluid are the same for the solid and fluid phases. This fact can be clearly seen from both pore scale and volume average temperature distributions. Fig. 7.1.8 shows the solid and fluid dimensionless mean temperatures ($\langle \theta \rangle_m^s, \langle \theta \rangle_m^f$) for $Ra_f = 10^2$ and 10^5 at the center of the domain for different time steps. Almost, a local thermal equilibrium state can be seen from this figure both from volume average and pore scale results.

The values of Ω_s and Γ_s are known and the location of the above two cases in the local thermal equilibrium map (Fig. 7.1.4) can be found. The location of two cases are marked in Fig. 7.1.4(a) for the case of air ($\Omega_s = 1.11, \Gamma_s = 1.08, Sp = 1.91$) and for the case of water ($\Omega_s = 0.068, \Gamma_s = 1.06, Sp = 48.6$). The location of marker for air case is in right place validating Fig. 7.1.4. A local thermal equilibrium exists for the case of air due to the small values of $\alpha_s^* / \alpha_f^* = 2.09$ referring to almost identical heat propagation in solid and fluid in spite of low value of Sparrow number ($Sp = 1.91$). Similar to the case of air, the location of marker for water case is correct, and a local thermal non-equilibrium must exist for the water case due to faster propagation of heat in the solid comparing to fluid phase ($\alpha_s^* / \alpha_f^* = 300$).

7.2 Result and discussions for Problem 2

The mechanism of heat transfer in closed cell cavities with different shapes such as right angle porous trapezoidal enclosure, triangular enclosure and even partially opened cavity were discussed in literature (Varol et al. (2009) , Oztop et al. (2009) (2011)). In all of those studies there is one Rayleigh number defined based in two temperatures in the domain. But, in the closed cell porous media there are two kinds of cavity as pore scale cavity and the entire domain cavity. Hence two kinds of Rayleigh number as pore scale Rayleigh number and the entire cavity Rayleigh number can be defined. In this study, the Rayleigh number (i.e., Ra_f) refers to the entire cavity Rayleigh number.

Fig. 7.2.1 (a) shows the temperature and velocity distributions of the studied domain for $\varepsilon = 0.9$ and $Ra_f = 10^3$ at $F_o = 0.67$.

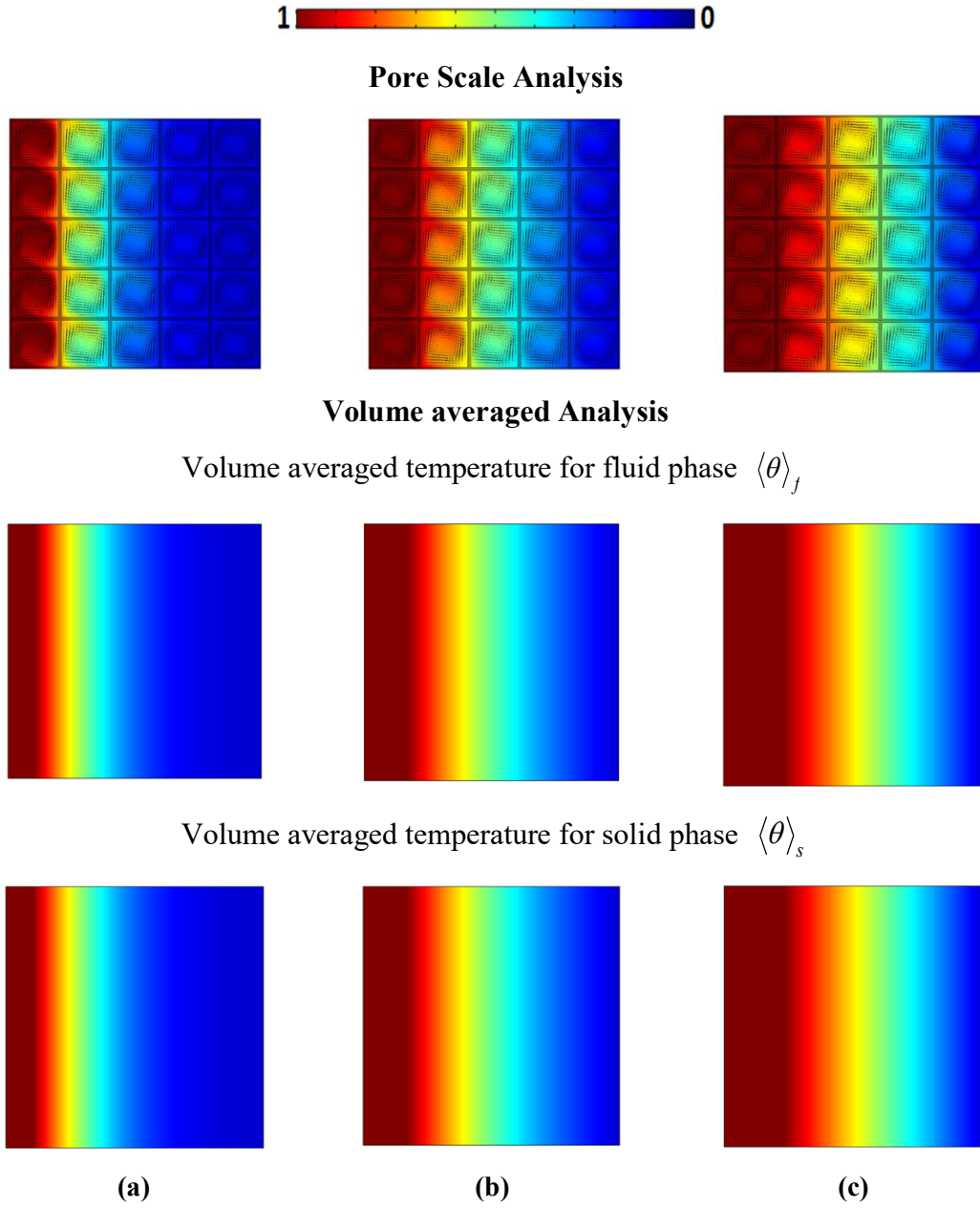


Fig. 7.1.7 The temperature and velocity distributions of air in the cells of domain with $Ra_f = 10^5$ and for the same domain for volume averaged when $\Omega_s = 1.11, \Gamma_s = 1.08$ and $Sp = 1.91$ for three different time steps (a) $\tau = 0.0510$ (b) $\tau = 0.1275$ (c) $\tau = 0.2550$

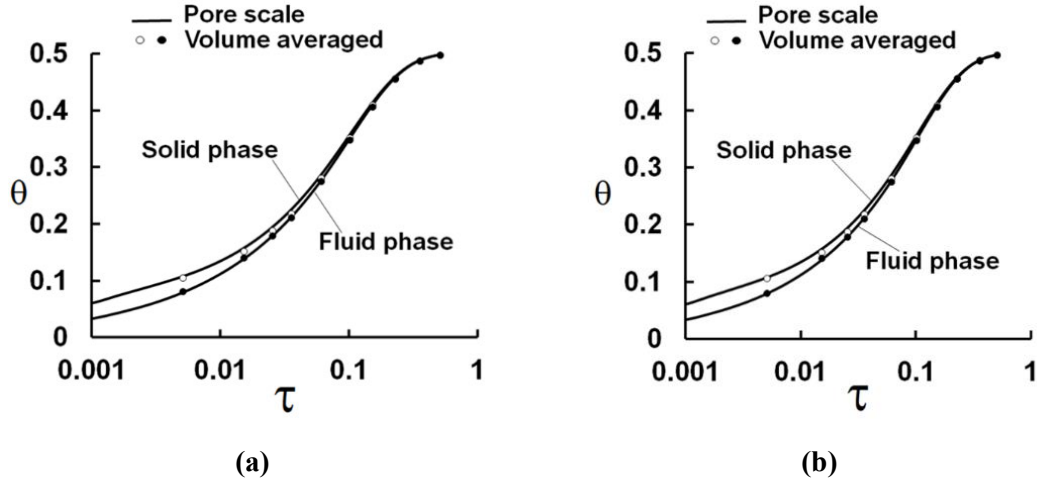


Fig. 7.1.8 The comparison of pore scale and volume averaged results for the centerline of the porous media in which voids filled with air for $\Omega_s = 1.11$, $\Gamma_s = 1.08$

(a) $Sp = 1.74$ (for $Ra_f = 10^2$) (b) $Sp = 1.91$ (for $Ra_f = 10^5$)

Fig. 7.2.1 (b) shows the temperature profile in the center line of the second row in studied cavity for different Rayleigh number as $Ra_f = 0, 10, 10^2, 10^3, 10^4$ at the same time step. All temperature profiles overlap each other showing that Rayleigh number does not have significant effect on the heat and fluid flow in the present problem when it is less than 10^4 . That is why, the continuity and momentum equations are discarded in the pore scale study and only the conduction heat transfer equations for the solid and fluid phases are taken into account.

7.2.1 Comparison of Pore scale and volume average results

In this study many runs were done to validate the VAM results based on the new formulation for phase change process assisted with closed cell porous media.

In general, a good agreement between the VAM and PSM was observed. In this section, two examples of the preformed studies are presented. Fig.7.2.2 shows the temperature distributions of PSM and VAM for the closed cell porous media when $\varepsilon = 0.9$ and $Ste = 1$ for the pore scale analysis and $Sp = 35$, $\alpha_r = 668$, and $Ste = 1$ for the volume average equations. These figures represent the temperature distributions for the

solid and liquid phases at the different dimensionless time of $F_o = 0.13$, $F_o = 0.34$ and $F_o = 0.67$. For the Fig. 7.2.2(a), the melting is rapid in the first column while in the last column no melting can be observed. By increasing time, the melted area expands and the melting fraction increases in the cavity. High speed heat propagation in the solid phase (frame) can be seen clearly in dimensionless time steps of $F_o = 0.13$, $F_o = 0.34$. Fig. 7.2.2 (b) shows the results of VAM for the solid and liquid phases. The domain is continuous since the independent parameters are integrated over the whole domain. The temperature increases by passing time in both solid and fluid phases, however it seems the heat transfer in the solid phase is the faster compared to the fluid phase. In order to show the consistence of the PCM and VAM results, Fig. 7.2.2(c) is presented in which the temperature profiles in the middle line of the cavity ($Y^* = 0.5$) for the solid and fluid phases at the same time step are plotted. The cell average of temperatures calculated from PSM results is also shown in the same figure. At the initial stages the heat transfer in the solid phase is the faster, however the temperatures become equilibrium at the end of melting process.

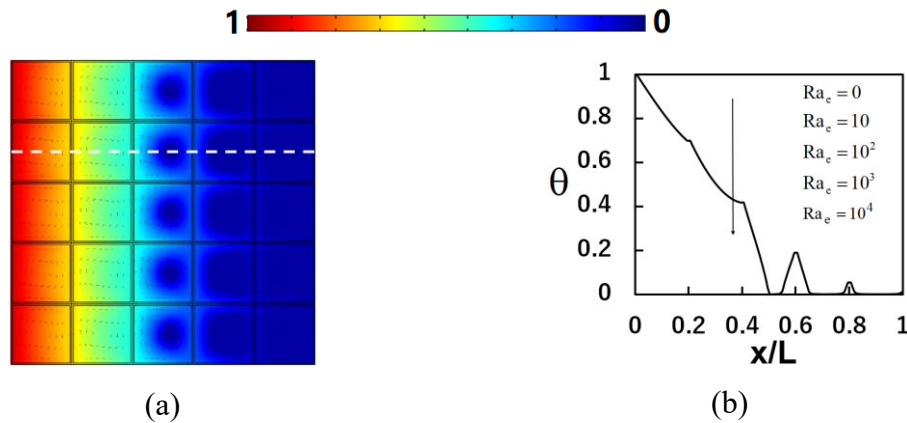
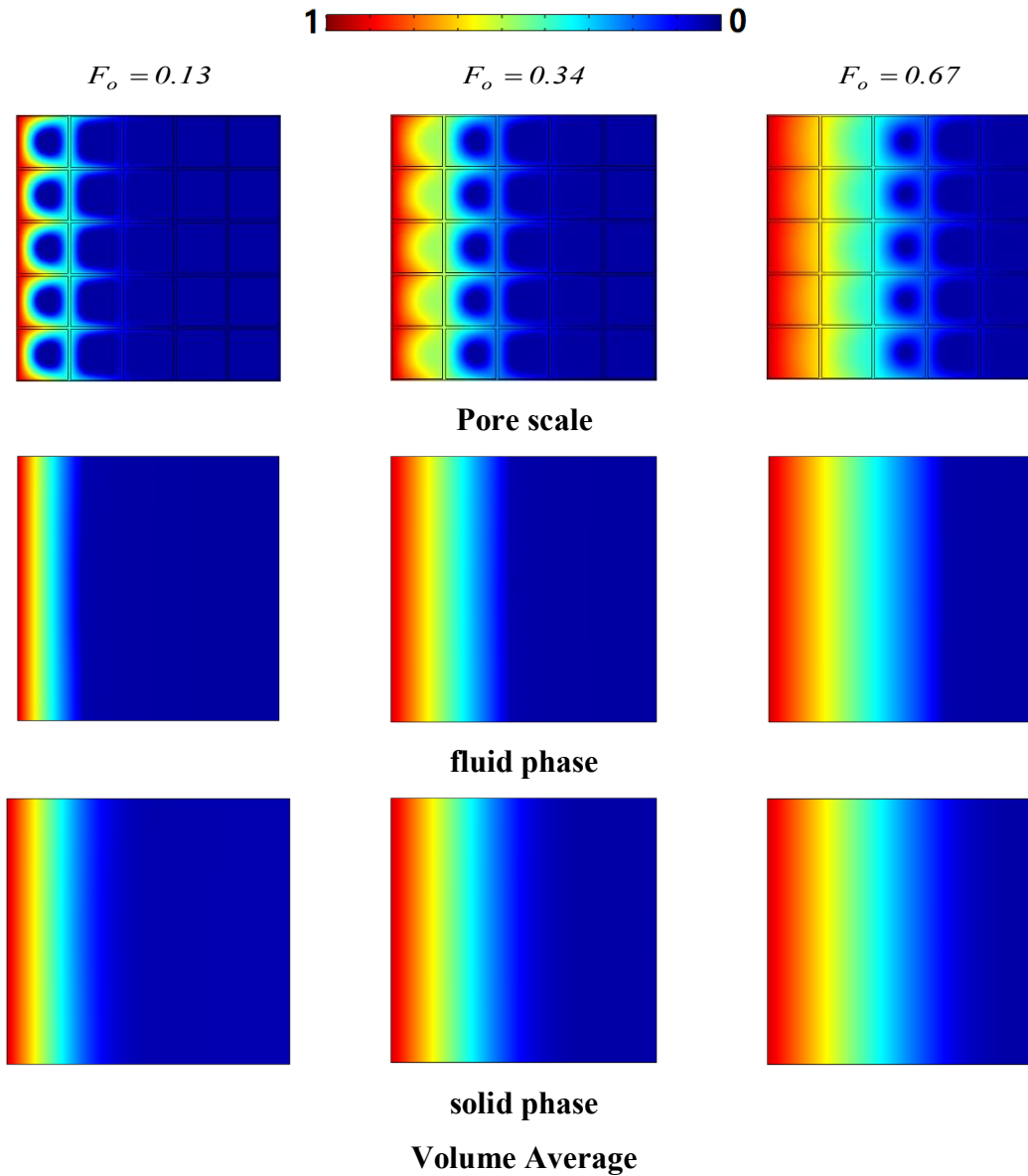
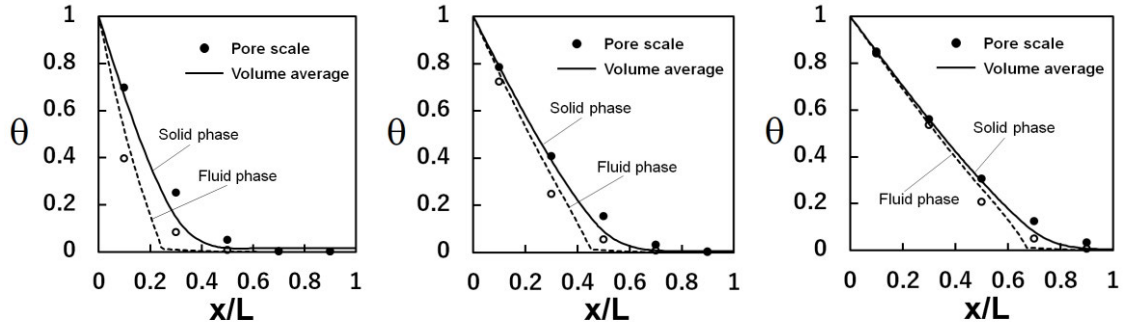


Fig. 7.2.1 Domination of heat conduction for the phase change in a closed cell porous medium (a) Temperature and velocity distributions for $Ra_f = 10^3$ in cavity with $\varepsilon = 0.9$. (b) The temperature profile in the center line of the second row of cavity for four different values of Ra number at $F_o = 0.67$

The same comparisons between the pore scale and volume average results under the same condition of Fig. 7.2.2 but for porosity of 0.7 is shown in Fig. 7.2.3. Good agreement between the PSM and VAM can be observed when $\varepsilon = 0.7$. The values of the Sparrow number and thermal diffusivity ratio for the volume average equations are 17 and 668, respectively. The melting period is shorter due to the larger amount of solid phase distributed in the entire domain. The faster heat transfer in the solid phase in initial stages can be observed more clearly due to the increase of cross section of the solid frame and reduction of thermal resistance in the solid phase.



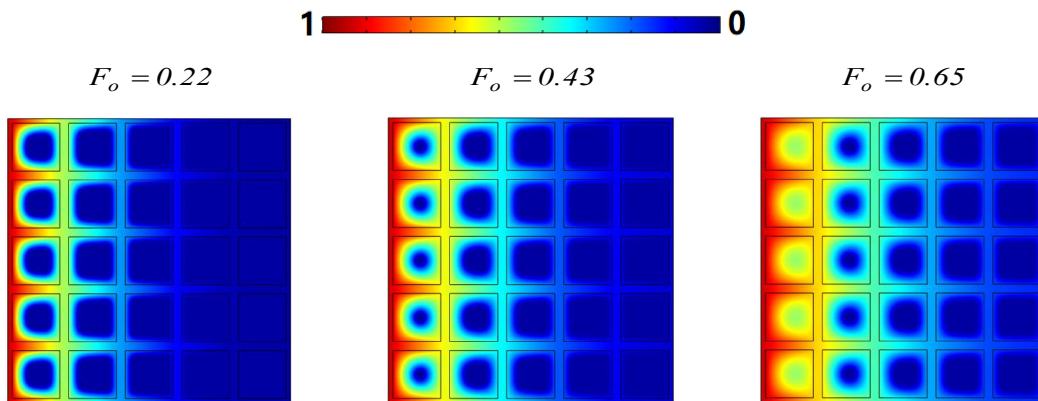


Temperature profiles

Fig. 7.2.2 The comparisons of the pore scale and volume average temperatures of solid and fluid phases at different time steps with $\varepsilon = 0.9$ and $Ste = 1$ for the pore scale equations and $Sp = 35$, $\alpha_r = 668$ and $Ste = 1$ for the volume average equations

Both Fig.7.2.2 and 7.2.3 show the good agreement between PSM and VAM results proving the validation of VAM for analyzing of heat and fluid flow for melting in the closed cell porous media.

The comparisons of melting fraction of PSM and VAM approaches for the three different porosities shown in Fig. 7.2.4. The melting fraction is shown in two diagrams both for the dimensional and dimensionless time. In both figures, a good agreement between the VAM and PSM can be seen. It should be mentioned that the melting fraction curves in Fig. 7.2.4(a) are different since the closed cell porous media with $\varepsilon = 0.7$ has more metal amount compared to the porous media with $\varepsilon = 0.9$.



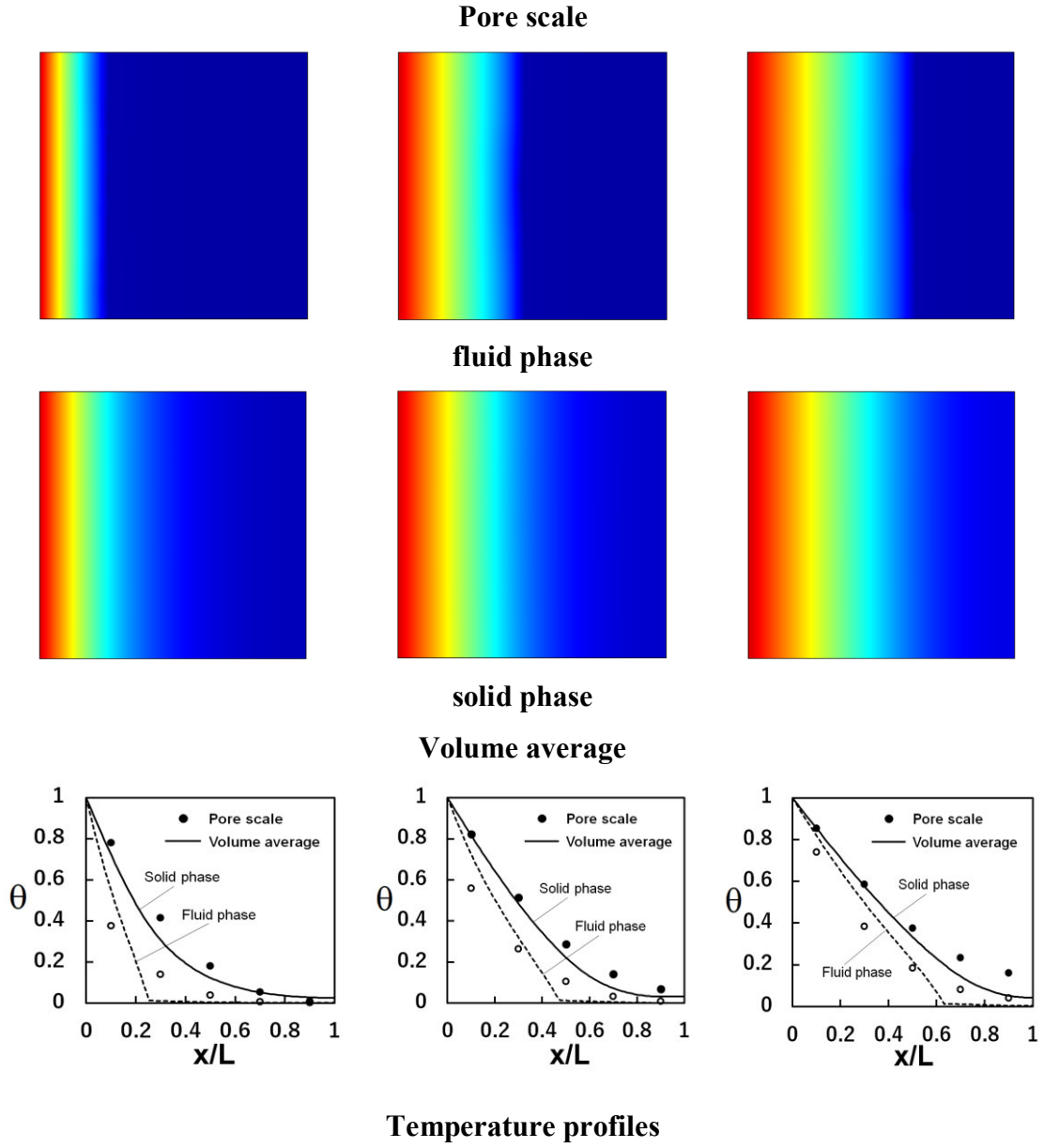


Fig. 7.2.3 The comparisons of the pore scale and volume average temperatures of solid and fluid phases at different time steps for $\varepsilon = 0.7$ and $Ste = 1$ for pore scale equations, and $Sp = 17$, $\alpha_r = 668$ and $Ste = 1$ for the volume average equations

However for the Fig. 7.2.4(b), the curves overlap each other since the value of $\alpha_r = 668$ and $Ste = 1$ are the same for three cases and the values of Sp are close to each other for three cases ($Sp = 17, Sp = 22, Sp = 35$).

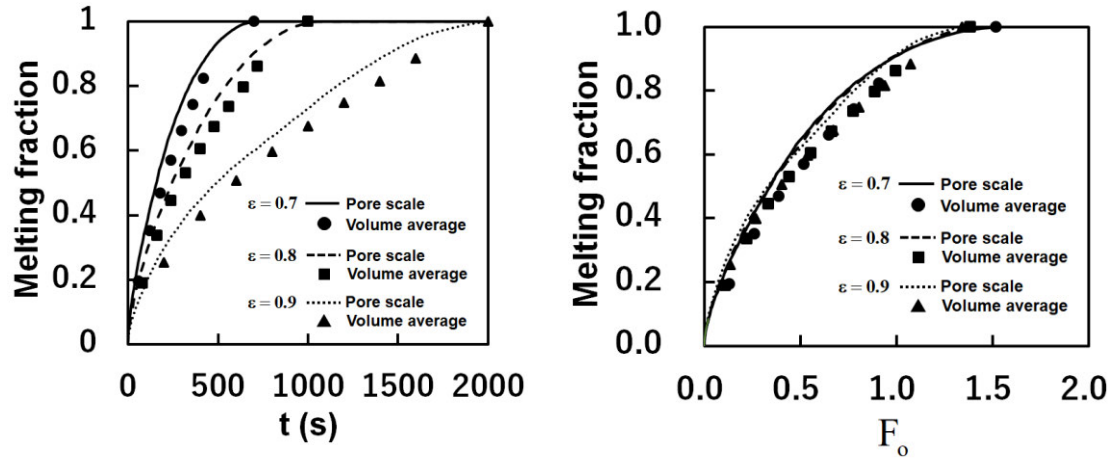


Fig. 7.2.4 Comparisons of the melting fraction between the pore scale and volume average results for three different porosities as $\varepsilon = 0.7, 0.8, 0.9$ when $Ste = 1$

7.2.2 Effective thermal conductivity and local Sparrow number

Effective thermal conductivity and interfacial heat transfer coefficient are two parameters which should be known to obtain the VAM results shown in the previous section. The change of effective thermal conductivity and the effective porosity is calculated and shown in Fig.7.2.5 for the different porosity value when $k_f / k_s = 0.0093$ for the cavity with no melted PCM and $k_f / k_s = 0.0026$ for the cavity with melted PCM. There is small differences between k_{eff} and ε^* of melted PCM (water) and no melted PCM (ice) cavities. The value of k_{eff} decreases with the increase of porosity due to the decreasing of metal amount while the value of ε^* increases. It should be mentioned that $k_{eff,f}$ and $k_{eff,s}$ are calculated in terms of k_{eff} and ε^* by using Eqs (4.11) and (4.12).

The interfacial heat transfer coefficient is an important parameter in the volume average method, unfortunately the number of studies on the interfacial heat transfer coefficient for the closed cell porous media is limited (Wang et al. (2019)).

In this study, the value of the interfacial heat transfer coefficient is determined from the pore scale results and used for calculation of the Sparrow number. Fig. 7.2.6 shows one sample of the obtained diagrams in which the change of local heat transfer coefficient with dimensionless time for $\varepsilon = 0.9$, $Ste = 1$ and $\alpha_r = 668$ for five different columns of the pore scale cavity is drawn.

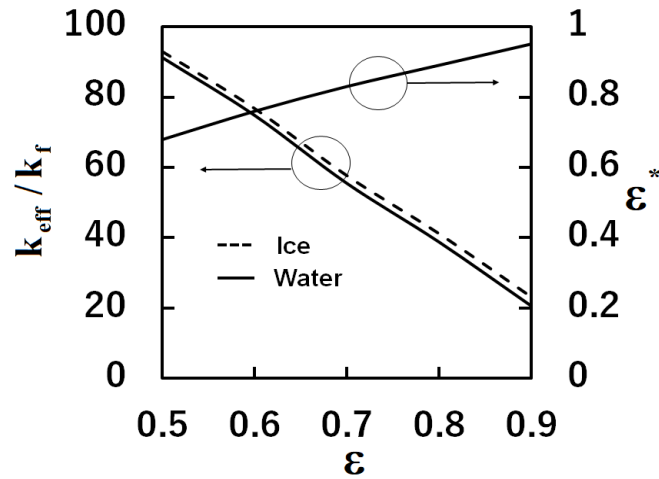


Fig. 7.2.5 The change of effective thermal conductivity and effective porosity with the different porosity for ice and water

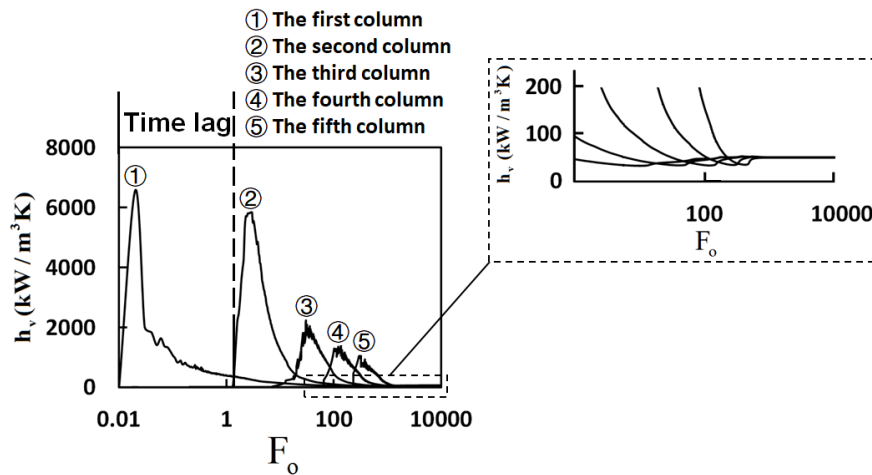


Fig. 7.2.6 The change of local heat transfer coefficient and Sparrow number for five different columns of the pore scale cavity when $Ste = 1$ and $\alpha_r = 668$

As can be seen from the figure, the interfacial heat transfer coefficient is not constant during the melting process and it changes by time. If the change of interfacial heat transfer coefficient with time for the second column is only considered, three different regions can be observed as no melted region (pure conduction heat transfer) in which the value

of h_v is almost constant, slurry region in which the value of h_v suddenly increases due to the phase change and then it decreases by the melting of PCM and finally fully melted region in which the value of h_v refers to the single phase pure convective heat transfer and the value of h_v is constant. Furthermore, the change rate of h_v not only depends on time but also varies with the location of cells. For the closest cell to the hot wall, the value of h_v rapidly increases and decreases while for the last cell the increase or decrease rate of h_v is the slower. The change trend of h_v with time is almost the same for all cells however a time lag exists between different columns. The increase of h_v in the first column is observed just after starting of the melting period while after a long time lag the same trend is seen for the last column. The final value of h_v is very close to each other after the melting process in the entire PCM referring to the value of h_v for the pure convective heat transfer.

As it can be seen, the change of h_v with dimensionless time is complicated to be formulized, however in this study the time and space average value of h_v is calculated and used in the volume average energy equations for the solid and fluid phases. The good agreement between the volume average and pore scale results is shown in the previous section proving that the time and space average of h_v provides sufficiently accurate volume average results.

7.2.3 Analysis of local thermal equilibrium and non-equilibrium assumptions

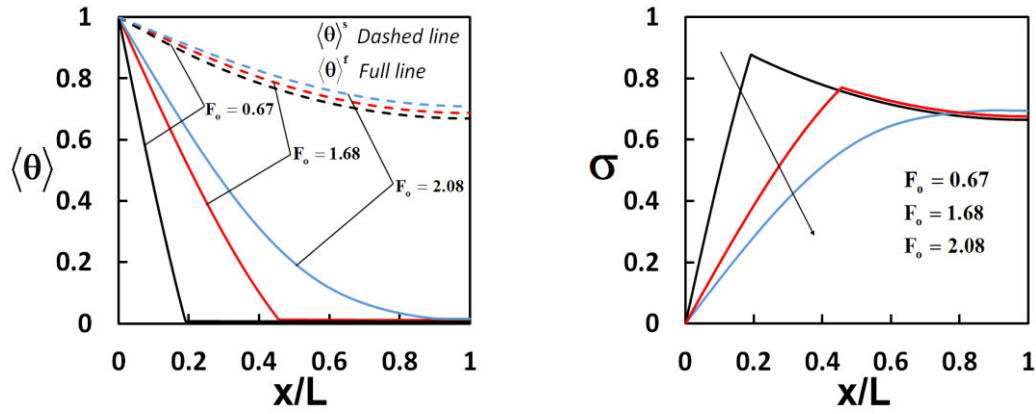
In this section, a parametric study is performed to investigate the effects of three dimensionless parameters as α_r , Ste and Sp on the local thermal equilibrium state. The volume average equations (Eqs. 5.29 and 5.30) are solved for different values of three dimensionless parameters in the range of $1 < \alpha_r < 500$, $1 < Sp < 500$ and $Ste = 0.3$ and 1 .

Fig. 7.2.7 shows the change of the volume average temperatures for the solid and fluid phases with $\alpha_r = 500$ and $Sp = 1, 10, 100, 500$ when $Ste = 1$. Fig. 7.2.7 (a)

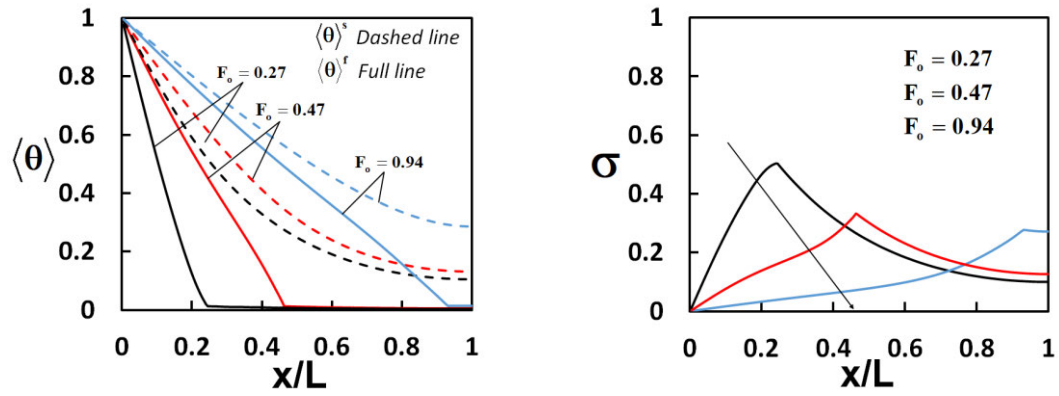
shows the volume average solid and fluid temperature profiles at $Y^* = 0.5$ when $\alpha_r = 500$ and $Sp = 1$ for different time steps as $F_o = 0.67, 1.68$ and 2.08 . In this study a parameter as σ ($\sigma = \langle \theta \rangle^s - \langle \theta \rangle^f$) is defined to show the level of local thermal equilibrium. As it can be seen, there is big difference between $\langle \theta \rangle^s$ and $\langle \theta \rangle^f$ showing an obvious local thermal non-equilibrium condition. In the same Figure (Fig. 7.2.7 (a)), the change of σ for three different time is shown. The maximum difference between $\langle \theta \rangle^s$ and $\langle \theta \rangle^f$ belongs to the initial stage ($F_o = 0.67$). By increasing of time, the degree of local thermal non-equilibrium also decreases. The main reason of the high degree of local thermal non-equilibrium in Fig. 7.2.7 (a) is the considerable high speed of heat propagation in the solid phase compared to the fluid phase due to high value of thermal diffusivity ratio ($\alpha_r = 500$) and the convection thermal resistance between the solid and fluid phases due to low value of Sparrow number ($Sp = 1$). The same diagram of Fig. 7.2.7 (a) is plotted for the same value of α_r (i.e., $\alpha_r = 500$) and $Sp = 10$ and presented in Fig.11(b). As it can be seen, still a local thermal non-equilibrium state between the solid and fluid phases and the same trend of variation of $\langle \theta \rangle^s$ and $\langle \theta \rangle^f$ exist, however the values of σ become smaller compared to Fig. 7.2.7 (a). The increase of Sparrow number increases the heat interaction between the solid and fluid phases and that is why the degree of local thermal non-equilibrium becomes smaller. The Fig. 7.2.7 (c) and 7.2.7 (d) show the change between $\langle \theta \rangle^s$ and $\langle \theta \rangle^f$ and also σ in three different time steps of the same thermal diffusivity ratio when $Sp = 100$ and 500 , respectively. By increasing the value of Sparrow number, the maximum value of σ becomes the smaller and its value is 0.3 for $Sp = 300$ when $F_o = 0.27$ and 0.1 for $Sp = 500$ when $F_o = 0.07$. As it can be seen from Fig. 7.2.7, a perfect local thermal equilibrium can be observed for $Sp = 500$ in the entire melting period. Fig. 7.2.7 clearly shows that Sparrow number plays an important role on the melting process and by increase of value of Sparrow number, a local thermal equilibrium can be achieved.

The same runs for different values of α_r as $1.7, 10, 100$ and 300 are done and based on the definition of local thermal equilibrium condition given by Eq. (6.5), a chart is

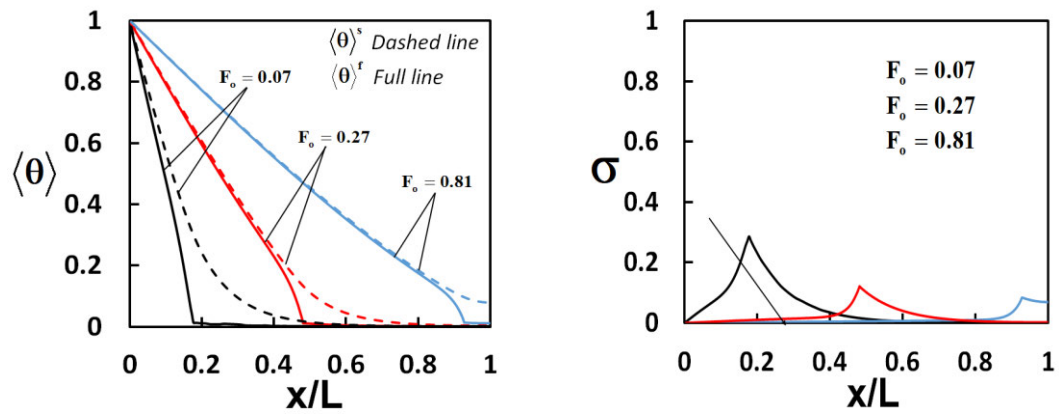
obtained and shown in Fig. 7.2.8 when $Ste = 1$. This chart clearly shows the effects of thermal diffusivity ratio and sparrow number.



(a) $Sp = 1$



(b) $Sp = 10$



(c) $Sp = 100$

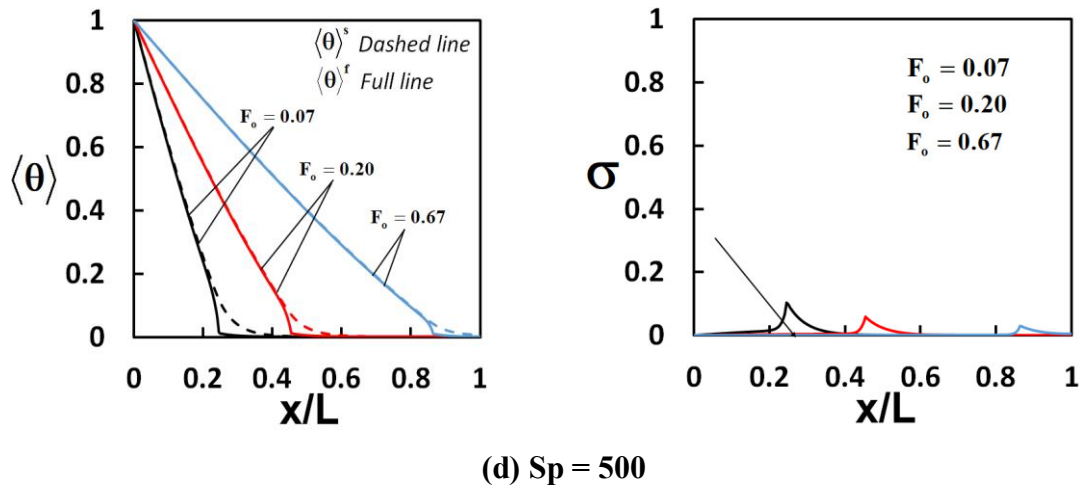


Fig. 7.2.7 The change of the solid and fluid volume average temperatures and σ for different values of Sparrow number when $\alpha_r = 500$ and $Ste = 1$

By decreasing of the value of α_r the possibility of the local thermal equilibrium increases since the rate of propagation of heat in the solid and fluid phases becomes closer to each other. Similarly, the local thermal equilibrium can exist for the high value of Sparrow number such as $Sp = 500$.

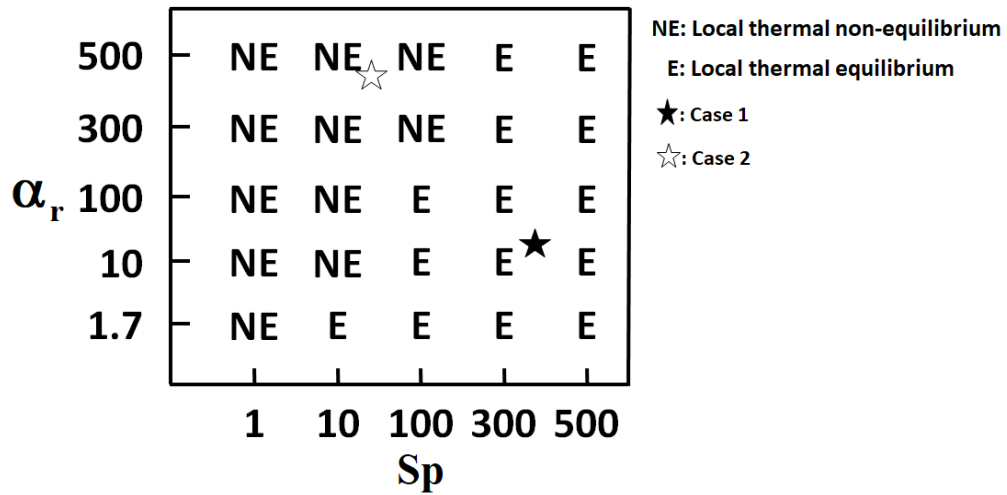


Fig. 7.2.8 Local thermal equilibrium condition in terms of different values of Sparrow number and thermal diffusivity ratio when $Ste = 1$

7.2.4 Validation of the thermal equilibrium condition chart

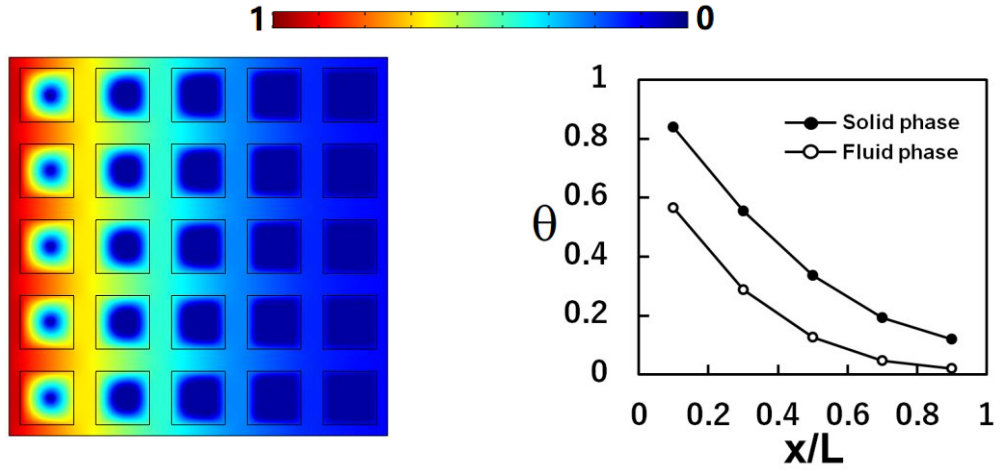
As it can be seen from the chart of Fig. 7.2.8, the regions for the local thermal equilibrium and non-equilibrium can be separated. A pore scale study is performed to support and to validate the results of chart presented in Fig. 7.2.8. The pore scale results for Case 1 (Ti-6Al-4V-water) and Case 2 (Al 2024-T6-water) are obtained. The thermophysical properties of the two metals are given in Table 7.2. Before doing the pore scale study, the interfacial heat transfer coefficient can be calculated roughly from the study of Wang et al. (2019). The values of h_v are calculated as $53917 \text{ W/m}^2\text{K}$ and $180226 \text{ W/m}^2\text{K}$ for the Case 1 and Case 2. Based on these values of interfacial heat transfer coefficients, the values of Sparrow number for the Case 1 and 2 are calculated as $Sp = 367$ and $Sp = 18$, respectively. Furthermore, the values of thermal diffusivity ratio for the Case 1 and Case 2 are $\alpha_r = 22$ and $\alpha_r = 499$. The positions of two studied cases are shown in Fig. 7.2.8. It can be clearly seen that Case 1 is in the local thermal equilibrium region while Case 2 is in the local thermal non-equilibrium region.

Fig. 7.2.9 shows that the pore scale results for the studied cases. The pore scale results for two cases are obtained and shown in Fig. 7.2.9 (a) and 7.2.9 (b). Fig. 7.2.9 (a) shows the temperature distribution and temperature profile of the solid and fluid phases at $Y^* = 0.5$ for Case 1 at $F_o = 0.15$ and Fig. 7.2.9 (b) shows the same temperature distribution and temperature profiles at $Y^* = 0.5$ for the Case 2 at $F_o = 0.36$. A clear local thermal non-equilibrium can be seen for Case 1 while a perfect thermal equilibrium exists for Case 2. These two examples validate the presented results in the chart of Fig. 7.2.8 and show that just knowing of Sparrow number and thermal diffusivity ratio may be sufficient to determine the state of local thermal equilibrium for phase change in a closed cell porous medium in which melting occurs.

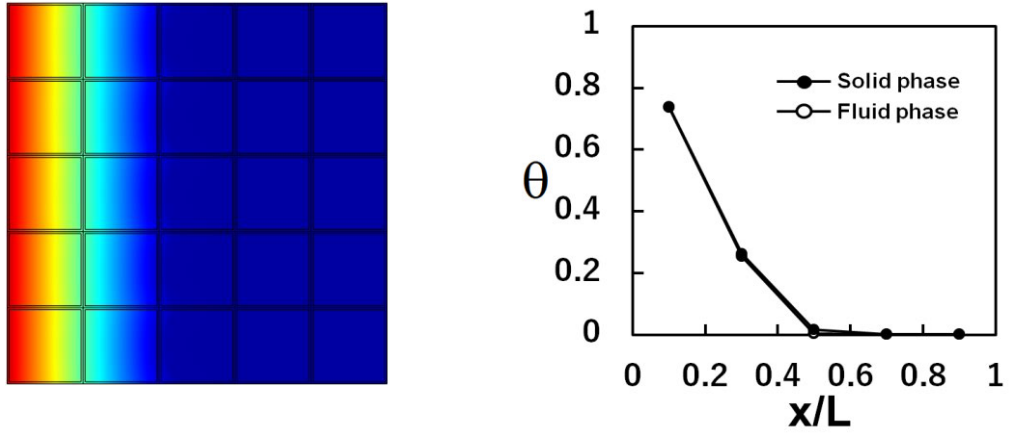
7.3 Result and discussions Problem 3

7.3.1 Comparison of pore scale and volume average results

As it was mentioned before, the PCM is water and the solid frame is aluminum 3D LMF in the present study. In order to determine the volume average solid and fluid temperatures, the values of permeability, the effective thermal conductivity for the solid and fluid phases and also interfacial heat transfer coefficient should be known.



(a)



(b)

Fig. 7.2.9 Temperature distribution and temperature profile at $Y^* = 0.5$,
(a) Case 1, $F_o = 0.15$ (b) Case 2, $F_o = 0.36$

These values are obtained in this study based on the pore scale results. Discussion on the values of permeability, effective thermal conductivity and interfacial heat transfer coefficient is given in the next section.

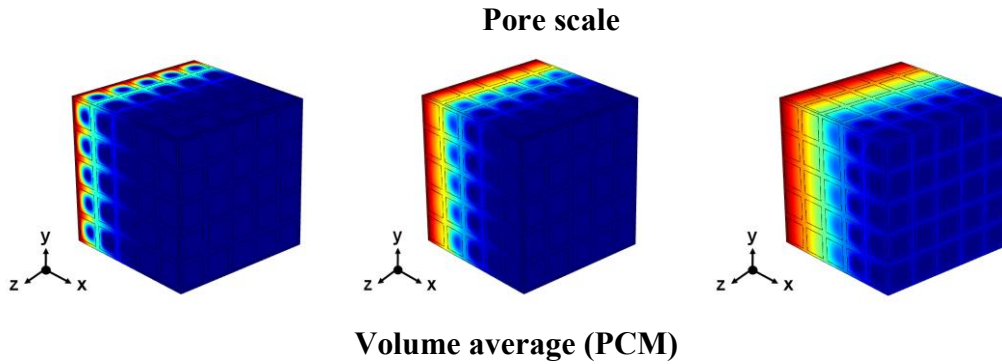
Fig.7.3.1 shows the pore scale and volume average solid and fluid temperature distributions in the domain for 3D LMF with porosity of $\varepsilon=0.9$ at different time step when $Ra = 1$. As it can be seen from the figure, the ice melts through 3D LMF by time.

Table 7.2 The thermophysical parameters of the porous media for Case 1 and 2

Parameters	Case 1	Case 2
$k(W/mK)$	7.6	177
$\rho(kg/m^3)$	4420	2780
$C_p(J/kg K)$	537	875
$k_{eff}(W/mK)$	0.779	87.69
$C(J/m^3 K)$	2373540	2432500
Γ	0.659	1.98
Ω	0.068	0.72
$\alpha(m^2/s)$	9.61	2.74
$\mathcal{E}$	0.9	0.5

Heat transfer through the solid frame is faster than heat transfer through PCM since the solid frame thermal conductivity and diffusivity are higher. The high speed of heat propagation in the solid frame can be easily seen by comparison of the volume average temperature distributions of PCM and solid frame. A good agreement between the pore scale and volume average results can also be observed.

In order to have concrete comparison between the pore scale and volume average results, the temperature profiles in the center line of pore scale cavity and also volume average cavities ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$) are plotted and shown in Fig. 7.3.2 for the same melting fraction shown in Fig. 7.3.1.



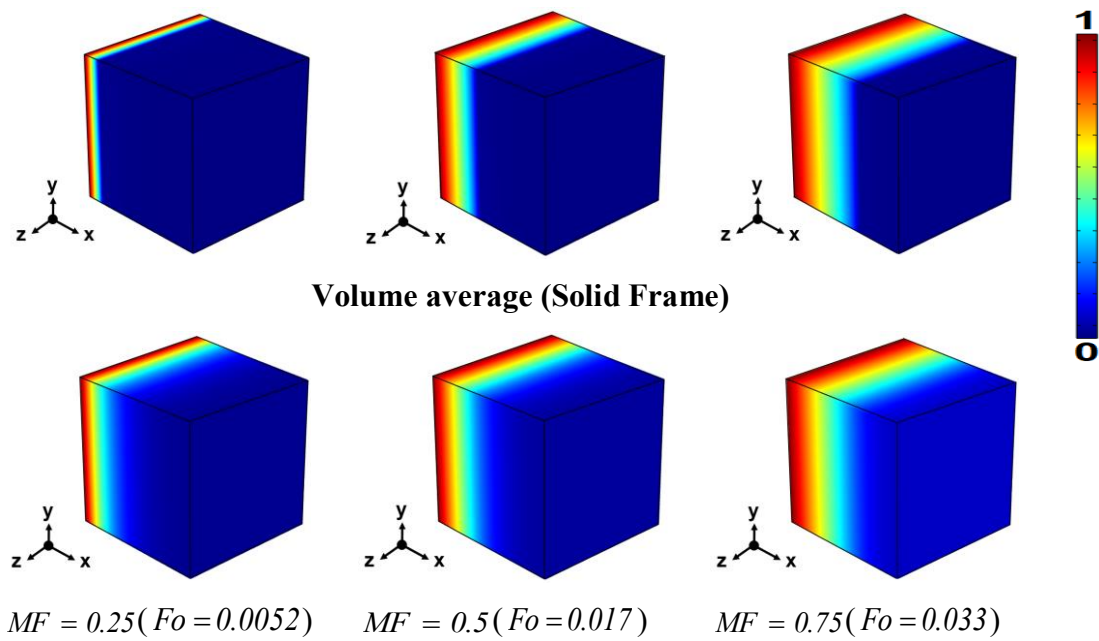
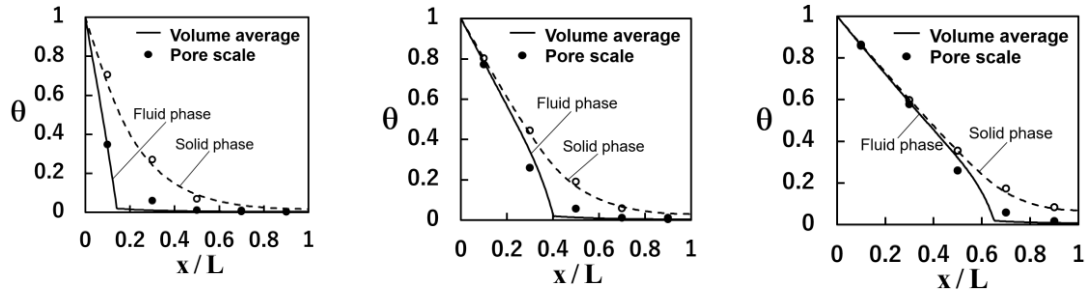


Fig. 7.3.1 The comparison of temperature distributions between the pore scale and volume average results when $Ra = 1$ at three different melting fractions

A good agreement between the pore scale and volume average results for the solid and fluid phases can be seen proving that volume average approach can represent a melting process in the studied 3D LMF. In all of these figures, it is seen that the solid temperature is above or equal the fluid temperature. Fig. 7.3.2 clearly shows that a local thermal non-equilibrium condition exists in the region under melting. Hence, the use of the two temperatures model (solid and fluid temperatures) for obtaining the volume averaged results is unavoidable. By increasing of the melting ratio and time, the fluid temperature approaches to the solid temperatures and a local thermal equilibrium occurs in wide region of the cavity as can be seen from temperature profile of $MF = 0.75$.

Fig. 7.3.3 shows the pore scale and volume average temperature for the same parameters of Fig. 7.3.1, except Rayleigh number which is 10^6 . The convection effect can be seen if Figs. 7.3.1 and 7.3.3 are compared. A good agreement between the pore scale and volume average results can also be seen for $Ra = 10^6$. If the temperature distributions of the PCM and solid frame are compared, it seems that the PCM temperature is higher than frame temperature in the middle and top regions for $MF = 0.5$ and $MF = 0.75$. The volume

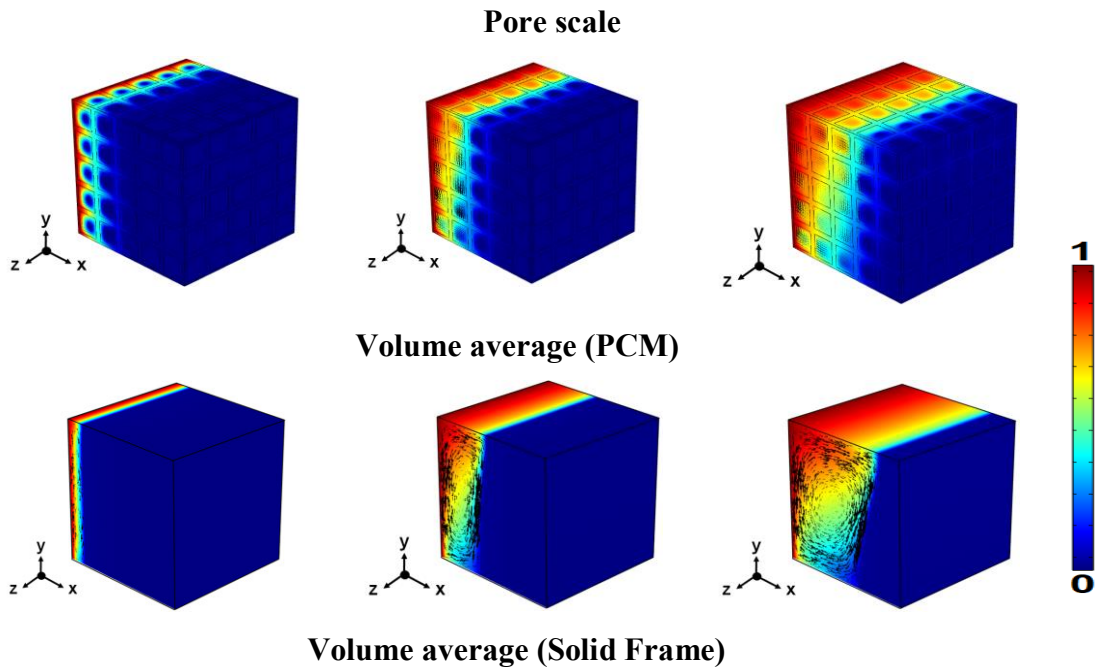
average of fluid temperature may be higher than solid temperature due to strong convection heat transfer and a reverse heat transfer from fluid to the solid may exists.



$$MF = 0.25 (Fo = 0.0052) \quad MF = 0.5 (Fo = 0.017) \quad MF = 0.75 (Fo = 0.033)$$

Fig. 7.3.2 The comparison of temperature profile between the pore scale and volume average approaches at $Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$ when $Ra = 1$

In order to understand the mechanism of heat transfer in the middle and top regions of the cavity, the temperature profiles of the cells in the middle line ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$) and top line ($Y^* = 0.9$, $Z^* = 0.5$, $0 \leq X^* \leq 1$) of the cavities are plotted and presented in Figs. 7.3.4 and 7.3.5.



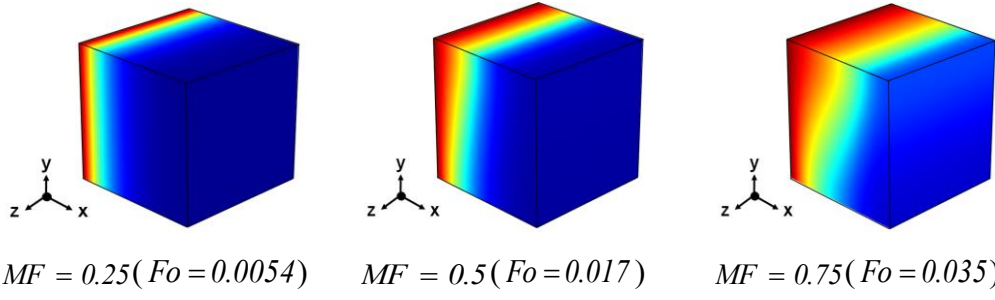


Fig. 7.3.3 The pore scale velocity and temperature distributions of the cavity with

$$Ra = 10^6 \text{ at three different melting fractions}$$

As expected, at the initial stages, the solid frame temperature is considerably higher than the PCM temperature. However, by increasing of melting ratio and the occurrence of free space for motion of the melted PCM, the situation changes. Fig. 7.3.4 shows that when the melting fraction is 0.6 and 0.75 (i.e., $MF = 0.6$ and $MF = 0.75$), the fluid temperature in the middle of cavity is higher than solid temperature and the heat may flow from the solid to the fluid. This fact can be seen from the results of both pore scale and volume average approaches.

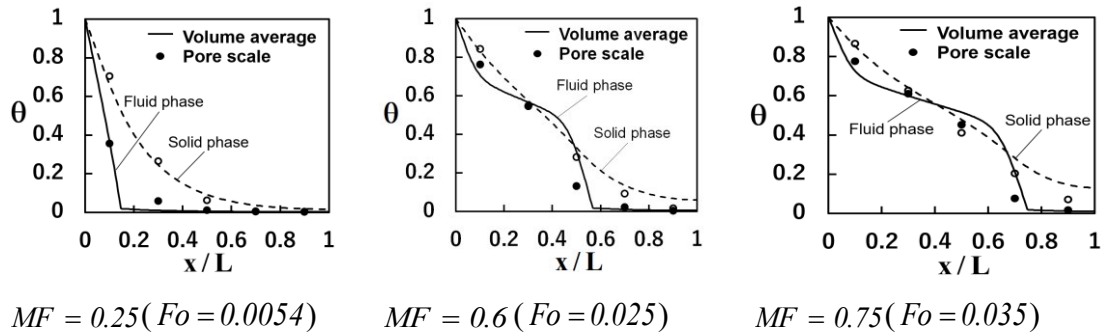


Fig. 7.3.4 The comparison of temperature profiles between the pore scale and volume average when $Ra = 10^6$ at the center line of cavity ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$)

More clear reverse heat transfer can be seen if the same temperature profile is plotted for the top region of the cavity. Convection in the top region of the cavity is stronger and the fluid temperature may be much more above the solid temperature. Again, the solid temperature is lower than the fluid temperature in the initial stage, however by increasing of time, the fluid temperature becomes higher than the solid temperature even at the cell

of $MF = 0.25$ for both volume average and pore scale results. By further increase of time, the convection becomes stronger (since further free space occurring for the motion of melted PCM). Almost in the half part of the top region, the fluid temperature is higher than solid and a reverse heat transfer exists. The comparison of Fig. 7.3.1 (for $Ra = 1$) and Figs. 7.3.4 and 7.3.5 (for $Ra = 10^6$) clearly shows the effect of the convection on the mechanism of heat transfer in the cavity and proves a reverse heat transfer in the middle and top regions of the cavity when the convection is strong.

7.3.2 Determination of the volume average transport parameters using pore scale results

In order to obtain the volume average results, the volume average transport parameters which are permeability, effective thermal conductivity for the solid and fluid, and interfacial heat transfer coefficient for the present PCM-3D LMF should be known. Precise value of these parameters yields precise results. The definition of these parameters are explained in the section 5 and the obtained values for the volume averaged parameters are explained in this section.

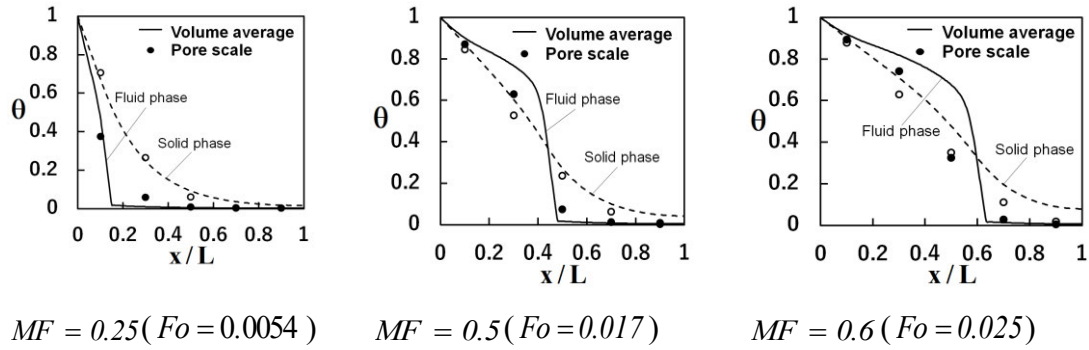


Fig. 7.3.5 The comparison of temperature distributions between pore scale and volume average when $Ra = 10^6$ at the top row of cavity ($Y^* = 0.9$, $Z^* = 0.5$, $0 \leq X^* \leq 1$)

7.3.2.1 Permeability and inertia coefficient

The continuity and momentum equations are solved for a unit cell of 3D LMF and also for the different inlet velocities. The change of the dimensionless pressure drop with pore scale Reynolds number is plotted in Fig. 7.3.6. The values of permeability and inertia

coefficient are obtained as $5.13 \times 10^{-7} m^2$ and 0.0246 from the obtained diagram (for details see Ozgumus et al. (2014) and Celik et al. (2019)). Our numerical results showed that the pore scale Reynolds number is less than 100 for the all cases of this study (i.e. $Re < 100$), hence the Forchheimer term is not included into the volume average momentum equation.

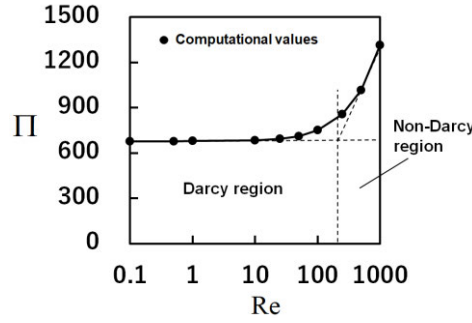


Fig. 7.3.6 The change of dimensionless pressure with pore scale Reynolds number for a unit cell of 3D LMF

7.3.2.2 Effective stagnant thermal conductivity of the solid and fluid phases

The effective stagnant thermal conductive for solid (i.e., frame) and fluid (i.e., PCM) phases can be found by solving the heat conduction equation for a unit cell as explained in the section 6. The change of effective thermal conductivity and the effective porosity with the porosity value for the studied 3D LMF are calculated and shown in Fig. 7.3.7 for pure ice with $k_s / k_f = 107.7$ and also for the pure water with $k_s / k_f = 388.5$. The ratio of effective stagnant thermal conductivity to thermal conductivity of PCM decreases by increasing the value of porosity due to the decreasing of metal amount while the value of ε^* increases. For our problem, the values of k_{eff} / k_f are found as 16.74 for water and 19.39 for ice, respectively and ε^* is 0.96. Based on these values, the stagnant thermal conductivity for the ice and water are found as $2.34 W / mK$ and $0.65 W / mK$ by using Eqs. (4.11) (Wang and Mobedi (2019)).

7.3.2.3 Interfacial heat transfer coefficient

One of the important parameters requiring for the volume average analysis is the interfacial heat transfer coefficient. Determination method of the interfacial heat transfer coefficient employed in this study is explained in the section 6. Fig. 7.3.8(a) shows the

change of interfacial heat transfer rate between the solid frame and PCM and also the temperature difference of the solid frame and PCM in the center cell of the cavity when $Ra = 1$.

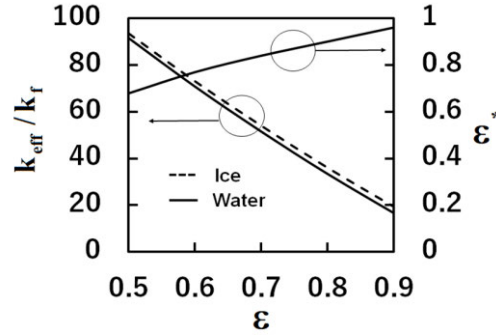


Fig. 7.3.7 The change of k_{eff}/k_f and ϵ^* with porosity for the studied 3D LMF

For the melting period, the heat transfer rate between the solid frame and PCM is very high and a big difference between the solid frame and PCM temperatures exists. After the melting period, the heat transfer rate decreases since just fluid is circulated in the cavity. The local instant Nusselt number is also calculated by Eq. (6.7) and (6.10), and plotted in Fig.7.3.8(b). The value of $\overline{Nu}_v(For)$ is very small and it increases dramatically during melting (considering latent heat of PCM) and it becomes constant after the fully melting since only the fluid is circulated in the cell under the natural convection.

The conditions of Fig. 7.3.9 is the same with Fig. 7.3.8, except Rayleigh number which is 10^6 . By increasing of Rayleigh number value, the convection effect in the cavity increases. Due to the strong convection effect, the behavior of volume average temperatures and interfacial heat rate between the solid frame and PCM, and local instant Nusselt number for the center cell completely change if Fig. 7.3.9 is compared with Fig. 7.3.8.

The temperature difference between solid frame and PCM, and also heat transfer rate between them is high during the melting process, but after finishing of the melting process, the heat transfer rate becomes negative and the PCM temperature in the cell becomes greater than solid frame temperature, that is why $\langle T \rangle^s - \langle T \rangle^f$ takes negative value. Higher temperature of PCM in the cell can also be observed from the temperature distribution of the center cell shown in Fig. 7.3.9.

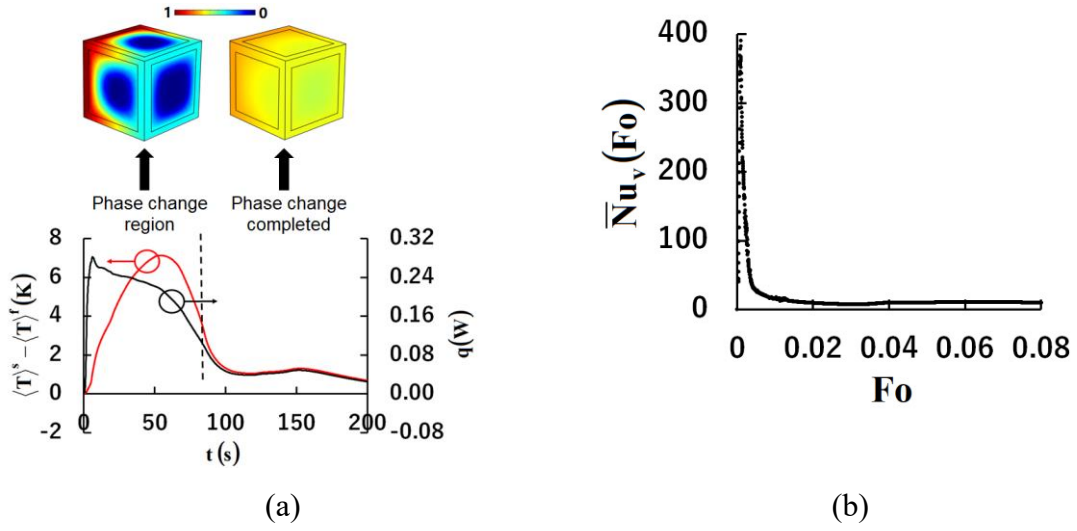


Fig.7.3.8 The change of volume average temperature difference, interfacial heat rate and local instant Nusselt number in the center cell of cavity during melting process when $Ra = 1$, a) volume average temperature difference and heat transfer rate assisted with temperature distributions in the center cell, b) local instant interfacial Nusselt number

This is an interesting result shows that after melting, the temperature of the PCM under strong convection becomes greater than solid frame touching ice in the neighbor cell. But this situation does not continue for long time since the melting front moves and the solid PCM region becomes far from the center cell and again the solid frame temperature becomes greater than PCM temperature. Our numerical observation shows that the change of sign of heat transfer rate and volume average temperature does not occur simultaneously. There is small time lag causing the appearance of two discontinuity regions in the variation of $\bar{Nu}_v(Fo)$ with time as seen in Fig. 7.3.9 (b). The same changes of $\langle T \rangle^s - \langle T \rangle^f$ and $\bar{Nu}_v(Fo)$ were also observed for the cells in the top region for high Rayleigh number.

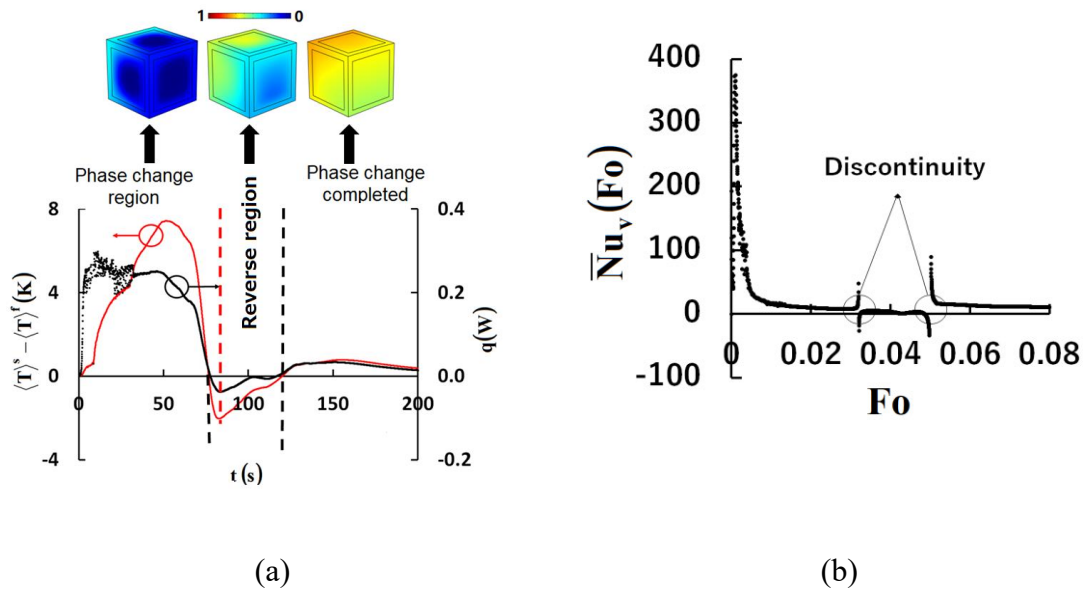


Fig. 7.3.9 The change of volume average temperature difference, interfacial heat rate and local instant Nusselt number in the center cell of the cavity during melting process when $Ra = 10^6$, a) volume average temperature difference and heat transfer rate assisted with temperature distributions in the center cell, b) local instant interfacial Nusselt number

7.3.3 Accuracy of the reported interfacial heat transfer correlations

The change of local instant Nusselt number with time of Figs. 7.3.8 and 7.3.9 is obtained from the pore scale results. However, in many volume average studies the suggested correlations in literature are used. Hence, it might be useful to compare the local Nusselt number of the present study with correlations suggested in literature for the phase change in porous media.

Table 7.3 shows the list of some correlations by researchers in the literature. All of these correlations are suggested for the single phase flow (liquid or gas) but they are used by researchers for the melting/freezing process of the PCM in porous media. The first equation was originally suggested by Zhukauskas (1972) and Calmidi and Mahajan (2000) applied it to the exchange of heat transfer between fluid and solid for a metal foam. As it can be seen, it is valid when the pore scale Reynolds number is greater than 1. Our numerical results showed that the value of pore scale Reynolds number changes

between 2.26×10^{-19} and 6.28×10^{-6} for the cavity with $Ra=1$ and 2.17×10^{-13} and 3.07 for the cavity with $Ra=10^6$. Hence, the use of this correlation may not be suitable for phase change in a cavity assisted with a 3D LMF. The other three correlations (Churchill and Chu (1975) and Yao et al. (2018)) are used for solving the volume average governing equations (Eqs.4.17-4.20) for the present problem. Among them, the correlation of Yao et al. (2018) cannot be used for the cavity with high Ra number (for instance $Ra=10^6$) since they limited the validation of their correlation to $Re=1$.

Fig. 7.3.10 shows the comparison of the pore scale Nusselt number of the center cell and the Nusselt number calculated by the suggested correlations. It is obtained from the volume average temperature difference between the PCM and solid frame in the center cell during the melting process. Fig. 7.3.10 (a) shows the comparison for $Ra=1$. As it can be seen, the value of $\overline{Nu}_v(Fo)$ of the reported correlations by Churchill and Chu (1975) is not far from the pore scale results except the initial stage (which is the melting stage). However, a big difference exists between our results with Yao et al. (2018). The value of $\overline{Nu}_v(Fo)$ of the present study is higher than the values of correlations. A big difference can be seen during the initial stage which is the melting stage. Due to high value of the latent heat and small change of fluid temperature during the melting period, $\overline{Nu}_v(Fo)$ takes large value. It takes constant value after fully melted since only natural convection exists.

Table 7.3 The interfacial Nusselt number used by researchers

Zhukauskas (1972)	$Re_d = \frac{\rho_f \sqrt{u^2 + v^2} d_f}{\varepsilon \mu_f}$
(Improved by Calmidi and Mahjan (2000))	$h_{sf} = \begin{cases} 0.76 Re_d^{0.4} Pr^{0.37} k_f / d_f, & 1 \leq Re_d \leq 40 \\ 0.52 Re_d^{0.5} Pr^{0.37} k_f / d_f, & 40 \leq Re_d \leq 10^3 \\ 0.26 Re_d^{0.6} Pr^{0.37} k_f / d_f, & 10^3 \leq Re_d \leq 2 \times 10^5 \end{cases}$
Churchill and Chu (1975)	$Ra_d = \frac{g \beta \Delta T d_l^3}{\alpha \nu}$

$$h_{sf} = \frac{k_f}{d_f} \left(0.6 + \frac{0.387 Ra_d^{\frac{1}{6}}}{\left[1 + \left(\frac{0.599}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right)^2$$

$$Ra_d = \frac{g \gamma \Delta T d_f^3}{\alpha_f \nu_f}$$

Churchill and Chu
(1975)

$$h_{sf} = \frac{k_f}{d_f} \left(0.36 + \frac{0.518 Ra_d^{\frac{1}{4}}}{\left[1 + \left(\frac{0.599}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}} \right)$$

$$Re = \rho u_{in} d_{fs} / \mu_f$$

Yao et al. (2018)

$$Nu_v = \begin{cases} 76.99 - 152.01\varepsilon + 75.04\varepsilon^2, & 0 \leq Re_d \leq 0.1 \\ \left(1.72 + 1.71\varepsilon - 3.46\varepsilon^2 \right) Re^{0.26} Pr^{0.28}, & 0.1 \leq Re_d \leq 1 \end{cases}$$

convection exists in the cell. The same behavior can also be seen for the cavity with $Ra = 10^6$. In addition to the big difference in the initial stage, the discontinuity of $\bar{Nu}_v(Fo)$ is another difference that cannot be observed by the correlation suggested in literature.

The volume average equations (Eqs.4.17-4.20) are solved by using the correlations suggested in literature. Fig. 7.3.11 compares the obtained results of the present study and the results based on the correlations of Table 7.3.

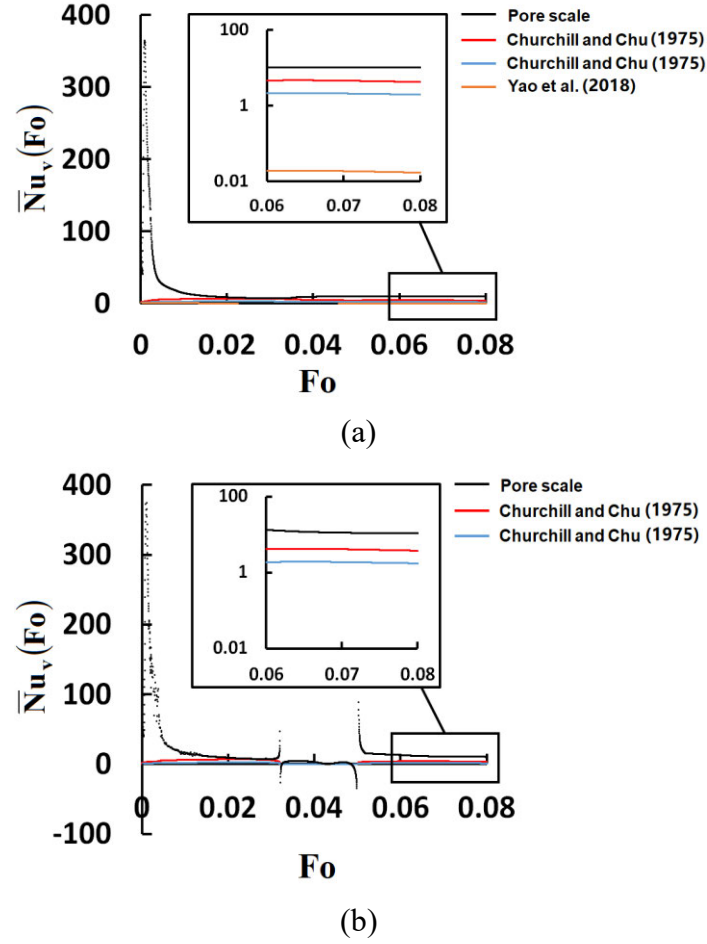


Fig. 7.3.10 The comparison of local instant Nusselt number obtained in the present study with correlations in literature for the center cell during the melting process, a)

$$Ra = 1, \text{ b) } Ra = 10^6$$

It shows the temperature profile at the center line of the cavity from the hot to the end wall ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$) for two different Rayleigh numbers. The pore scale results are also shown in this figure. For $Ra = 1$, there is no big difference between our pore scale and volume average results with the results of two correlations suggested by Churchill and Chu (1975). However, it is a big difference between our results with the results of correlation suggested by Yao et al. (2018). The same behavior is valid for $Ra = 10^6$. Good agreement between our results and the results based on correlation of Churchill and Chu (1975) can be observed.

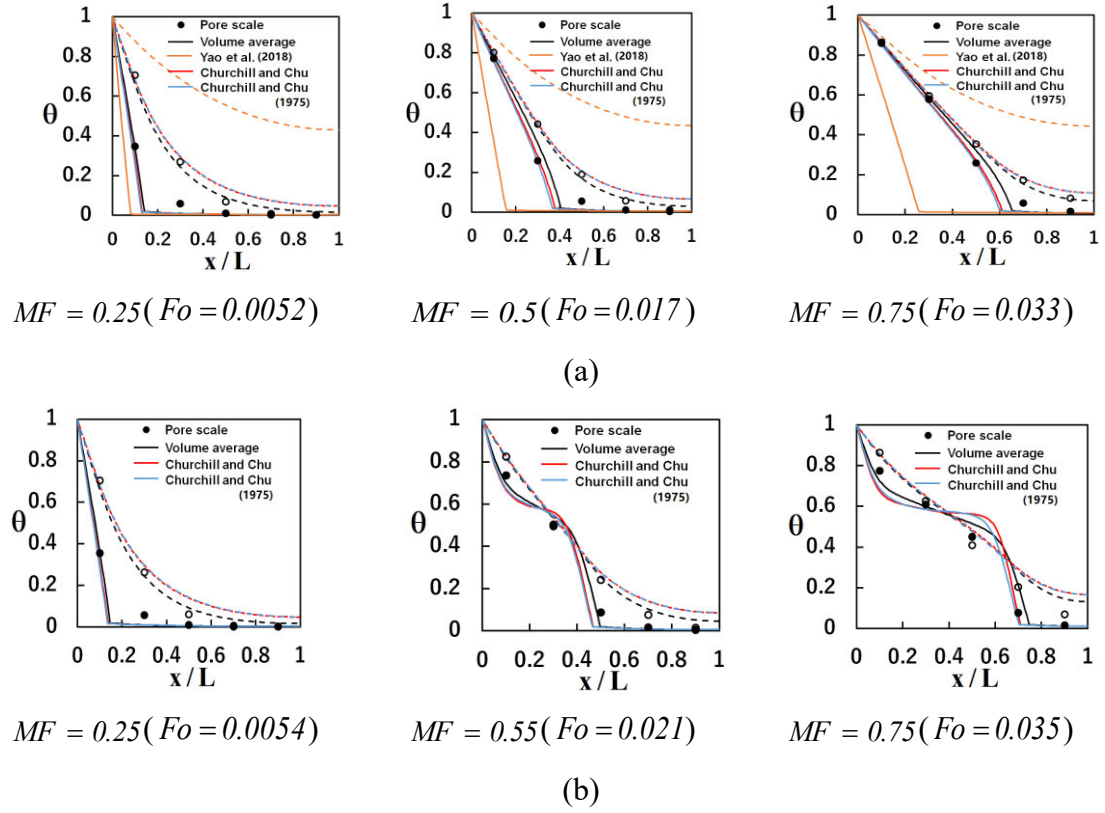


Fig. 7.3.11 The comparison of temperature profile between our results and correlation results at the middle row of cavity ($Y^* = 0.5$, $Z^* = 0.5$, $0 \leq X^* \leq 1$), a) $Ra=1$, b)

$$Ra = 10^6$$

Chapter 8

Conclusions

In general, the present study caught the aims of the study,

- The results of the pore scale and volume average methods are compared for two kinds of the porous media as closed cell porous media and open cell porous media. It has been done both for the single phase and also solid/liquid phase change problems. Good agreement between the pore scale and volume average methods was observed for the both problems showing that volume average method can provide sufficient correct results. Particularly, the second problem which is phase change in the closed cell porous media took the attentions of researchers in the conference and also attentions of the reviewers.
- For separation of local thermal equilibrium and local thermal non-equilibrium states, charts for the problems of 2D closed cell porous media are established in terms of effective thermal diffusivity ratio, Sparrow number and Stefan number. The accuracy of the established chart is proved by giving two real examples. To the best of our knowledge, this is the first time these charts are reported to the literature.
- A special attention was given to the interfacial heat transfer coefficient. It was observed that interfacial heat transfer coefficient is not constant during the melting process and at the beginning the value of interfacial heat transfer coefficient reaches to a maximum point and the decreases to the value of interfacial heat transfer coefficient of single phase. However, the space and time average of the heat transfer coefficient is sufficient to obtain the volume average results. Unfortunately, no correlation for interfacial heat transfer coefficient in the closed cell porous media was found, that is why no comparison could be done with literature. But, this comparison was done in problem 3 and it was found that the results of some correlations are far from the pore scale results which are accurate.

In this Chapter, the conclusions of three studies done on three problems are summarized separately based on the obtained results discussed in Chapter 7.

Problem 1

A numerical study on the local thermal non-equilibrium state for the transient heat transfer through the closed cell porous media is performed. Based on the obtained results and performed discussions, the following remarks can be concluded.

- If the governing equations are non-dimensionalized according to the equilibrium thermal diffusivity, the dimensionless parameters as porosity, the solid and fluid thermal diffusivities and thermal capacitance ratio and Sparrow number are obtained. Sparrow number appears automatically showing it is a governing parameter.
- Two relations between the dimensionless solid and fluid thermal diffusivity and thermal capacitance are found resulting in the decrease of dimensionless governing parameters.
- The Sparrow number is interpreted as the ratio of conduction to convection thermal resistance through the porous media. High value of Sparrow number (such as $Sp = 1000$ referring to the higher convection in the pores compared to heat conduction through the porous media while low values ($Sp = 50$ refers to a large convection resistance in the pores and consequently a weak heat exchange between the solid and fluid phases.
- When the value of Sparrow number is low (such as 50 , a local thermal non-equilibrium heat transfer occurs for the cases in which the thermal diffusivity ratio is considerably greater or smaller than 1 (such as 100 or 0.01 . A local thermal equilibrium independent of the value of Sparrow number exists if the thermal diffusivity ratio is around 1.
- For high values of Sparrow number (such as 500 , a local thermal equilibrium state is observed for the all studied parameters due to the considerable heat exchange between the solid and fluid phases.
- The results of parametric study are supported by the pore scale of two real cases of closed cell porous media. For closed cell porous media when the solid is aluminum and working fluid is water, a local thermal non-equilibrium is seen due to large value of thermal diffusivity ratio ($\alpha_s^* / \alpha_f^* = 300$ and small Sparrow number ($Sp = 38$.

For the closed cell porous media with air a local thermal equilibrium is observed because almost the same propagation of heat in the solid and fluid ($\alpha_s^* / \alpha_f^* = 2$).

Problem 2

A new formulation is suggested in terms of Sparrow number. Both the pore scale and volume average equations are solved and the obtained results are compared to validate the suggested volume average formulations. Based on the obtained results following remarks can be concluded.

- The good agreement between the pore scale and volume average results shows the suggested volume average formulation can represent heat transfer during the melting of PCM in a porous medium.
- The suggested formulation is based on three dimensionless parameters as the Stefan number, thermal diffusivity ratio and Sparrow number. Sparrow number plays an important role on heat transfer between the solid and fluid phases and appears automatically if the dimensionless governing equations are derived by using equilibrium thermal diffusivity.
- Based on the pore scale results, the interfacial heat transfer coefficient is not constant during the phase change process. During the phase change process, the interfacial heat transfer coefficient takes the maximum value and it becomes almost constant after the phase change in the cells. However, the time and space average of the interfacial heat transfer coefficient can be used in the volume average equations to provide sufficiently accurate volume average results.
- The Sparrow number and thermal diffusivity ratio are used and a thermal equilibrium condition chart is established to predict the local thermal equilibrium state of the phase change process, if the values of Sparrow number and thermal diffusivity ratio are known.
- The established local thermal equilibrium chart is validated by giving two examples of different closed cell porous media having different sparrows number and thermal diffusivity ratio. The obtained pore scale results validated the suggested thermal equilibrium chart.
- It is found that the possibility of local thermal non-equilibrium is high for the low values of Sparrow number (such as $Sp = 1$) and high values of thermal diffusivity ratio (such as

$$\alpha_r = 500 .$$

Problem 3

Based on the obtained results of present study, the following remarks can be concluded,

- The pore scale and volume average governing equations are solved for the phase change in the 3D LMF cavity and a good agreement is observed between their results.
- The pore scale governing equations are solved for the single phase in a representative cell and the values of the effective thermal conductivity for the PCM and solid frame, permeability and interfacial heat transfer coefficient are calculated successfully.
- The change of interfacial heat transfer coefficient during melting process are obtained by using pore scale results. For the initial stage (melting period , the interfacial heat transfer coefficient takes high values however for the fully melted period, it becomes constant since only natural convection condition of heat transfer exists in the cells.
- For the high values of Rayleigh number, a reverse heat transfer from fluid PCM to solid frame is observed in the center and top cells due to the strong convection. Pore scale and volume average results showed that the fluid temperature becomes higher than the solid temperature. However, when the melting front moves away from the considered cell, the reverse heat transfer disappears.
- The sign of heat transfer and temperature difference between the solid frame and fluid do not change simultaneously and this causes the appearance of two discontinuities for the local instant interfacial Nusselt number.
- The volume average results for the correlations by researchers in literature are also obtained and compared with the pore scale of this study. It is observed that for wide values of Rayleigh number ($1 \leq Ra \leq 10^6$, there is no big difference between our pore scale and volume average results and the results based on the Churchill and Chu correlations.

Future works

The study should be continued and the same separation charts found for the closed cell porous media should be determined for the open cell porous media. Although the number of governing parameters is many but the possibility of the combining of some governing

parameters and reducing the total number of the governing parameters is possible. By this way, before starting a numerical method it is possible to determine the governing parameters and decide whether solid/liquid phase change is local thermal equilibrium for 3D problem or not. Furthermore, the studies on the interfacial heat transfer coefficient for the solid/liquid phase change should be continued. The interfacial heat transfer coefficient should be found from the pore scale results and it should be compared with available correlation in literature for different values of the governing parameters and a general correlation should be suggested to the literature.

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The list and explanations of his academic achievements till now are given as below,

Research Articles (SCI Journals)

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1. Chunyang Wang, Moghtada Mobedi, Fujio Kuwahara, Akira Nakayama, A study on comparison of volume averaged and pore scale results of solid/liquid phase change assisted by porous media, 16th International Heat Transfer Conference, August 10-15, 2018, Beijing, China
2. Chunyang Wang, Moghtada Mobedi, Fujio Kuwahara, Akira Nakayama, Developing criteria for evaluation of solid/liquid phase change material heat exchangers, 15th Joint Symposium between Sister Universities, August 18-20, 2018, Shizuoka University, Japan
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National academic conferences

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Awards

Chunyang Wang, Award for the excellent presentation, 15th Joint Symposium between Sister Universities, August 18-20, 2018, Shizuoka University, Japan