Republic of Iraq

Ministry of Higher Education

and Scientific Research

University of Babylon

College of Engineering Mechanical

Engineering Department

Experimental and Numerical Study of Natural Convection Inside Porous Cavity with Sinusoidal Walls Filled with Fluid

A Thesis

Submitted to the College of Engineering, University of Babylon Partially fulfilling the requirements for the degree of Master in Engineering \Mechanical Engineering \Power

By

Ruqayah Nassr jawed

Supervised by:

Assist. Dr. Hussein Mahmood Jassim

2023 A.B   **1444H**

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

هُوَ الَّذِي جَعَلَ الشَّمْسَ ضِيَاءً وَ الْقَمَرَ نُوراً وَقَدَّرَهُ مَنَازِلَ

لِتَعْلَمُواْ عَدَدَ السِّنِينَ وَ الْحِسَابَ مَا خَلَقَ اللَّهُ ذَلِكَ إِلاَّ بِالْحَقِّ

يُفَصِّلُ الآيَاتِ لِقَوْمٍ يَعْلَمُونَ

صدق الله العلي العظيم

سورة يونس آية رقم ﴿ 5 ﴾

Dedication

To my late father, God bless his soul

Ruqayah 2023

Acknowledgment

Firstly, I would like to express my gratitude and thanks to ALLAH (be glorious) for all the blessings bestowed upon me. I wish to express my deepest thanks and sincerest gratitude to my supervisor *Dr. Hussein Mahmood Jassim* for his guidance, comments, invaluable instructions, help and continuous encouragement during the preparation of my study.

Special thanks to the staff at Babylon University, mechanical Engineering Department for their support and teaching especially *Mr. Hussein H. Rashid*. Last but not least special thanks and gratitude goes out to my supportive mother and my husband, my siblings, and to all my friends for their help during this work.

Ruqayah 2023

Abstract

In the present work, the experimental and numerical realization has been achieved to study the heat transfer by natural convection in a cavity filled with a porous medium.Two studies are carried out using two forms of cavities, (the first cavity with outward sinsoiudal walls and the second cavity with inward sinsiudal walls). In the numerical study, a three dimensional model is solved by ANSYS-FLUNT 19.2, using silica-sand as a porous materials (silica-sand), with two porosities 0.36 and 0.38, The two models are practically studied under the same boundary conditions, where a constant thermal flux is applied with three values ranging between (1000-2000) W/m^2 .The sinsoiudal walls are completely insulated and the upper surface of the cavity is assumed to be at a consatnt temperature.A sand is used as a porous media with aporosity (0.36) and twenty four of thermocouples are used to measure the temperature at different places inside the porous media .The results are presented in the form of velocity, isothermal contours and average Nusselt number. The experimental and numerical results are compared for all cases and showed good converges. The experimental results for a heat transfer behavior inside the sinusoidal porous cavity indicated that the percentage approach with the corresponding numerical results is approximately closed to (86%).The results show that the average Nusselt number increases with increasing the heat flux, porosity and a Rayleigh number. the cavity with outward sinsoiudal walls gives the largest difference in a temperature, as this difference is considered as a basis to study the other properties.When the porosity of porous medium increases, the temperature difference deceraces and thus the heat transfer coefficient of convection increases,which leads to an increase in a Nusslet Number.

Nomenclature

Symbols	Notations	Units
A	Area	m^2
C_d	Drag coefficient	…………
C_P	Specific heat	J/kg.ºC
D	Diameter	m
Da	Darcy number	…………
g	Gravitational acceleration	m/s^2
h	heat transfer coefficient	W/m^2.°C
H	Height of cavity	m
I	Supplied electrical current.	Amper
k	Thermal conductivity	W/m.ºC
K	Permeability	Darcy
L	Length of cavity	m
Nu	Nusselt's number	…………
Q	Supplied electric power.	W
q	Heat flux	W/m^2
Pr	Prantle number	…………

Ra	Rayleigh number	…………
Ra_m	Modified Rayleigh number	…………
T	Temperature	°C
T_{calib}	calibrated temperature value	C°
V	Voltage	volt
W	Width of cavity	m

Greek letters

ε	Porosity	…………
ρ	Density	(kg/m^3)
α	Thermal diffusivity coefficient	m^2/s
μ	Dynamic viscosity	(kg/m.s)
B	Thermal expansion coefficient	c^{-1}
$\forall$	Volume	m^3
a	Wave amplitude	…………
A	Aspect ratio	…………
N	Number of wavness	…………

Subscripts

h	Hot
c	Cold
f	Fluid
s	Solid.
b	Base surface of the cavity
Wa	Water
av	Average
e	Effective

Abbreviations

CFD	Computational Fluid Dynamic
FEM	Finite Element Methods
FVM	Finite Volume Methods
GFEM	Galerkin Finite Element Method
3D	Three dimensional
SEM	Spectral Element Method
LBM	Lattic Boltzam Method

Table of Contents

Chapter one
Introduction

Introduction

1.1. General

A natural convection heat transfer is very important due to its many applications in many fields of nature. Although there is no forced velocity that generates this type of flow, natural convection currents are generated within the fluid that urges it to flow as a result of the effects of the buoyancy force or what is called the flotation force. As this force results from the density gradient as a result of the presence of temperature gradients and the force of gravity. Since the flow velocity of the fluid under normal convection is much smaller than that which accompanies forced convection, the transmission rates under normal convection are also smaller. This may be an encouragement to give less importance to natural convection processes.However, this must be resisted, as it see that in many devices operate by relying on a multiple ways of heat transfer, and in which it is required to reduce heat transfer rates or operating costs, natural convection plays an important role in the design of these device, which is much preferred over forced convection.

1.2. Porous Media

The porous media is a solid media saturated by fluid (air, water, etc.) and is simulated as a two-phase. Usually both the solid matrix and the fluid are assumed to be continuous as detailed by Michele [1]. A typical porous medium is illustrated in Figure (1-1). Typically, naturally occurring porous media exhibits the irregular geometry depicted in Figure (1-1). Porous media found in engineering applications are typically comprised of solid particles such as spheres or raschig rings. A porous medium composed of spheres is illustrated in Figure (1-2). Porous media composed of large solid particles find numerus applications in chemical
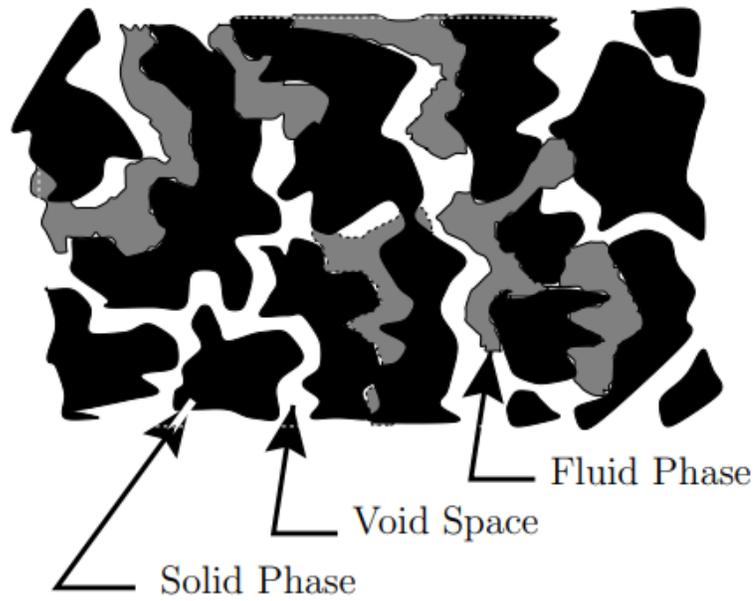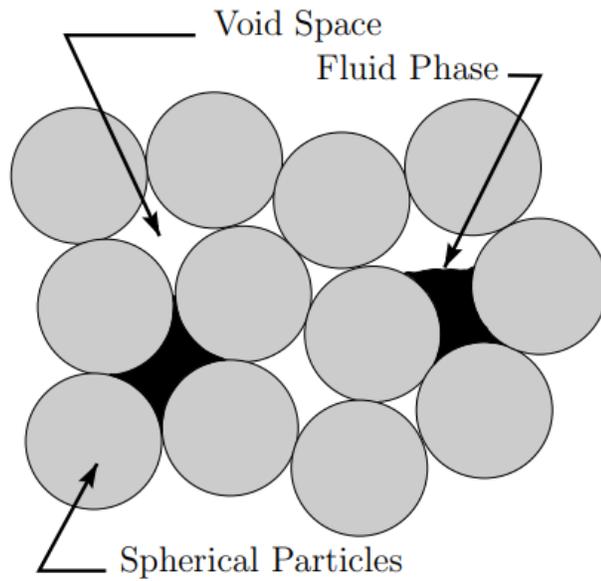
Figure (1-1).Porous medium.

Figure (1-2). A porous medium encountered in engineering applications.

Engineering, the most important of which are packed bed reactors. In addition, porous media composed of gravel has energy storage applications. Alternatively, porous media can also consist of fibrous materials. Many examples of these types of media have both natural and man-made applications. In particular, when air is trapped in the void space of fibrous porous media, the overall thermal conductivity of the medium is very low; consequently these media have many applications as thermal insulation.

1.3. Heat Transfer in Porous Media

The heat transfer convection in a porous media has emerged as a new interest due to new technological developments. Thermal attributes enable applications such as heat dissipation media and recuperation elements. Hence, it has become important to understand the interaction between mass and thermal transport as well as the resulting effects on the thermo-mechanical characteristics of the porous media. The phenomenon of convective heat and mass transfer in saturated porous media has received considerable attention due to its relevance in various applications. Natural and manufactured porous materials have broad applications in engineering processes, heat sinks, catalytic reactors, high breaking capacity fuses, heat exchangers, and mechanical energy absorbers. In general, it can be noted that there are many examples of natural convection through porous media in industrial systems, such as thermal insulation, drying processes, biomedical engineering applications, and nuclear reactors (Nield and Bejan [2].

Heat transfer occurs through a porous material depending on the interaction between the following mechanisms:-

1. Heat conduction.
2. Thermal radiation.
3. Convection.

1.4. Thermal Properties of Porous Media

The thermal properties of porous media should be reinforced, since most forms of energy are eventually converted into heat by combustion, chemical and nuclear reactions, and mechanical friction. The thermal properties of interest for any material include thermal conductivity, density, thermal diffusivity, and specific heat. The thermal conductivity is an index related to the rate of heat flow and the thermal diffusivity corresponds to the rate of temperature change for a particular material when a temperature gradient exists, while the specific heat indicates the thermal capacity of that material. Knowledge of these properties for porous media is needed in many projects, in connection with the thermal design of underground construction, such as basements, under-sea channels, buried electric cables or steam pipes, and ground-coupled heat pumps. Thermal conductivity of dry porous media varies considerably due to the molecular structure, chemical composition, bulk density, and temperature. A crystal lattice material has greater thermal conductivity than an amorphous one. Higher mineral bases and bulk density cause a material to be more conductive as detailed by Deng [3]. Therefore, the selection of material with appropriate thermal conductivity for a particular thermal design becomes a key factor, which may lead to the consideration of mixing two or more different materials in order to obtain a desired thermal conductivity. to analysis of the macroscopic heat transfer through heterogeneous media, the local volume-averaged (or effective) properties such as the effective thermal conductivity $k = k_e$ are assumed as described by Kaviany [4]. These local effective properties such as the heat capacity (cp_e) and thermal diffusity (α_e) need to be arrived at from the application of the first principles to the volume over which these local properties are averaged, that is, the representative elementary volume. Kaviany [5]

showed that the effective thermal conductivity is expected to depend on the following:

1. The thermal conductivity of each phase.
2. The structure of the solid matrix (the extent of the continuity of the solid phase is very important).
3. The contact resistance between the nonconsolidated particles (the solid surface oxidation and other coatings are all important).

1.5. Application of Porous Media

The natural convection in a porous medium has become significant in the recent published research due to its many applications in various fields. In general, many examples of using a porous medium can be observed in industrial systems such as granular insulators, high-capacity electrical coil structures, and the heart of nuclear reactors, and geothermal systems, underground spread of pollutants, storage of nuclear waste materials, solidification of casting, thermal insulation, electronic cooling, petroleum reservoir modeling, burying of drums containing heat generating chemicals in the earth, design of chemical catalytic reactors, powder metallurgy, ceramic engineering, food and medical industries. While those engineering applications that benefit from studding the natural convection within enclosures filled with porous media are: geothermal energy resources, nuclear energy systems, petroleum reservoirs, analysis of insulating systems, storage of grain fruit and vegetables, flows through tobacco rods, pollutant dispersion in aquifers, post-accident heat removal from nuclear reactor rubble beds, the processes of crystal manufacture, foam metals and fibrous media [5]

1.6.The Objective of is Research

This study aims to investigate the mechanism of heat transfer by natural convection practically as follows:

1. Comparing the change in the heat transfer process when two different shapes of porous cavities with sinusoidal curvy walls are used.

2-Comparing the change in the heat transfer process when a different porosity is considered.

3-Studying the effects of a Rayleigh number and how this parameter affects on the convection phenomena inside a closed porous cavity.

4-Analyzing and comparing the theoretical and experimental results to establish the conclusions and suggestions for a future work.

1.7. Outline of the Thesis

Basically, this thesis involves six chapters and each chapter will be briefly introduced as follows:

- Chapter one: deals with the introduction and the outline of aims.
- Chapter two: is concerned with reviews and the previous related literature.
- Chapter three: Displays the theoretical explains of the mathematical model to analyze the temperature distribution inside the porous cavities with sinusoidal walls.
- Chapter four: introduce the details of experimental apparatus, setup, and procedure.

- Chapter five: introduces the results and discusses the experimental and theoretical work.

- Chapter six: summarizes the conclusions and the suggestions for future works.

Chapter Two

Literature Review

Chapter Two
Literature Review

There are a lot of numerical and experimantal research have been carried out to study a two or three dimensional model with different boundary conditions.The geometry of cavities has attracted great intrest,therefore several shapes have been studied including closed rectangular with horizontal, vertical and inclined porous layers,horizontal and vertical rings, and cylindrical shapes immersed in the porous medium. Due to the large number of these studies, the focus will be on the research that is related to cavities with wavy walls and containing porous medium.

2.1 Numerical Study.

Kumar.[6],[2000], analyzed numerically the Free convection heat transfer induced by a vertical wavy surface with a uniform heat flux in a porous enclosure using finite element method FEM . A wavy vertical wall with uniform heat flux causes rise in a wavy surface temperature distribution. The surface temperature was very sensitive to the drifts in the surface undulations, phase of the wavy surface, and the frequency of the undulations. The wavy wall with an amplitude of 0.15, phase of 60° , and with large N was seemed the best choice to enhance a convection process in a saturated porous enclosure under Darcian flow considerations.

Kumar and Shalini. [7], [2003], in this work effect of surface undulation on natural convection in a thermally stratified vertical porous enclosure has been analyzed numerically by the finite-element method. It was noticed that increasing either the number of waves, wave amplitude (a) or thermal stratification (S) decrease Nusselt number (Nu) .Also it was noticed that secondary circulations

occure near the wavy wall and multicellular circulations in the core of the flow field.

Kumar and Shalini.[8],[2003], studied Forchheimer extended Darcy model numerically. This study a wavy vertical enclosure loaded with a porous material under the effect of non-Darcian natural convection. The non-Darcian effects demonstrated in the Numerical results. The rise in the wave amplitude or the number of waves per unit length will lower the average or GNN because of the secondary circulation zones that occur in the adjacent region to the curved wall. These primary circulation areas trap the liquid, resulting in a decrease in the rate of the heat transfer convection currents.

Jue.[9][2003], studied the natural convection inside cavity Filled with a fluid-saturated porous medium in the presence of internal heat generation (thermogenesis) and with heating inside walls using the semi-finite element method, the semi-implied finite element method (assuming that the Rayleigh number values range between the values ($10^3 <$ Ra $<10^8$)and Darcy and ($10^{-10}<$ Da $<10^{-1}$) .The results showed that the effect of porosity on heat transfer was started at (Da $\geq 10^{-2}$),the reduced in the porosity was caused decreased in the force of external thermal vortices . which caused allowing for Changes in internal vortices generated from heat generation.

Das et al,[10][2003] ,investigated numerically the laminar steady natural convection heat transfer and fluid flow inside a wavy enclosure with two horizontal wavy walls and two straight vertical walls. The effects of aspect ratio and surface waviness on heat transfer were studied. For a constant Rayleigh number, heat transfer falls gradually with an increasing surface waviness up to a certain value of surface waviness. Whereas for higher aspect ratio, heat transfer gradually increases with an increase of surface waviness up to a certain value of

surface waviness and subsequently heat transfer falls gradually up to certain waviness, above which heat transfer increased again like the other case.

Dalal and Kumar. [11], [2005], studied the effect of undulations number on natural convection in an inclined cavity with a sinusoidal temperature profile applying on the corrugated wall. The tests were carried out for different inclination angles, amplitudes and Rayleigh numbers while the Prandtl number was kept constant. The results obtained showed that the angle of inclination effects on the flow and heat transfer rate in the cavity it was noticed the increased in the amplitude produced higher heat transfer rate at low Rayleigh number.

Misirlioglu et al. [12], [2005], Studied the steady natural convection inside a cavity made of two horizontal straight walls and two vertical wavy walls which follow a profile of cosine curve and was filled with a fluid-saturated porous medium. The governing equations were solved using the Galerkin Finite Element Method (FEM). The study was indicated that for large values of the Rayleigh number, Ra (=1000), and moderate values of the aspect ratio A (smaller than 3) and of the surface waviness =0.5, the local Nusselt number from the vertical walls may even become negative; this means the heat generated in the porous medium cannot be transferred through the porous medium from the right (hot) wall to the left (cold) wall.

Dalal and Das.[13][2006], Buoyancy-induced flow and heat transfer inside a cavity with sinusoidal temperature boundary condition on the bottom wall and constant cold temperature boundary condition on other three walls were investigated numerically. The presence of undulation in the right wall affects local heat transfer rate and flow field as well as thermal field. The heat rejection from the fluid to wavy wall increased up to Ra=$10^4$for one-undulated cavity compared to square cavity without undulation and then it decreased. But the reverse scenario

was observed for the left wall. With the increased of amplitude, the average Nusselt number on the wavy wall was reduced. Up to Ra=10^4 , the heat transfer increased by undulating the wall. However, it was decreased as the number of undulations was increased. As the Ra was increased, undulations on the wall reduced the heat transfer.

Salih et al.[14], [2006], Investigated mathematically the heat transfer of a two-dimensional natural convection in a rectangular porous cavity, the sides were adiabatic, and the horizontal walls were heated to a uniform but various temperatures. The study appeared that the rates of heat transfer were dependent on the porous Rayleigh number (Ra). The porous Rayleigh number from this study was based on Nu and the cavity geometry. The increase of Ra was due to a change of pattern flow from unicellular to multicellular flow.

Mahmood, et al.[15],[2008], performed a non-Darcian natural convection heat transfer in a triangular duct loaded with a viscous fluidsaturated porous medium. The range of the enclosure aspect ratio is ($2 \leq A_s \leq 30$) which is in the region of the tall layer at medium Ra (2000), Darcy number (Da=10^{-3}, 10^{-4} and 10^{-5}), porosity (ε =0.35, 0.45, and 0.55), and ratio of the thermal conductivity of particle to fluid (k_s/ k_f) = (5.77, 38.5, and 1385.5). The effects displayed that the Nu increases with the medium Ra and porosity but decreases with the Darcy number, the ratio of thermal conductivity of particle to fluid and the aspect rate of the enclosure, also their good effects on the heat transfer were described by the average Nusselt number (Nu).

Khalil Khanafer et al[16],[2009], Forchheimer–Brinkman-extended Darcy model was for studied natural convection heat transfer in a wavy cavity filled with porous-saturated medium. The vertical surface was considered to follow a wavy

pattern, the horizontal walls were insulated. Effects of dimensionless groups representing the wavy geometry, Rayleigh number which was ($10^4 \leq$ Ra $\leq 10^6$)($0{\leq}n{\leq}3$) and ($0{\leq}a{\leq}0.25$), and number of undulation was highlighted to study their impacts on flow structure and heat transfer characteristics. . The result of this investigation illustrated that the amplitude of the wavy surface and the number of undulations affect heat transfer characteristics inside the cavity. Furthermore, the intensity of convection within the cavity was observed to increase with the increase in the Rayleigh number.

Hussein.[17],[2010], investigated numerically the free convection of air flow through a porous media in an inclined rectangular cavity .The top and lower surfaces were thermally insulated while the left and right walls were maintained at isothermal hot and cold temperatures respectively, the Darcy model was used for flow characterstics of Prandtl number at 0.7 , an aspect ratio was 1.5, Rayleigh number ranging(50 $\leq$Ra$\leq$100), and inclination angles of 30° , 50° and 90° .It was observed that the intensity of circulation increases with increasing the angle of inclination .Also, the greater circulation causes more heat to be distributed in the central of the cavity The circulation was found in the flow domain due to stronger free convection effect. The average nusselt number was increased when the values of Ra number and the inclination angle were increased.

Mushate.[18], [2011], investigated numerically the natural convection heat transfer and fluid flow inside a square cavity having two wavy walls were maintained at different isothermal temperatures The cavity was filled with a porous medium, while the horizontal walls were kept insulated .The study was performed for Rayleigh numbers up to 1000.The results were showed the rate of heat transfer was increased with the increase of the Rayleigh number and amplitude values for(

$0.05 \leq$ a ≤ 0.075) . After that was decreased. The number and size of rotating vortices was increased with the increase of undulations number.

Eiyad Abu-Nada et al. [19],[2011], verified numerically the heat transfer enhancement of Al_2O_3-water nanofluids in natural convection applied to differentially heated wavy cavities. the result was showed the geometry parameter was an important control on heat and fluid flow also heat transfer was increased with increasing of geometry parameter for the same Rayleigh number and nanoparticle fraction. Which mean that the increased in the Rayleigh number produced significant increased in the average Nusselt number. For all cases, heat transfer increases with the addition of nanoparticle into the base fluid.

Bhuvaneswari et al.[20] ,[2011] , investigated numerically the aspect ratio effect and the active zones of partially thermally on the heat transfer and convective flow in a rectangular porous enclosure. The sidewalls bottom and top of the enclosure were adiabatic, while along the vertical walls, there were five different zones of cooling and heating. The location of zones had a significant effect on the flow pattern and the heat transfer in the enclosure. The heat transfer rate was decreased by raising the aspect ratio. Very low Darcy number makes the heat transfer rate approximation to a constant value.

Abood.[21],[2011], presented numerically the heat transfer by free convection in two enclosures having different shapes. The first enclosure was a right-angle trapezoidal with an aspect ratio ranging between A (0.25-0.45), while the second enclosure was a square with an aspect ratio equals to one. A saturated porous medium filled the enclosures. The upper wall was cooled, the lower wall was heated and the other walls were adiabatic. A finite element software package (FLEXPDE) was used to solve the equation. The range of Ra (100 to 1000) was

used to study the characteristics of flow and heat transfer. The results appeared that the coefficient of heat transfer increases with the increase of aspect ratio and Ra.

Saleh et al. [22],[2011], numerically studied the transit heat transfer of natural convection in an enclosure having an inclined cylindrical shape and filled with a fluid-saturated porous medium. The range of the Ra that was taken in the analysis was (50-300). The inclination angles (0°, 25°, 45°, 60°, and 90°), the periods (0.005, 0.01, and 0.02), and the sinusoidal amplitude of temperatures (0.2, 0.4, and 0.8) were used. Results showed that the maximum velocity and temperature occurred at angle 45°, and there was a strong buoyancy force influenced on the convective flow from the calculated average and local Nu. The heat transfer was proportional directly with time, angle of inclination, Rayleigh number, period, and amplitude.

Ismael. [23],[2011] , numerically investigated the heat transfer by natural convection and fluid flow inside a fluid-saturated porous media wavy enclosure heated by an internal circular cylinder. Darcy modified Rayleigh number (100-1000), and waviness of the wavy walls (0-0.35) was studied. It was found that for any value of the inner cylinder position and wall waviness, the heat transfer is an increasing function of Darcy modified Ram. Higher heat transfer was obtained when the inner cylinder was positioned below the mid enclosure height, and whatever the wall waviness, the lower position of the inner cylinder (0.45) was the largest the values of Nu, while the influence of the wall waviness ratio was found to be very small.

Nardini et al. [24], [2013], investigated free convection in a 2-D square enclosure due to some heat sources on the vertical sidewalls. Main efforts were focused on the size of the sources on the fluid flow and heat transfer characteristics. The results were showed that the effect of the various heating sizes

of the vertical walls explored the fluid field and thermal characteristics for free convective in 2-D square enclosure.

Tahavvor et al.[25],[2014],analyzed numerically the natural convection inside cavity ,the two vertical walls were wavy and straight top wall was kept isothermal and the bottom wall temperature was higher and spatially varying with cosinusoidal temperature distribution, Ra number varies(3400 -76000)and Pr was 0.71. The results were indicated that the Nusselt number was highly affected by number of waves although the Nusselt number was not highly affected by surface waviness when the number of undulations was below one.

Sompong and Witayangkurn.[26],[2014], studied the effects of wavy geometry on natural convection in an enclosure with two wavy vertical walls and filled with fluid saturated porous media ,the values of wave amplitude a(0.05and0.1) and number of undulations N(1and2) were chosen with constants Ra=10^5,Da=10^{-3},andPr=0.71.The result was showed that the increase in number of undulations has small effect on natural convection inside the enclosure where the increase in wave amplitude was reduced the strength of convection because higher wave volume was played a barricade role so that the increase in number of undulations has small influence on natural convection compared to the increase in wave amplitude.

Kalaoka and Supot.[27],[2014], numerically studied the natural convection in a partly cooled square enclosure filled with a porous medium. The related limits for calculations were the number of Darcy (Da =$10^{-5} - 10^3$), (Ra = 10^4 -10^6), Prandtl numbers (Pr = 0.70-10) and cold length (D = 0.50). It was found that varied Darcy and Rayleigh numbers can lead to difference temperature flow and heat fields. The results of this study can be used in the thermal insulation of buildings and cooling systems of electronic devices.

Yousaf and Usman .[28],[2015], numerically studied natural convection in a two-dimensional square cavity in the presence of roughness on vertical walls ,the study was performed for a range of the Rayleigh number from(10^3 to 10^6)and amplitude(0.025 to 0.15) for a Newtonian fluid of the Prandtl number 1.0. The sinusoidal roughness elements were located on both the hot and cold walls simultaneously with varying number of elements .When the amplitude of sinusoidal roughness elements approximately equal to 0.025 has no significant effects on the average heat transfer. The maximum reduction in the average heat transfer was calculated to be 28% when the sinusoidal roughness elements were located on hot and both the hot and cold walls simultaneously. Eddies formation was observed at Ra number equal to 10^4 with a small amplitude of 0.05 with number of roughness elements equal to 10 while varying the dimensionless amplitude if the roughness elements.

Ali Maseer et al.[29],[2017], studied laminar free convection heat transfer inside a closed curvy porous cavity heated from below by using of Darcy-Forchheimer model .The result showed that the sinusoidal curviness of the cavity's walls was not help to rise the rate of heat transfer, but in contrary it decreases this rate except when the number of waves per cavity's height is equal to one (i.e. N=1), where it was found that this value enhances the heat transfer rate inside the cavity especially when the dimensionless amount of the wave's amplitude be equal to (0.075).

Dalal and Das.[30],[2017], analyzed numerically the natural convection inside a square cavity. For different cases with one and three undulations. The wave amplitude (a) for both the cases is taken as 0.05. The fluid considered was air (Pr= 0 .71). The Rayleigh number was varied from 10^3 to 10^6. The top wavy wall was heated by a spatially varying temperature and other three walls were kept

constant lower temperature .The results showed the presence of undulation in top wall was affected local and overall heat transfer rate, flow and thermal field. Maximum heat addition on top wall occurs for the cavity with three undulations, but overall heat addition was higher for the cavity with one undulation. On the contrary the maximum heat rejection and over all heat rejection from the fluid to right wall was higher for the cavity with with one undulation.

Cheong et al.[31],[2017],verified numerically the natural convective flow and heat transfer in a sinusoidal heated wavy porous cavity with the presence of internal heat generation or absorption. Sinusoidal heating was applied on the vertical left wall of the cavity while the wavy right wall was cooled at a constant temperature. The bottom top and walls were taken to be adiabatic. The Darcy model was adopted for fluid flow through the porous medium in the cavity .The result was showed that the flow field and temperature distribution in the cavity were affected by the waviness of the right wall also the wavy nature of the cavity enhances the heat transfer into the system. The heat transfer rate in the cavity was decreased upon the raise of the internal heat generation/absorption parameter.

Cheong et al.[32],[2018],studied the effect of the aspect ratio, natural convective and heat transfer numerically in cavity saturated with porous medium. The wavy right wall was cooled at a lower temperature where higher temperature was applied on the vertical left wall. The horizontal top and bottom walls were taken to be isolated. The Darcy model was adopted for the fluid flow through the porous medium method over arrange of cavity aspect ratios, wavy wall amplitudes, number of undulations and Darcy–Rayleigh numbers. The result was showed that the waviness of the cavity enhances the heat transfer inside the cavity, and the rate of heat transfer was more enhanced when the aspect ratio of the cavity was close to (1). When the cavity was low aspect ratio eddies of re-circulating fluid were

formed in the area between crests of the wavy wall.

Abdul kadhim et al. [33], [2018], numerical investigation was presented to illustrate the effect of aspect ratio in a conjugate heat transfer enclosure filled with porous media and partially heated from vertical walls. The left and right walls were partially heated and cooled, respectively. The remaining partitions of the vertical walls in addition to the top and bottom walls were considered to be adiabatic. It was studied two different cases: Top- Bottom (case 1) and Bottom-Top (case 2). The parameters of interest were the modified Rayleigh number $10 \leq \text{Ra} \leq 10^3$, the finite wall thickness $(0.02 \leq \text{D} \leq 0.5)$, $(0.1 \leq \text{Kr} \leq 10)$ and the aspect ratio $(0.5 \leq \text{A} \leq 10)$. The results indicated that the locations of partially active walls had great influence on heat transfer rate and the Bottom-Top arrangement was gave better heat transfer rate compared to that of Top-Bottom. It was also found that by increasing the Rayleigh number, the rate of heat transfer increased. In contrast, increasing the wall thickness and aspect ratio reduced the heat transfer rate.

Saglam et al.[34], [2018], submitted study for the effect of free convective in a rectangular enclosure with hot sidewall The additional sidewall was reserved at a constant temperature, while the horizontal walls were unheated. The result was showed that the surface temperatures increase with increase in Rayleigh number.

Sadeq and Kadhim.[35],[2020], studied how the Porous media was played a major role in improving heat transfer and saving system from three decades for energy production and storage system, the porous media was investigated in a container with 20 cm width, 20 cm high and 2.7 cm depth. The two side of the container was left isolated; the base of the container was subjected to heat flux of 500 W/m^2, whereas the top of the container was set to heat convection with 10 W/$m^2.c^0$, heat transfer coefficient. Three materials were used as medium (Aluminum,Al_2O_3 ,Silica -sand and Glass). The results were showed that the

Glass and water porous media gave the maximum velocity and pressure, Aluminum and water porous media was gave the minimum velocity, temperature and pressure.

Mohammed et al.[36],[2020], studied numerically the influence of thermal conductivity of porous media on the heat transfer and fluid flow characteristics in a square cavity containing concentric circular cylinder .the results were showed that the temperature was reduced with increase in the thermal conductivity of porous media.

Moria.[37],[2021], investigated numerically how porous layers and different block heating shapes with different locations improvement of natural convection and heat transfer of L-shape enclosure ,the location of blocks and porous layer were (along the walls of the cavity) to achieve the maximum heat transfer rate. It was showed that the porous layer enhances the convective heat transfer performance especially in higher values of Rayleigh number. Furthermore, heating block location was crucial factors in enhancing heat transfer throughout the cavity; Triangular heating blocks illustrate a slightly better convective heat transfer performance.

Rao and Barman.[38],[2021], investigated numerically of natural convection in wavy cavity filled with fluid structured porous media subjected to a local heat source . The right side wall was wavy, kept at a fixed ambient temperature where as partial heat source with constant heat flux was placed at the right wall and other walls were kept adiabatic. The pertinent parameters under consideration were non-dimensional length $(0.25 \leq \varepsilon \leq 1.0)$ of heater placed at the middle of the left vertical wall, effective Rayleigh-Darcy number $(10 \leq Ra \leq 10^3)$ and the waviness of the right vertical wall, which was controlled by the amplitude $(0.05 \leq a \leq 0.25)$ of the wave and number of undulation $(1 \leq N \leq 5)$ per unit length . it is observed that convection inside the wavy cavity filled with fluid structured

porous media depend on ε only at high Ra also strong convection inside the cavity is observed when surface roughness gets increases.

Barman and Rao.[39],[2021], investigated numerically natural convection, cooling of a heat source embedded with a wavy porous cavity containing an insulated obstacle was investigated. A heat source was submitted to the left vertical wall, and the wavy right vertical wall was kept at fixed low temperature keeping top and bottom walls as insulated. The insulated obstacle which was placed inside the cavity was either square or circular in shape. The parameters considered for the investigation were Rayleigh-Darcy number) (Ra=10,10^3,10^3),amplitude of the wavy wall (a=0.05,0.15,0.25), undulation of wavy wall per unit length ($N=3$) and shape of the obstacle. The result was showed that the presence of a square insulated body reduces the convection process over a circular body; also, for a fixed Ra, the effect of obstacle at a particular portion of the cavity falls off with increment in a

Barman and Rao .[40],[2021], investigated numerically natural convection in a wavy porous cavity and effect of aspect ratio on natural convection in a wavy porous cavity is investigated. The vertical right wavy wall of cavity is kept at constant low temperature, whereas a partial heat source is embedded at the left vertical wall ,while top and bottom walls as adiabatic. Aspect ratio ($A_s = 0.2$, 0.5, 2.0, 5.0), Rayleigh-Darcy number ($Ra = 10$, 10^2, 10^3), dimensionless length of heat source ($\varepsilon = 0.25$, 0.50, 1.0) along with number of undulations ($N = 1$, 3, 5) per unit length and dimensionless amplitude of the wave ($a = 0.05$, 0.15, 0.25) which controls waviness of the wall. The result was showed that the waviness resisted fluid flow, so midway vertical velocity decreased with an increment of a and N and The increment in aspect ratio increases the cooling efficiency of the heat source.

Zachi and Luma.[41],[2021], investigated numerical study of the natural convection in a square enclosure ,this enclosure was filled with saturated porous medium with same fluid (lower layer) and air (upper layer).The enclosure vertical walls were cooled at constant temperature and the horizontal top wall was adiabatic and the bottom wall was subjected constant heat flux for different three size of heater numerically .The results were showed that symmetrical distribution of local Nu along the bottom heated wall and it was be minimum at midpoint. Also, the heat transfer and fluid flow were affected by thickness of porous layer and were maximum at porous layer thickness (0.25L) which was observed with large heater size to be approximately (93%) for the average Nu. Generally, the heat transfer was enhanced for large Darcy number.

2-2 Experimental Study.

Mohammed et al.[42],[2015], studied experimentally the result of the varied convection heat transfer in a package filled with a metallic porous material from stainless steel beads with a spherical shape with water as the working fluid ,the experiments were carried out with a Rayleigh number range from Ra=122418.92 to 372579.31 and Reynolds number that based on the particles diameter of Red=14.62, 19.48 and 24.The result showed that the local heat transfer coefficient increased with the increase of the imposed heat flux and Re. As well, the mean Nusselt number (Nu_m) increased with the increase of Ra and Re.

Grobler et al.[43],[2015], studied experimentally natural convection inside cavity having porous media and Nano fluid which was had an impact on the heat transfer capabilities of thermal systems. The Nano fluid consists of Al2O3 nanoparticles in the base fluid of 60% ethylene glycol (EG) and 40% water. A Rayleigh number range of $6 \times 10^3 <$ Ra $< 106 \times 10^4$, for a volume fraction of

0.2% nanoparticles. The porous medium was used glass spheres of 16mm. The results were showed that heat transfer was affected by both the porous medium and the Nano fluid, so that the heat transfer in the case of porous media with Nano fluid was more than the case of pure base fluid.

Alwan et al.[44],[2017], experimentally investigated the unsteady heat transfer natural convective through a porous material sample. As the porous layer with distilled water was the saturating fluid, glass spheres of diameter 3, 5, 8 and 18 mm and plastic ball striper of 6 mm were used, the heat flux was subjected as a boundary condition to the lower surface. The (h, Nu_e,Nu_f and Ra_m) parameters were calculated from the temporal and spatial distribution of temperature profiles at different locations of the sample. It was found that the value of air velocity was less than 0.08 m/s. The Re was experimentally less than 10. It was showed that the heat transfer parameters (h,Nu_e,Nu_f) were decreased with increasing the time of heating.

Ali Maseer et al.[45], [2017],It was performed an experimental study to identify how can the porous medium behave inside a closed curvy porous cavity. The facing vertical walls were to be wavy sinusoidal walls. One of them (right one) is reflected about the vertical center line of the cavity. Number of waves per wall (N) is equal to (1) with wave's amplitude (a) equal to (0.15). As boundary conditions, the vertical walls were kept insulated to be adiabatic walls. The top surface is exposed to outside environment while the bottom surface is exposed to constant heat flux. The result was showed that the sinusoidal curviness of the cavity's walls was not help to rise the rate of heat transfer, but in contrary it was decreased this rate except when the number of waves per cavity's height is equal to one (N=1).

Noah M Salah et al.[46],[2021], investigated experimentally the natural convection heat transfer in a square enclosure filled with saturated porous medium and partially heated from below. Two locations (left and middle of the enclosure) was studied to explain heat and temperature distribution inside the enclosure. The experimental results were obtained under constant heat flux within the range of (1000- 10000 W/m^2), and modified Rayleigh number within the range of ($0 < Ra_m < 420$). The location of the heating element was a noticeable effect on the distribution of heat and temperature, the thermal flux a significant impact and clear on the process of heat transfer during natural convection in porous media since higher heat flux was lead to an increase in the modified Rayleigh number and increases the Nusselt number of two cases. The study was indicated that the Nu number depends on the Ra number and was directly proportional to it.

2.3 Summary

The literature presented in this chapter are summarized in Table (2.1)

Table (2.1): Summery for the Previous Literatures

Author	refrence	Year	Model	Finding
Kumar	6	2000	Numerical	A wavy vertical wall with uniform heat flux gives rise to a wavy surface temperature distribution
Kumar and Shalini	7	2003	Numerical	It was noticed that Increasing either number of waves or wave amplitudes or thermal stratification (S) was saw to decrease Nusselt number (Nu) also it was noticed secondary circulations near the wavy wall and multicellular circulations in the core of the flow field .

Kumar and Shalini	8	2003	Numerical	The increase in wave amplitudes or number of waves per unit length would lower the average or GNN because of the secondary circulation zones that occur in the adjacent region to the curved wall.
Jue. T.C	9	2003	Numerical	The result was showed reduced in the porosity was caused decreased in the force of external thermal vortices which caused allowing for Changes in internal vortices generated from heat generation.
Das et al	10	2003	Numerical	Heat transfer falls gradually with an increasing surface waviness up to a certain value of surface waviness, above which heat transfer increases again for low aspect ratio. Whereas for higher aspect ratio,
Dalal and Kumar	11	2005	Numerical	The results obtained showed that the angle of inclination effects on the flow and heat transfer rate in the cavity It was noticed the increased in the amplitude produced higher heat transfer rate at low Rayleigh number.
Misirliogu	12	2005	Numerical	The local Nusselt number from the vertical walls may even become negative;this means the heat generated in the porous medium cannot be transferred through the porous medium from the right (hot) wall to the left (cold) wall.
Dalal and Kumar	13	2006	Numerical	The heat rejection from the fluid to wavy wall increases up to Ra=$10^4$for one-undulated cavity compared to square cavity without undulation, the heat transfer increases by undulating the wall

Selah M.Salih, Ala'a A.Mahdi,and Majid H.Majeed	14	2006	Numerical	The rates of heat transfer dependent on the porous Rayleigh number.find the correlation for Nu and Ra also AR ,
Mahmood, et al.	15	2008	Numerical	The Nu is raise with Ra and porosity but fall with the Darcy number ratio of particle to fluid thermal conductivity and enclosure aspect ratio, as well as better for their effects on heat transfer which is represented by mean Nusselt Number
Khanafer	16	2009	Numerical	The results of this investigation illustrated that the amplitude of the wavy surface and the number of undulations affect heat transfer characteristics
Hussein	17	2010	Numerical	It was observed that the intensity of circulation increases with increasing the angle of inclination .Also, the greater circulation causes more heat to be distributed in the central of the cavity
Mushate	18	2011	Numerical	The results were showed the rate of heat transfer was increased with the increase of the Rayleigh number and amplitude values for($0.05 \leq a \leq 0.075$) . After that was decreased. The number and size of rotating vortices was increased with the increase of undulations number.
Eiyad Abu-Nada et al	19	2011	Numerical	The result was showed the geometry parameter was an important control on heat and fluid flow also heat transfer was increased with increasing of geometry parameter for the same

				Rayleigh number and nanoparticle fraction
M.Bhuvane swari, S.Sivasank aranb, and Y. J. Kima	20	2011	Numerical	1-The heat transfer rate is fall with raised the aspect ratio. 2-Very low Darcy number makes the heat transfer rate approximation to a constant value
Falah A.Abood	21	2011	Numerical	The coefficient of heat transfer increases with increasing of aspect ratio and Ra
Mohamma d Mahdie Saleh and Ihsan Y.Hussain	22	2011	Numerical	1-The maximum velocity and temperature occur at angle 45° 2-The strong buoyancy force influenced on convective flow from calculated average and local Nu . 3-The heat transfer proportional directly with time, angle of inclination, Rayleigh number, period and amplitude
Muneer A Ismael 2011	23	2011	Numerical	1-Higher heat transfer is obtained when the inner cylinder is positioned below the mid enclosure height and whatever the wall waviness the lower position of the inner cylinder (0.45) is the largest the values of Nu . 2-the influence of the wall waviness ratio is found to be very small
Nardini et al	24	2013	Numerical	The effect of the various heating sizes of the vertical walls explored the fluid field and thermal characteristics for free convective in 2-D square enclosure
Tahavvor	25	2014	Numerical	Nusselt number was highly affected by number of waves and increasing it

et al				decreased the wavy walls Nusselt number; although the Nusselt number was not highly affected by surface waviness when the number of undulations was below one.
Sompong and Witayangk urn	26	2014	Numerical	The increase in wave amplitude was reduced the strength of convection because higher wave volume was played a barricade role
Kalaoka1 and Supot	27	2014	Numerical	It was found that varied Darcy and Rayleigh numbers can lead to difference temperature flow and heat fields
Yousaf and Usman	28	2015	Numerical	Study showed that the sinusoidal roughness considerably affect the hydrodynamic and thermal behavior of fluid in a square cavity. The maximum reduction in the average heat transfer was calculated to be 28% when the sinusoidal roughness elements were located on both the hot and cold walls
Gati et al	29	2017	Numerical	The result showed that the sinusoidal curviness of the cavity's walls was not help to rise the rate of heat transfer, but in contrary it decreases this rate except when the number of waves per cavity's height is equal to one
Dalal and Das	30	2017	Numerical	The presence of undulation in top wall was affected local and overall heat transfer rate, flow and thermal field. Maximum heat addition on top wall occurs for the cavity with three undulations, but overall heat addition

				was higher for the cavity with one undulation
Cheong et al	31	2017	Numerical	The wavy nature of the cavity enhances the heat transfer into the system. The heat transfer rate in the cavity was decreased upon the raise of the internal heat generation/absorption parameter
Cheong et al	32	2018	Numerical	The rate of heat transfer was more enhanced when the aspect ratio of the cavity was close to 1. when the cavity was low aspect ratio (Ar < 1) eddies of re-circulating fluid were formed in the area between crests of the wavy wall.
Abdulkad him	33	2018	Numerical	Locations of partially active walls had great influence on heat transfer rate and the Bottom-Top arrangement was gave better heat transfer rate compared to that of Top-Bottom increasing the wall thickness and aspect ratio reduced the heat transfer rate.
Saglam et al	34	2018	Numerical	The result was showed that the surface temperatures increase with increase in Rayleigh number.
Sadeq and Kadhim	35	2020	Numerical	The results shows that the Glass and water porous media give the maximum velocity and pressure, Aluminum and water porous media give the minimum velocity, temperature and pressure
Mohammd et al	36	2020	Numerical	The results were showed that the temperature was reduced with increase in the thermal conductivity of porous media

Moria	37	2021	Numerical	1-Porous layer enhances the convective heat transfer in higher values of Ra.2- Heating block location was a crucial factor in enhancing heat transfer .3-Triangular heating blocks illustrate a slightly better convective heat transfer performance.
Rao and Barman	38	2021	Numerical	It is observed that convection inside the wavy cavity filled with fluid structured porous media depend on surface waviness only at high Ra also strong convection inside the cavity is observed when surface roughness gets increases.
Barman and Rao	39	2021	Numerical	It was observed that the presence of a square insulated body reduces the convection process over a circular body; also, for a fixed Ra, the effect of obstacle at a particular portion of the cavity falls off with increment in a.
Barman and Rao	40	2021	Numerical	The increment in aspect ratio increases the cooling efficiency of the heat source.
Zachi and Luma	41	2021	Numerical	The heat transfer and fluid flow are affected by thickness of porous layer and are maximum at porous layer thickness (0.25L) which clearly observed with large heater size to be approximately (93%) for the average Nu. the heat transfer is enhanced for large Darcy number

Mohammed et al	42	2015	Experim-ental	The Local heat transfer coefficient increased with the increased of the imposed heat flux and Re. As well as mean Nusselt number (Num)is increased with the increased of Ra and Re.
Grobler et al	43	2015	Experim-ental	The results were showed that heat transfer was affected by both the porous medium and the nanofluid, so that the heat transfer in the case of porous media with nanofluid was higher than that in case of pure base fluid.
Alwan et al	44	2017	Experim-ental	The (h , Nue , Nuf and Ram) dependent upon the dimensions of solid and the heating time and fluid layers of sample.
Ali Maseer Gati et al	45	2017	Experim-ental	The sinusoidal curviness does not help to increase the rate of heat transfer. Except when (Nw=1).
Noah M Salah et al	46	2021	Experim-ntal	Higher heat flux causes to an increase in the modified Rayleigh number and the Nusselt number for the two cases.
Present work		2023	Experim-ental and numerical	Higher heat flux and higher porosity cause to an increase in the modified Rayleigh number and Nusselt number.

2.4 Scope of the Present Work.

It was shown from the preceding review that there exist significant literatures pertaining to the problem of natural convection in porous media. It was

pointed from the above researchers reported here, that their mainly studies concentrated on the case of one phase flow to simulate the natural convection inside the porous media and the using of Navier Stokes equation for this simulation.Additionaly they considered how the parameters such as Rayleigh number, porosity and wavy walls affected on the heat transfer convection inside the porous media.There for in the present work, it was examined the problem of natural heat convection in a porous media with considering the all vertical walls of cavity are undulating in sine wave while the shape of these walls was once inward and in the second cavity is outwards. During designing these walls of cavities they are isolated. The bottom of the cavity is subjected to a constant heat flux and the upper of the cavity is at a constant temperature. The behavior of heat transfer inside the porous medium is numerically studied using ANSYS19.2 and then both numerical and experimental results are compeared.

Chapter Three

Theoretical Work

Chapter Three

Theoretical Work

This chapter involves the numerical analysis to solve a mathematical system by using an (ANSYS 19.2) (FLUNT) program under CFD-solver manager to analyze the flow field and temperature distribution in three dimensions.As this flow through this porous medium occurs as a result of free convection. Based on the model finite volume, the governing equations are solved to evaluate the numerical results of a computational fluid dynamics model. The governing equations include the mass, momentum, and energy equations

3.1 Mathematical Model

Finite volume method by (ANSYS 19.2) (FLUNT) program is employed to solve equations for 3D-steady state, laminar flow through sinusoidal walls cavity with appropriate boundary conditions. Solid work is used to draw geometry of cavity as present in *(Appendix)*.

3.2   Problem Formaltion

To simulate a flow in porous media, the following boundary conditions are specified as shown in figure (3.1) which is the detailed view of the boundary conditions for the two shapes of the investigated cavities.

The numerical model is a three dimensional closed cavity filled with a porous media. The side walls are sketched to be wavy sinusoidal walls. In addition, it will take the bottom surface and upper surface of the cavity as a flat surface, As a boundary conditions, the facing side walls of the model are kept insulated to be adiabatic walls. The top surface is exposed to constant temperature   while the

bottom surface is exposed to constant heat flux. The chosen porous media consists of silicasand as a solid phase and saturated by air.
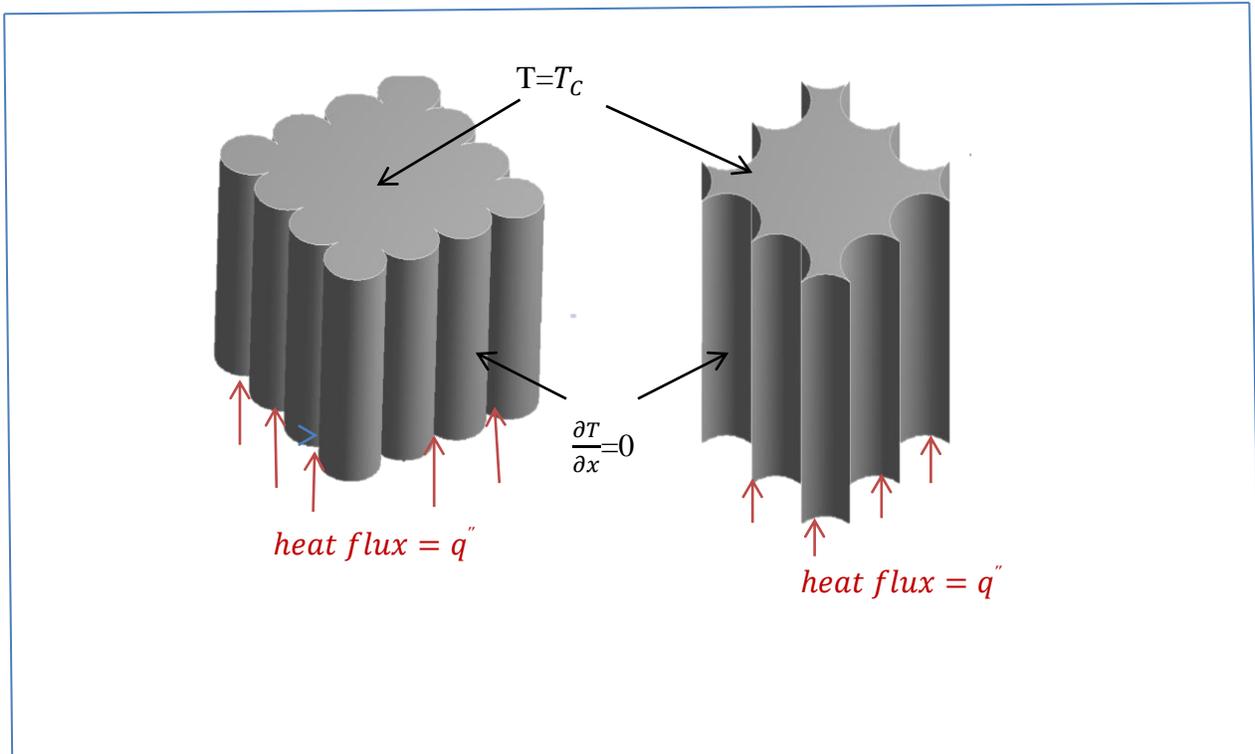
Figure (3-1). The applied boundary conditions.

3.3 Governing Equations

The momentum and heat transport equations are used. The partial differential equations (PDE) of the present system are complex; the finite volume method converts these equations into an algebraic matrix depending on the boundary conditions and the mesh distribution. The algebraic equations of the momentum transport are solved first at the initial temperature condition. Then, the resultant velocity profile is introduced to the heat transfer equation in the

convection term. The resultant temperature distribution is used to estimate the physical properties of momentum and heat transport. The momentum transport equation is solved again with a new temperature distribution and so on. The governing three-dimensional equations in the Cartesian coordinate system for the present study are described in this section by using the following assumptions:

1. No leakage.

2. Steady-state.
3. Three-dimensional flow.
4. Laminar flow.
5. Incompressible flow.
6. The convective fluid remains a single-phase.
7. Porous medium model, assuming the porosity is isotropic.
8. Body forces are neglected.
9. Physical properties of the solid and the convective fluid are assumed

to be constant.

10. No-slip boundary condition.
11. The radiation effect and viscous dissipation are neglected.
12. In thermal equilibrium ($T_f = T_s$)

Therefore, the continuity, momentum and energy equations in the dimensional form are given by [47]:

3.3.1 The Continuity Equation for Porous Media

The continuity equation for the flow in the porous mean is a partial differential equation derived from the equation of conservation of mass, and

imposes the fluid with three dimensions and is stable in the porous mean of equal properties in all directions The equation of continuity is as follows[47]:

$$(\nabla . v) = 0 \tag{3.1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3.2}$$

3.3.2 The Momentum Equation for Porous Media

When identifying the mechanism of motion of a fluid inside a saturated porous material, there are many practical experiments that led to the conclusion of mathematical laws used to solve such problems, and one of these laws is Darcy's law, which is based on readings taken from practical experiments. This scientist has confirmed that it is the rate of speed of the fluid during a certain stream of porous matter that is proportional to the pressure decline during this substance. Besides, Forchheimer and Dupit, by modeling the Navier-Stokes equation, presented a more complete equation that is the following [47]:

$$\rho_f \left[\varepsilon^{-1} \frac{\partial v}{\partial t} + \varepsilon^{-2} (v. \nabla) v \right] = -\nabla P - \frac{\mu}{K} v$$

$$\tag{3.3}$$

3.3.3. Energy Equation.

The energy equation of the homogeneous porous medium is represented by two parts, steel and fluid, and assuming that the medium is two-dimensional and

for the state of stability over time and the absence of heat generation and by neglecting the heat generated by the viscosity effect, the energy equation will be as follows[47]:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha_e[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}] \qquad (3.4)$$

The value of α_e is the effective thermal diffusivity of porous medium which is [48]

3.3.4. Properities of Porous Media

The thermal properties of interest for any material include thermal conductivity, density, thermal diffusivity, and specific heat.Thermal conducivity(k_e) is an intensive macroscopic property ,therefore, in addition to being a function of the fluid and solid phase, k_e is also a function of the microstructure of the porous medium .In the case when the fluid phase is stagnant,the effective thermal conductivity is determined by conduction through the porous medium.If the solid and fluid phases are assumed to be in local thermal equilibrium ,then both phases can be represented by a single volume-averaged continuum. Using the model to calculate effective thermal conductivity from past studies emphasizing that the thermal conductivity is varied with temperature [48],where

$$\frac{k_e}{k_f} = \frac{2k^2(1-\varepsilon)+(1-2\varepsilon)}{(2+\varepsilon)k+1-\varepsilon} \qquad (3.5)$$

Correlation values of k_s and k_f are done to give more accurate calculations in equation (3.5) ,The value of α_e is the effective thermal diffusivity of porous medium which is[46] :

$$\alpha_e = \frac{k_e}{(\rho c_p)_e}$$

………… (3.6)

The term $(\rho c_p)_e$ that is appeared in equation can be defined as (3.7)

$$(\rho C_P)_e = \varepsilon(\rho C_P)_f + (1 - \varepsilon)(\rho C_P)_s$$

………….(3.7)

3.4 .Numerical Anlieysis

3.4.1.ANSYS- CFD

ANSYS-CFD software is usually used to simulate fluids and it has physical modeling capabilities that are required in many industries.Typically,many companies throughout the world have used this program as an integral part of their product development. The software is used to model a fluid-flow for the transfer of heat and mass and others. The popularity of ANSYS-CFD is increasing due to its highly advanced technology which gives accurate and fast results .The first step is creating the geometry which can be done in the ANSYS geometry generation or other programs specified for geometry generations. The next process would be generating a suitable mesh for the geometry in this case it is done in the ANSYS meshing facility. Then, the time for the simulation step-up process includes setting the boundary conditions for the model and solving the equations. The -post-processing step is where the results are obtained. The optimization process would be applied if the results were not good enough.

3.4.2 Geometry Creation

In any CFD analysis, the first and important step is the definition and creation of the geometry of the flow region.Design Modeler or Solid works with ANSYS-CFD 19.2 software is used to create a three-dimensional geometry in this study.Where, the present The geometry model is a three-dimensional cavity filled with a porous medium. Two shapes of cavity are taken into account ; the first one is sinusoidal outer wavy walls and the second is an opposite wave in which the sinusoidal wavy walls ripple in. Porous media is assumed to be a silica-sand of (1 and 3) mm diameter. The cavities are explored under the same conditions, where the upper surface is assumed to be at a constant temperature, while the lower surface is under the effect of a constant heat flux and the sidewalls are completely insulated. This software consists of many modifying tools and drawings that help to finish the required design as shown in figures (3.2) and (3.3).
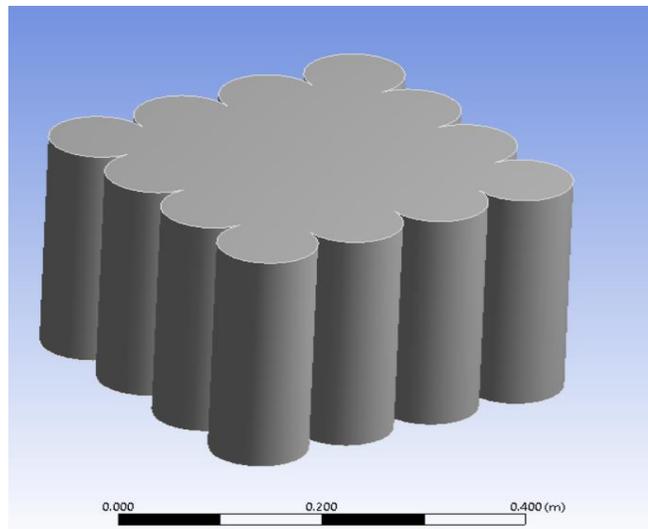
Figure (3.2). A three- dimensional geometry with outward wavy walls
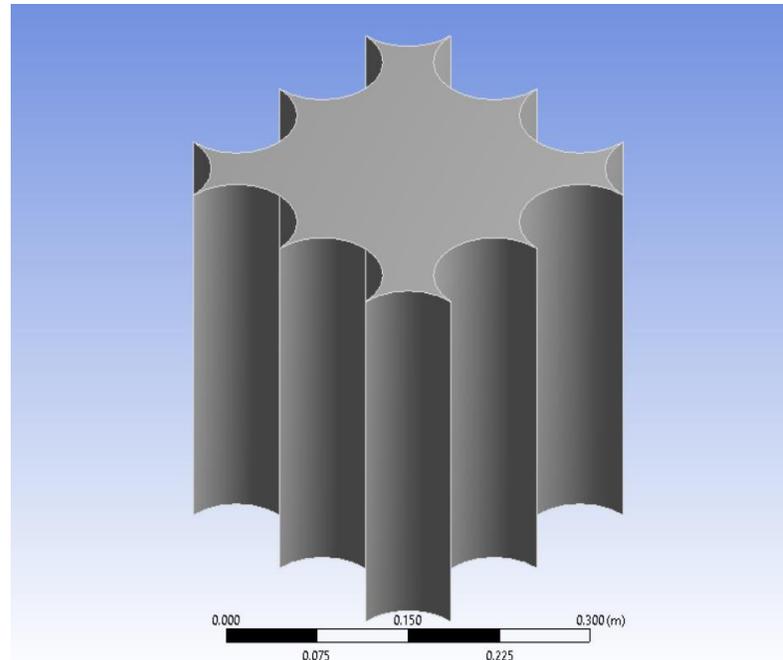
Figure (3.3). A three- dimensional geometry with inward wavy walls

3.4.3. Meshing Generation

There are so many types of meshes and choosing the type of mesh depends on different parameters such as flow field, geometry, and complexity (Bakker, 2006)[48]. The size and type of mesh have a major impact on the CPU time requisite, accuracy of solution, and convergence rate (Bakker, 2006)[48]. In this software, there is a very important tool that can be used to produce a high degree of accuracy in the result depending on the type of mesh and the number of elements . Structured and unstructured grids are classified as the approaches of volume meshing. For complex geometries, the unstructured grids like tetrahdral are used to get more accurate results. In this investigation, the tetrahedral type is generated (82600) elements and (48884) nodes for theoutward sinusoidal wavy walls and

39

(35800) elements with (23230) nodes for the inward sinusoidal wavy walls .Figure (3-4) depicts the mesh that is used in current simulations.
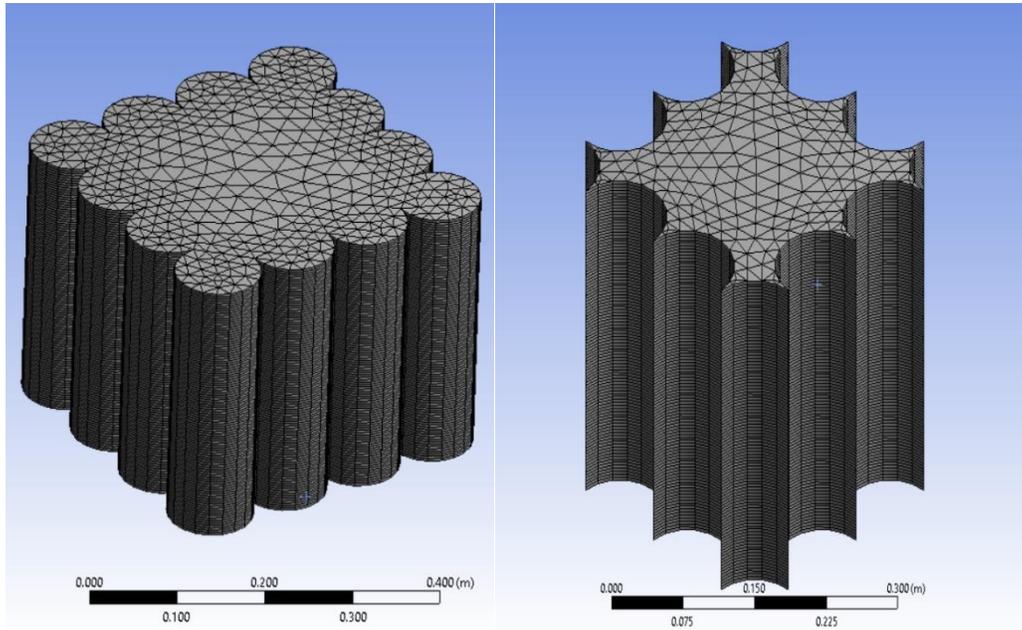
Figure (3.4). Tetrahedral mesh for the two cavities.

3.5. The Solution

ANSYS includes various solvers and provides the ability for examining the best one for a given application. It reviews which settings or parameters can select for solving a wide range of different problems and how can analyze the problem to improve convergence.Moreover, the number of iterations is completed to the maximum number before the solver ends. In the most recent instance, (100) iterations are used in most cases, which is found to be enough for getting a convergent solution, with a maximum error equal or less than (10^2), as showen in Figure (3-5)
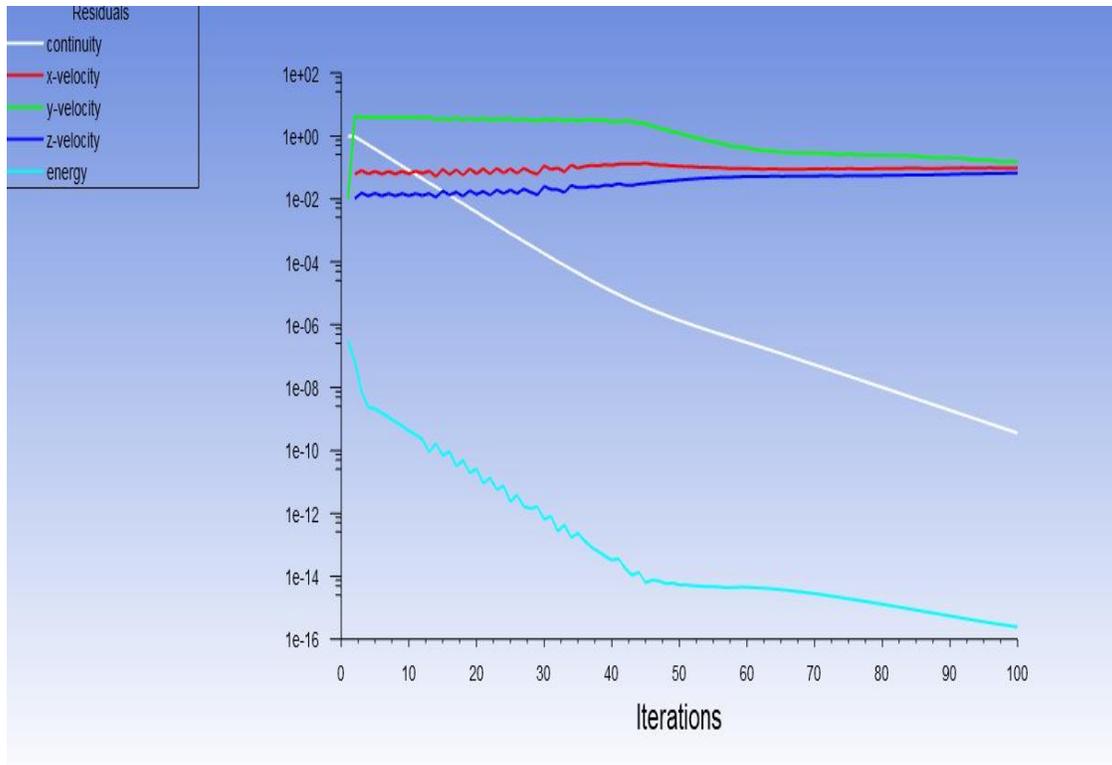
Figure (3.5). The relation between the error and itration number

3.6. CFD Setup

In this stage, the results are calculated after inserting the data and boundary conditions.Different materials were selected to represent the solid phase; table (3.1) shows the materials that are used along with their properties. If the material is not included in the schedule of materials in the program, the name of the material and properties are entered by inserting the materials item, then the porous field is selected.In this work, air is chosen for the fluid phase within the domain. The porosity is selected depending on the particle diameter as indicated by equation (3.8), [49], where two diameters are used for particles (1and 3) mm .While a permeability is determined using equation (3.9), [49].The permeability and porosity are listeded as showen in table (3.2)

41

$$\varepsilon = 0.3454 + 11.6985 D_P \tag{3.8}$$

This value of the permeability of the silica-sand that used in this test approximately can be gotten by using of the kozeny-karman equation which is used to estimate the permeability mathematically. This equation can be written in the general form as follows [49]:

$$K = \frac{\varepsilon^3 \, D_p^2}{150(1-\varepsilon)^2} \tag{3.9}$$

- ε is the porosity of the bed (or core plug) [fraction]
- D_p is average diameter of sand grains [m]
- K is absolute (i.e. single phase) permeability [m^2]
- $\emptyset_s$ is the [sphericity] of the particles in the packed bed = 1 for spherical Particles
- The Permeability (K) of silica _sand is (3.2e-10) m^2

Table (3.1): Materials properties.

Substance	ρ (kg/m³)	C_P (J/kg.°C)	k (W/m.°C)	$T_{melting}$ (°C)	μ (kg/m.s)
air	1.184	1007	0.0255	—	$1.562 * 10^{-5}$
Silica sand	2300	1170	0.1976		—

Table (3.2): Porosity and permeability

No.	Porous particle diameter (mm)	Porsity(ε)	Permeability(K)
1	1	0.36	$7.593*10^{-10}$
2	3	0.38	$8.564*10^{-9}$

3.7. Advantages of Numerical Analysis

Many researchers have performed experimental investigations on the fluid flow, heat, and mass transfer phenomena. But, the experimental approach is quite costly in many cases and time-consuming which may not be desirable. To reduce the problem, numerical analysis becomes a very attractive approach today. On the other hand, this technique provides accurate results with reducing time effort. The key advantage of the numerical analysis is:

- This technique usually requires less time to find out the solution.
- This is a useful and very powerful technique for functions that have moderately complex structures or geometry
- This technique discretizes the physical problem into small domain.
- Lower cost is involved in the numerical procedure compeared with the experimental approachometry.
- This technique converts complex geometry into simpler one.

3.8. Solution of Differential Equations

The mathematical model of complex geometry may be of very large shapes and the limitations can be arised in this case during numerical modeling. Therefore, scientists and researchers have sub-divided the complex system into smaller components or elements to analyze it easily. In many cases, adequate accuracy of the solution is obtained using a finite number of well defined components (discrete variable problems), whereas, for other problems, an infinite number of sub-divisions or elements is possible (continuous variable problem). Since the capacity of any computational machine is finite, continuous variable problems are solved using a finite number of elements. This results in an approximate solution rather than an exact one. Therefore, different computational methods are suggested so that the entire problem domain can be subdivided into points, or elements, or volumes that make the approximation close to the exact solution. Based on the way of discretization, a different types of solution methods are available such as,

- Finite difference method (FDM).
- Finite element method (FEM).
- Finite volume method (FVM).

There are numerous other methods such as SEM, LBM, etc. to solve a problem in CFD. There are many software packages such as ANSYS, COMSOL Multiphysics, MARC, etc. available nowadays to model that methods.In this work, ANSYS is used for simulation.

Chapter Four

Experimental Work

Chapter four

Experimental Work

4.1. Introduction

The present work investigated experimentally the temperature distribution inside porous cavity. The cavity is heated from below with constant heat flux. During the heating processes, the temperatures distribution in the cavity is measured using many of thermocouples located at different position inside the cavity.

4.2. Rig Equipment

The experimental rig is manufactured in the Mechanical Engineering Fluid Laboratory of Babylon University. The experimental was carried out in June ambient laboratory conditions about $30^{O}C$. The experimental apparatus consists basically of as shown in figure (4-1):

1- Cavity.

2- Outer container box.

3- Cooling system.

4- Electrical heater.

5- Instrumentation (measurement device).

Figure (4-2) illustrates the schematic diagram of the present study:
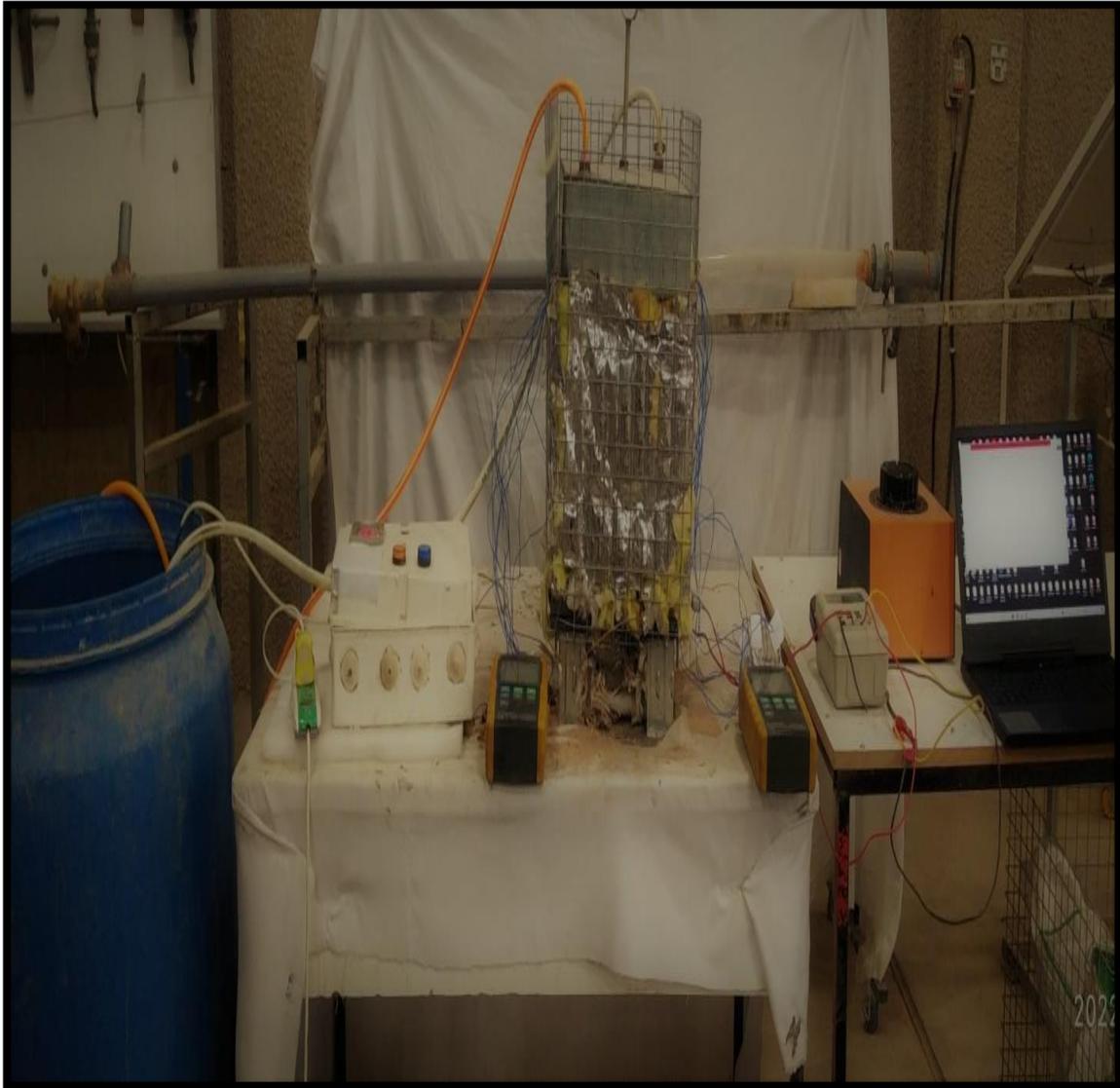
Figure (4-1). The photography rig of equipment.

Figure (4-2) Schematic diagram of the rig.
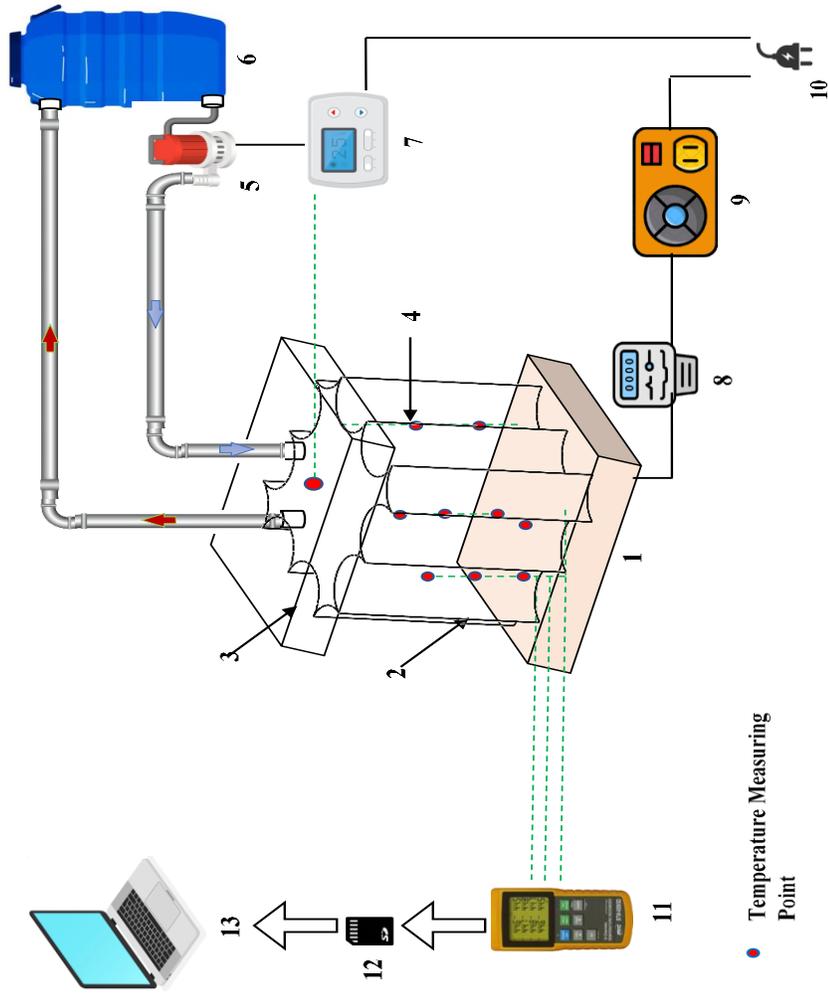
1	Elecrical Heater	8	Power Analyzer
2	Porous Cavity	9	Power Supply
3	Cooling System	10	Electrical Source
4	Temperature Meauring Point	11	Temperature Recorder
5	Pump	12	Memory Card
6	Water Tank	13	Personal Computer
7	Thermostat		

4.2.1. Cavity

An iron pipe with a diameter of (10 cm) is cut in a half as shown in figure (4-3) using an electric saw, each half of the pipe is (30 cm) height . Then the halves of the section pipe are welded to obtain the desired shape of the sinusoidal walled cavity where the porous media is placed as indicated by figure (4-3).Two cavities are made, the first cavity, named as cavity No.1 with dimensions (30×30) cm made from iron with sinusoidal walls , as shown in figure (4-4) and the second cavity is named as cavity No.2 with dimensions (30×30) cm, as shown in figure (4-5).cavity No.2 has walls with opposite curvature direction compeared to the walls of cavity No.1.These cavities are filled with a uniform porous medium.

4.2.1. Outer Container Box

Each of these sinusoidal cavities is inserted in a rectangular box the rectangular box is made from galvanized iron wire. The dimensions of this box are length (L = 35 cm), width (W = 35 cm), and height (H = 50 cm), the purpose of this box is to add insulating material to ensure complete isolation of the curvy sides walls.

Figure (4-3). Halves iron pipe.

Figure (4- 4). Cavity No.1

Figure (4- 5). Cavity No.2.

4.2.2.Heater

In order to supply a uniform heat flux which is required in this study, a flat plate heater is used to heat a test sample.The dimensions of this heater are (30cm*30cm) as shown in figure (4-6).
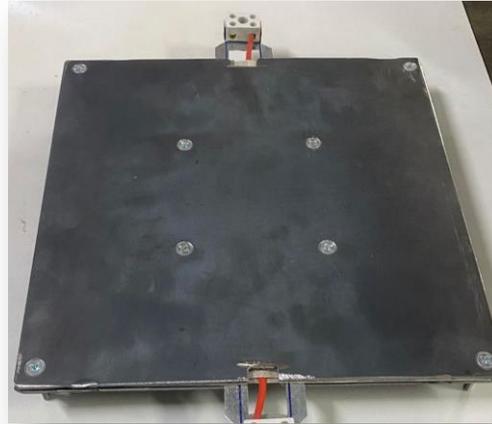
Figure (4- 6). Heater

This heater gives nearly (3000) watt at full load, which can be controlled by using device of variable voltage. The heat flux required for the present work must be directed upward just. To get a better distribution of temperature , a piece of copper with dimensions (30cm*30*cm*1.5cm) is used as shown in figure (4-7).Copper is known for having good thermal properties, where the typical thermal conductivity of pure copper is 391.00 $w/(m.k)$.This means that heat passes quickly through the metal, this is due to the close lattice structure of the copper atoms that vibrate more as the temperature rises, transferring heat internally .Copper also has a high melting point (1,083°C), making it ideal for high-temperature applications[50].

Figure (4-7). Copper plate.

Test is carried out to ensure that the temperature of the heater surface is equal, where the temperatures at five different points on the surface are recorded using a thermal imager device (see figure (4-8)).

Figure (4-8). Thermal imager device.

The surface temperatures at the five points are shown in table (4-1).

Table (4-1) Temperature recorded on the surface of the heater.

T (1)	T (2)	T (3)	T (4)	T (5)
$70C^\circ$	$70.5C^\circ$	$71.3C^\circ$	$69.86C^\circ$	$71C^\circ$

4.2.3 Voltage Variation Device

The voltage of the heater is controlled by using a variable voltage device shown in figure (4-9). This device can provide different values of voltage in the range of (0-260 volts). The required value of the voltage is reached by changing the internal resistance.

Figure (4- 9). Voltage variation device.

4.2.4 Power Analyzer Device

The power generated by heater is determined by using a power analyzer. A Digital power analyzer type LUTRON model (Dw – 6091) with a maximum current (10 A) and a maximum voltage (600 V) is used to convert an analog voltage signal from a power supply into digital data that is possible to read, as shown in figure (4-10).
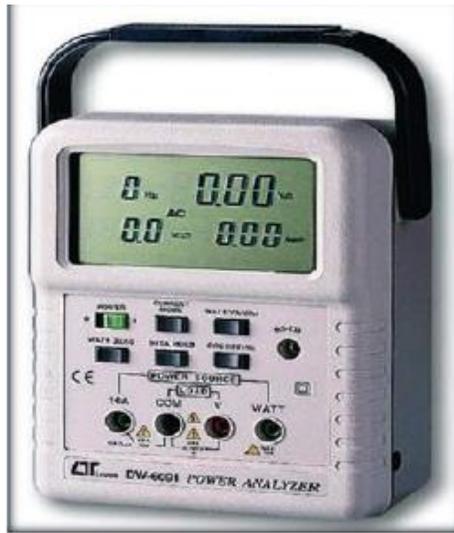
Figure (4- 10) Power analyzer device.

The values of power are produced for the entire cavities as listed in table (4-2). Thus, the heat flux values are (1000 - 2000) w/m^2, which are obtained by dividing the power values for each sample over the surface area of the sample.

Table (4-2) The values of supplied power

Samples	Voltage (Volt)	Current (Ampere)	Power (Watt)	Heat flux (W/m²)
No.1	120	7.25	870.1	1000
	160	8.156	1305	1500
	200	8.7	1740	2000
No.2	120	4.58	511.73	1000
	160	5.207	766.5	1500
	200	5.55	1022	2000

4.2.5 Cooling System

In order to make the temperature of the upper surface of the sinusoidal cavity a constant temperature, a water tank made of galvanized alloy steel with ASTM A653 specifications and coating G90 is used.This tank is placed at the upper wall of the cavity. The shape of the water tank is rectangular with dimensions (cm 30* cm 30 cm *15cm),as shown in figure(4-11).Where the water tank on the upper surface contains two holes ,one for water to enter the tank and the other for water to exit from the tank .The water entry and exit holes are connected to a larger tank that contains an electric water pump connected to a thermostat.When the temperature of the upper surface of the cavity rises ,the electric water pump operates ,cold water rises from the large tank and hot water goes down to the large tank in a circulation cycle
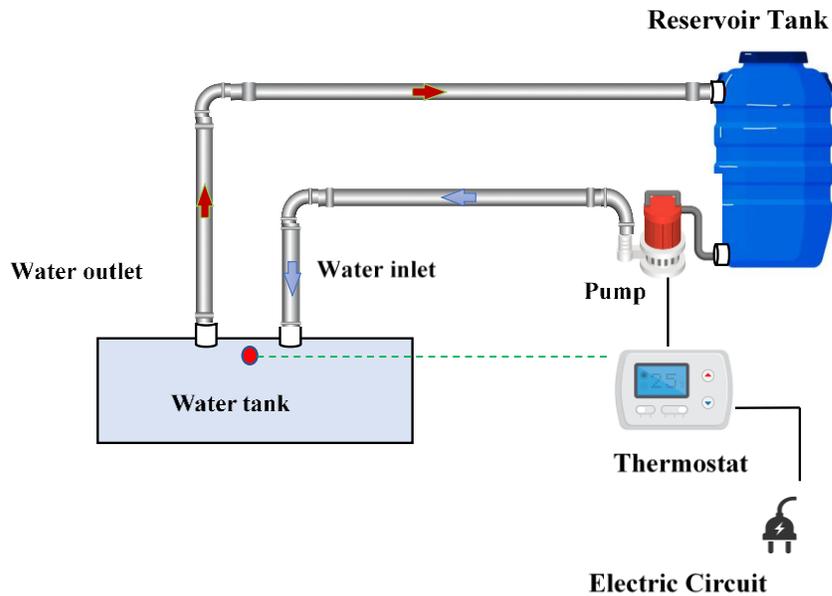
Figure (4-11) Schematic diagram of cooling system.

4.2.6.Thermostat

In this work,athermostat is used to read the room temperature.Thermostat connects to the bottom surface of the water tank located above the cavity by thermocouple and connects to it water pump which it placed inside the reservoir tank ,as when the temperature of the bottom surface of the water tank is higher than constant temperature the thermostat is separated and the hot water comes out from the outside of the water tank ,and cold water enters from the inlet by raising the water by water pump .Figure(4-12) represent the thermostat device.

Figure (4- 12) Thermostat device.

4.3 Measuring Devices

4.3.1 Thermocouples

Thermocouples of type (K-Type, pin wire, range:(0°C to 800°C), and (accuracy:±0.25 °C) are used in this work as shown in figure (4-13), and positioned at different locations to measure the temperature of pours media in different areas.The heater surface and the thermocouple are connected to the bottom surface of the tank and the thermostat to fix the upper cavity temperature.
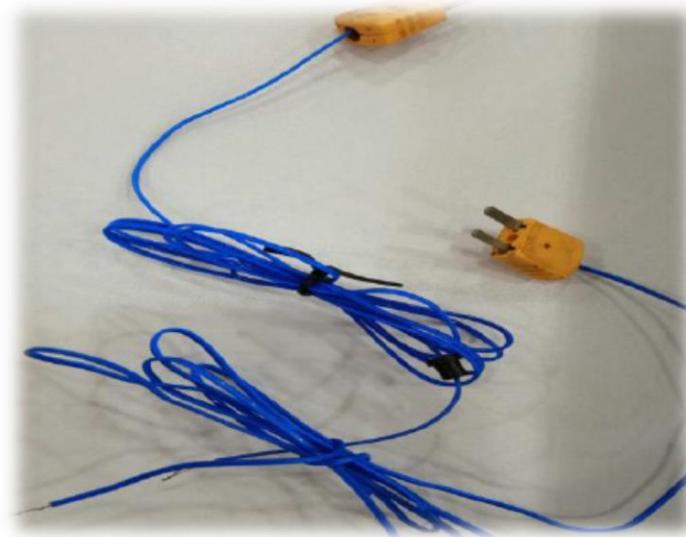
Figure (4- 13) Thermocouples type (K).

4.3.2 Temperature Recorder Device

Temperature recorder device type LUTRON and model BTM-4208SD of accuracy (±0.4%) °C with 12 channels is displayed in figure (4-14). The temperature reading data is stored in the S.D card. This data is recorded with time and loaded on excel sheet. It uses different types of thermocouples such as T, S, R, K, and J. It works as a data logger on a manual basis, (data logger automatic) with time range (01 to 3600) seconds.

Figure (4- 14) .Temperature recorder device

In the present work, two devices of temperature recorder are used to measure the temperature inside the cavity and twenty four thermocouples type (K) are used to measure the temperature, with a range of (-50°C to 1000°C), as shown in figure (4-13). Figure (4-15) represent the position of thermocouples inside the cavity for inward sinusoidal wall. Twenty-two thermocouples are distributed on three different levels inside the cavity, and two thermocouples No. 23 and No.24 are placed in the center of heater as indicated by figure (4-15). The following figure shows the distribution of thermocouples for inward sinusoidal wall cavity, where seven thermocouples are placed at a height of 9 cm. For the second level,

eight thermocouples are placed at a height of 18 cm, and seven thermocouples are placed in the third level, at a height of 27 cm.
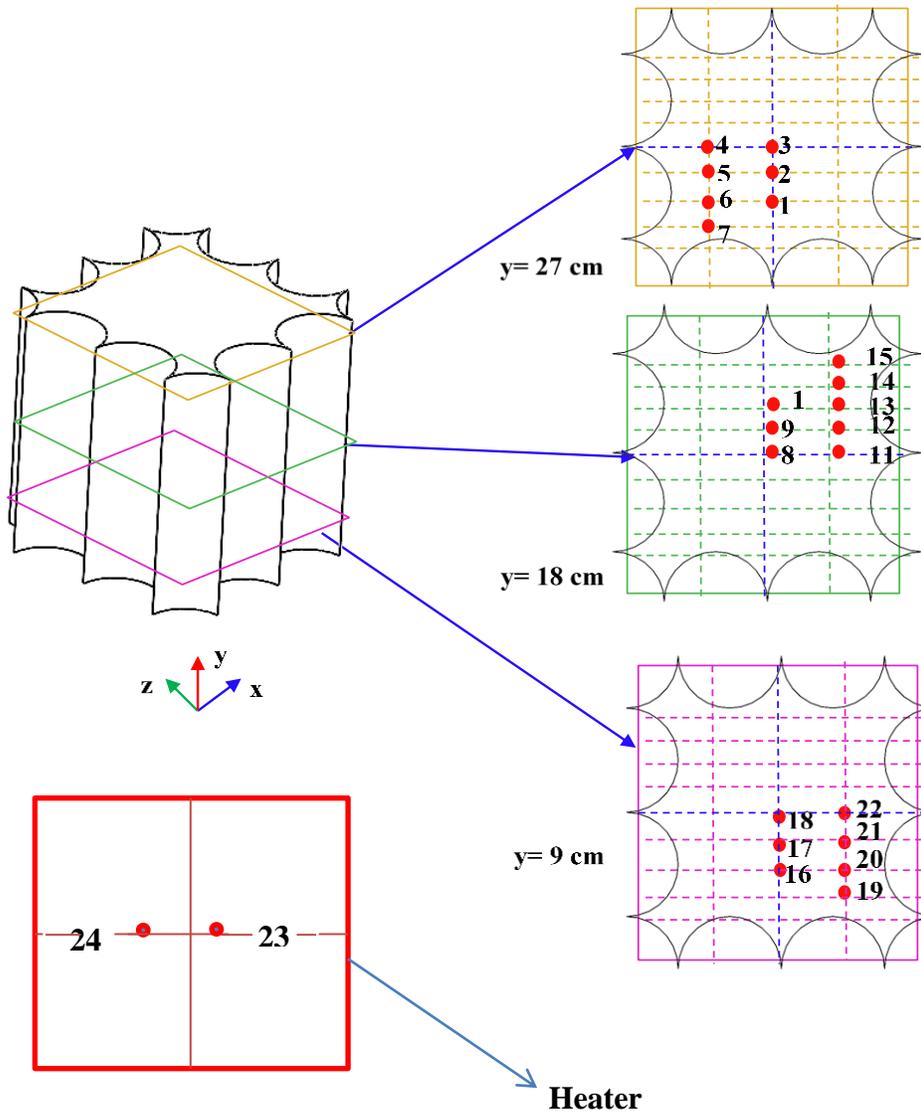
Figure (4- 15) Thermocouples location in the cavity No.2.

4.3.3 TemperaturerReading Calibration

A digital calibration device (PROVA MODEL 123) is used to calibrate temperature readings of the 24 thermocouples, as shown in figure (4-16). The calibration signal of the device is determined by The signal being converted into a temperature reading by the device, which is powered by the batteries. Next, the calibration signal of the device is transmitted to the thermometer through a thermocouple wire. The following points summarize the device calibration steps:

1. Turn on the electricity for about 1 minute, till the sign vanishes.
2. For calibration, connect the thermocouple connectors, corresponding K-type connections to the calibration device's terminals. The sliding switch should be set to positions C and F.
3. Press any key on the keypad (including the minus button) to directly enter the temperature value.
4. Enter a temperature value between (10 and 85) $C°$ as shown schematicly in figure (4-17).
5. Figure (4-18) depicts the relationship between the temperature measurements of the two devices. For adjusting the measured temperature measurements, a polynomial equation is derived:

$$T_{re} = 4E\text{-}5T^3_{calib} - 0.0044\ T^2_{calib} + 1.1499T_{calib} - 1.1594$$

.... (4.1)

Figure (4- 16). Calibration temperature reading device (PROVAMODEL123).
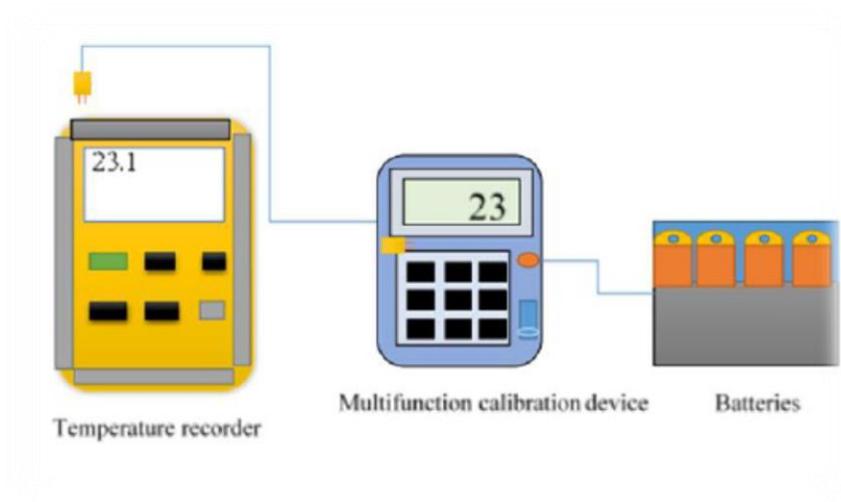
Figure (4-17). Schematic diagram of calibration of the temperature recorder.
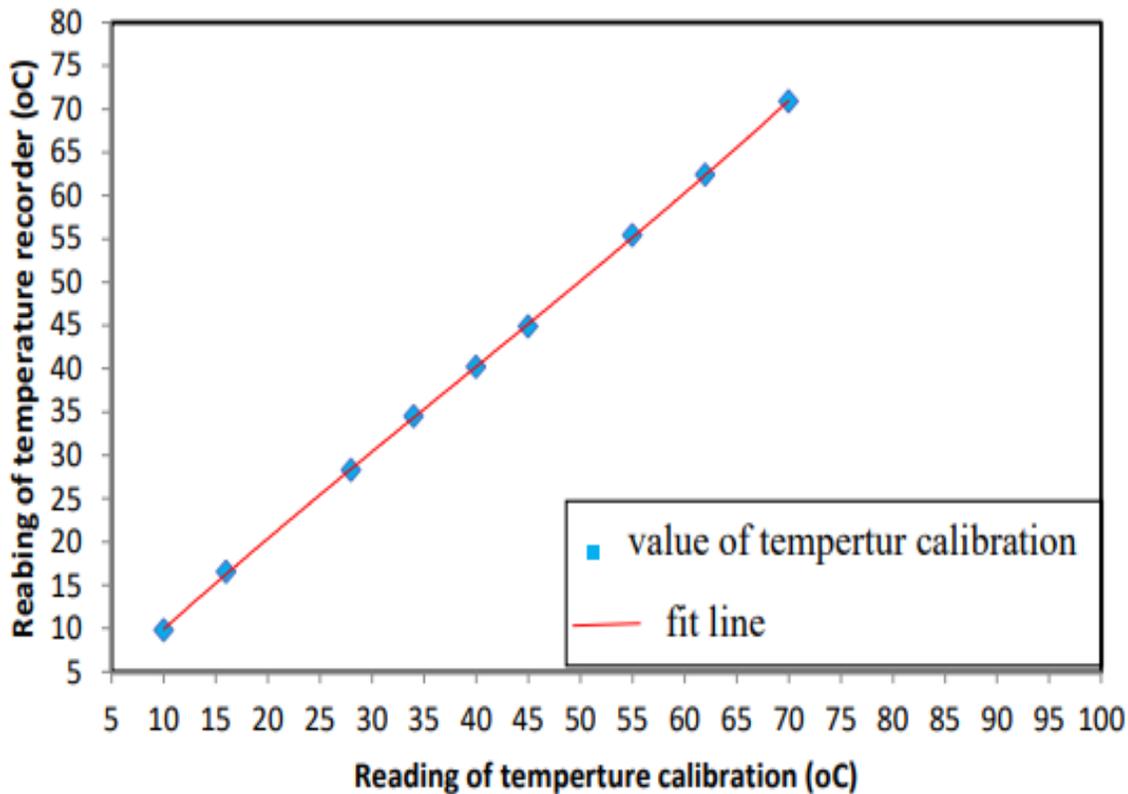
Figure (4-18). Calibration curve of the temperature recording device.

4.4. Equipment Assembly

4.4.1. Sample Preparation.

Silica sand is used to form the porous media indicated by figure(4-19)The sand is sieved by a sieve to get sand of (1mm) diameter and it is fulfilled with air .the two cavities are filled with sand sifted with air. The surface area subjected to uniform heat flux is(0.073) m² in the first cavity ,while the surface area of the second cavity is(0.057) m² in all test samples .That's mean the heat generated in heater divided by ratio area 0.78 areas to give the value of heat flux which caused the temperate increasing in sample

Figure (4-19). Sample of silica- sand

4.4.2. Measuring the Porosity

The porosity of a chosen silica-sand has been measured practically depending on its own law. Where the porosity represents the fraction of the void size from the total volume of the porous media. Thus, it had been using the following steps are used to measure the porosity see Figure (4-20):

1. Taking a certain volume from the chosen silica-sand ($\forall_s$) by using a flask listed in volume,($\forall_s$) $=$ $\forall_s$) Total $= 250$ ml).

2. Taking a certain volume from water ($\forall_{wa1}$)) by using the same flask listed, ($\forall_{wa1}$) $= 250$ ml)

3. Pouring all the water ($\forall_{wa1}$)) over the silica-sand($\forall_s$)), then after a sufficient period of time measuring the volume of the remaining water($\forall_{wa2}$)) which appears above the level of the chosen silica-sand,($\forall_{wa2} = 160$ ml).

4. The porosity then will be estimated mathematically using the above measuring amounts as follows:

$\forall_S = \forall$Total $= 250$ ml

$\forall_{wa1} = 250$ ml

$\forall_{wa2} = 160$ ml

$\forall_{po2} = \forall_{wa1} - \forall_{wa2} = 250 - 160 = 90$ ml

The porosity $\varepsilon = \forall_{po1}/\forall$Total $= 90 / 250 = 0.36$

Flask listed in volume (50-500)ml

$\forall_{wa1} = 250$ ml

$\forall_s = 250$ ml

$\forall_{wa2} = 160$
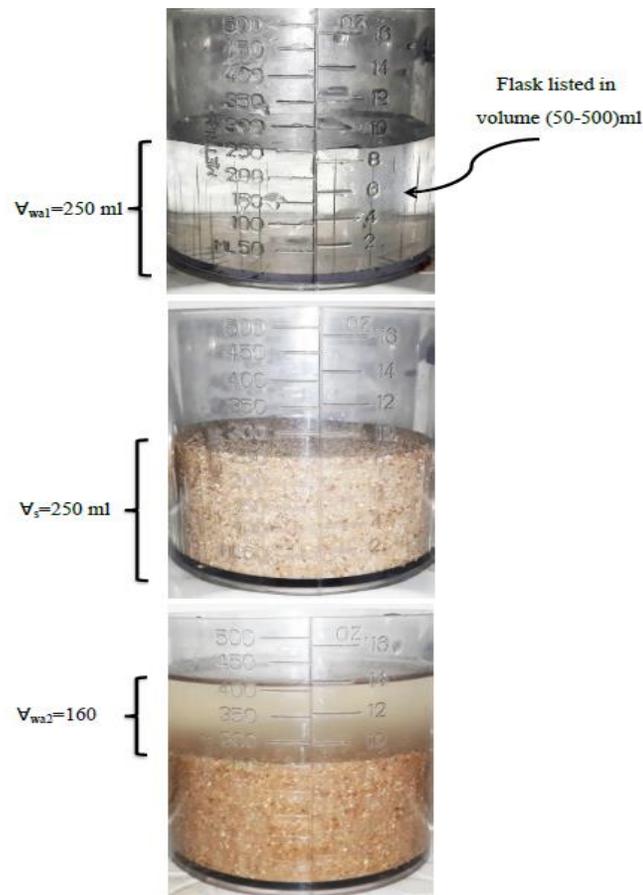
Figure (4-20). Steps of measuring the porosity for a chosen silica-sand.

4.5. Experimental Procedure

The voltage variation device and Thermostat device turn on and start to control the voltage variation until the required value is reached. Then the power was supplied to start the heating process for the samples. The stages of the experimental work are:

1-The temperature recording device began to record temperature at each point, where the thermocouples had been fixed through interval time five minute during the heating processes. This device tabled the results at every five minute during the heating process for each test.

2-The test has been repeated at different values of power supplied. This is equipped for the samples by using the voltage variation device to change the value of the voltage to the appropriate voltage.

3-All the above stages are repeated for each sample at the appropriate value of power supply.

4.6. Data Processing

To calculate the amount of heat transferred and other parameters (h,Nue, Ra_m) from the practically recorded temperatures for sinsoidal cavity using sand porous media, they are listed as follows:

1-Supplied power [41]

$$Q = I \times V \times COS\theta \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.3)$$

Where $COS\theta$ is an ability   factor   and its value is   (0.92)

2- Heat flux equal to heat input the system [41]

$$q = \frac{Q}{A} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4.4)$$

3- Calculate the heat transfer coefficient [41] by dividing the net heat flux by the temperature difference.

$$h = \frac{q}{\Delta T} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \quad (4.5)$$

where $\Delta T = T_{base} - T_{bulk}$

base temperature is taken to be equal to $T_{base} = [(T23 + T24)/2]$.

While the bluk temperature equal to

$T_{bulk} = [(T1+T2+T3+T4+T5+T6+T7+T8+T9+T10+T11+T12+T13+T14+T15+T16 +T17+T18+T19+T20+T21+T22) /22]$

4- Effective Thermal Conductivity

It can be easily to find the effective thermal conductivity as mantioned in equation (3.9).

5- Effective Nusslet Number [41]

$$Nu_{e=\frac{h*H}{K_e}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. \quad (4.7)$$

6- Modified Ra_m [41]

$$Ra_m = \frac{K\rho_{0}g\beta H\Delta T}{\mu_f \alpha_e} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(4.8)}$$

Whereα_e and$(\rho c_p)_e$ can be calculated as [41]

$$\alpha_e = \frac{k_e}{\rho c p_e} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\text{(4.9)}$$

$$(\rho c_p)_e = \phi(\rho c_p)_f + (1-\phi)(\rho c_p)_s \dots\dots\dots\dots\dots\text{(4.10)}$$

This can be done for each cavity at different three values of heat flux by using the

above

Chapter Five
Results and Discussion

Chapter Five

Results and Discussion

5.1 Introduction

The effects of the geometrical model of two porous cavities have sinusoidal wavy walls, one outward and the other inward have been studied numerically by using the famous engineering computational software program ANSYS-CFD R19.2. The physical flow model that will be adopted here is a model with Darcy and Forchheimer momentum extensions with neglecting the viscous dissipation. The lower surface of the cavity is subjected to a constant heat flux while the upper one is exposed to a constant temperature, while all other surfaces are kept isolated. In addition a validation is done to support the numerical results .The numerical results are used to build the experimental design and to discover out how the porous media and different cavities behave in practice and then compare the obtaining results with corresponding numerical model. Thus, the present results will be extended towards these two directions, numerical and experimental results as follows.

5.2 Numerical Results

5.2.1 Validation of the Numerical Model

Numerical solution validation is the process of checking the accuracy and reliability of a numerical solution obtained from a mathematical model or algorithm. Numerical solution validation is an important step in the numerical modeling process, as it helps to ensure that the results of the model are reliable and accurate. The numerical model that was used in the current study was verified by solving some cases that the researcher **Ali Maseer [51]** used during his numerical study. **Ali Maseer [51]** used a cavity filled with a porous media with a porosity

(0.36) and studied the heat transfers by free convection inside a two-dimensional curvy cavity (0.2m height * 0.2m width) enclosing a porous media to estimate the best sinusoidal curvy shape. Figure (5-1) shows the comparison between the temperature contour of the current study and **Ali Maseer [51],** it can be noted that the behavior is similar between the two solutions, where the heat is concentrated in the lower central regions until it becomes less than that in the wavy regions. Figure (5-2) shows the comparison between the results of the ANSYS Fluent softwere used in the current study and the numerical results of the researcher **Ali Maseer [51]**. The convergence of behavior can be seen in both solutions, as Nusselt number increases with the increase of Ra number in both solutions. The average error between the current study and **Ali Maseer [51]** study is 4.1 %.

(a)   (b)
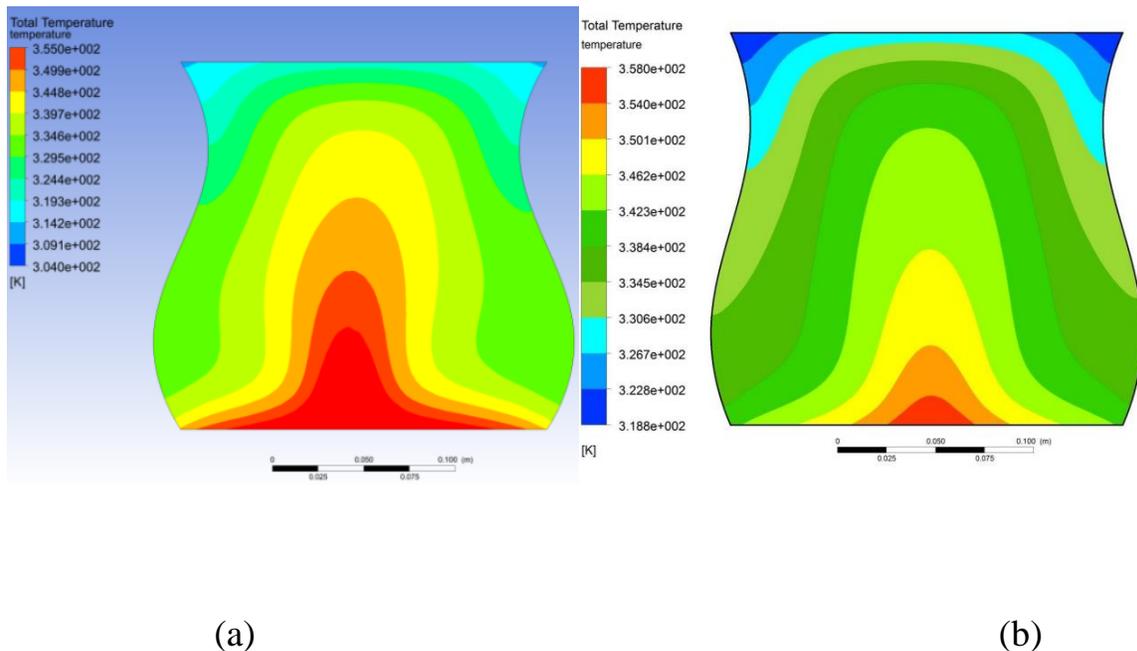
Figure (5-1). Validation of numerical solution for temperature distribution with Ali Maseer [51]. (a) Ali Maseer and (b) Present work.
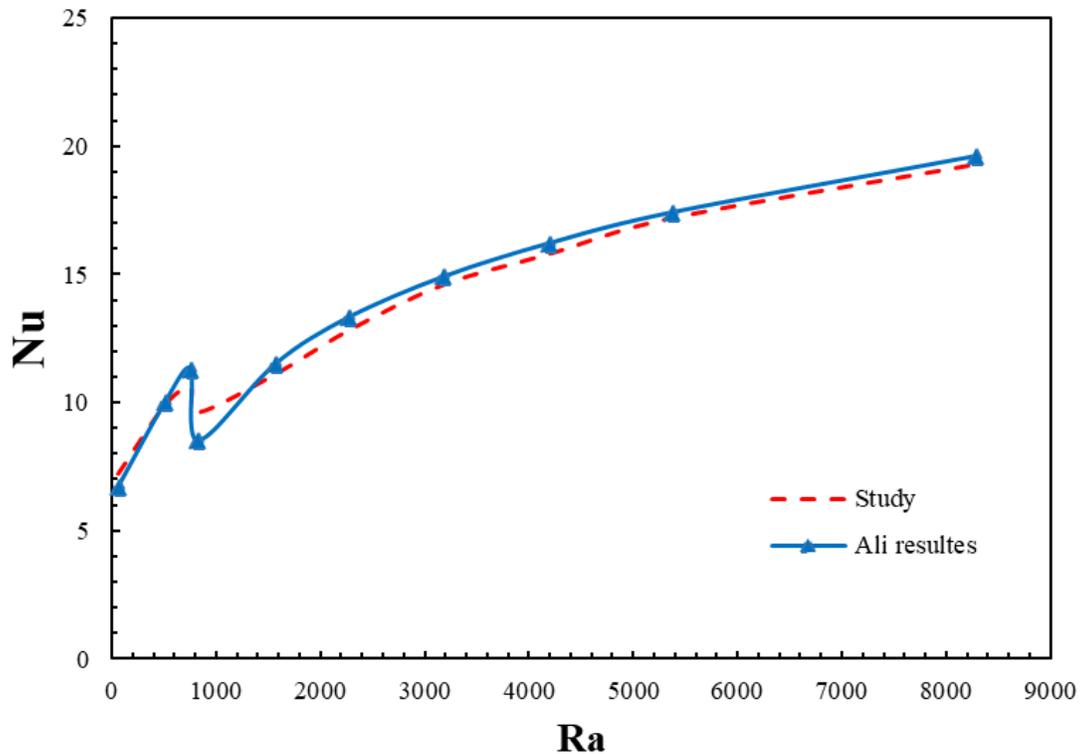
Figure (5-2).Validation of numerical solution for average Nusselt number versus Rayleigh number with Ali Maseer [51].

5.2.2 Temperature Distribution

Figures (5-3) to (5-8) show the prediction results of temperature distribution for prous media with outward sinusoidal walls for different heat flux values(1000,1500 and 2000) W/m^2 and for different porosity 0.36 and 0.38. The results are represented numerically at two planes at the center of cavity, the first cavity is represented vertically at (x,y) plane and the second plane represented horizontaly at (x,z)plane.These results are taken for distribution of temperatures at three different values of heat flux(that was shed on the bottom surface of the cavity) and for two different values of porosity .These results indicated that the temperature variation increase with increasing the values of heat flux.

Figures (5-3) ,(5-4) and(5-5) represent the temperature distribution of the silica sand at(0.36) porosity and at different heat flux values(1000,1500,2000) W/m^2 respectively . Its is observed that even by increasing the heat flux , the distribution of temperature is symmetrically and consistently around the cavity center lines as displayed in figure (5-3) to(5-5). High temperature distribution is illustrated at the base of the container while low temperature distribution is illustrated at the top of the container, which means that the temperature distribution of porous cavity with outward sinsoidal walls is parall. In general that the amount of temperature difference increases with the increas in the thermal flux. This is due to the fact that the increase in thermal flux leads to an increase in the growth of the thermal layer, which in turn causes increasing in the buoyancy strength.Also it is indicateded the result for temperature distribution when used (0.38) porosity as shown in figures (5-6),(5-7)and(5-7)and different heat flux values(1000,1500,2000) W/m^2 also it is noticed temperature difference increases with the increas in the thermal flux for porosity (0.38) and this increase leads to an increased in the growth of the thermal layer, which in turn causes increasing in the buoyancy strength.But temperature difference porosity(0.38) is lower than (0.36)porosity at the same cavity outward sinusoidal walls and same heat flux. When the porosity of the medium increasead in porous cavity with outward sinsoidal walls the hot fluid rise up from the hot surface to the upper wall and lays down beside the cold side walls in other words, when porosity of the medium increased the flow intensity increased and thus, the convection heat transfer has been enhanced.This due to porosity effect in enchancing convection heat transfer.The maximum value of average Nusselt number is observed to be more for higher medium porosity.Virtually, average Nusselt number for all values of medium porosity and that enhance natural convection process.

The distribution for the temperature changes clearly and significantly when the thermal flux increases on the lower surfaceas. But when the porosity of the porous medium changes, the temperature distribution also changes, asit is notice that heat transfer better as the porosity of the porous medium increases.
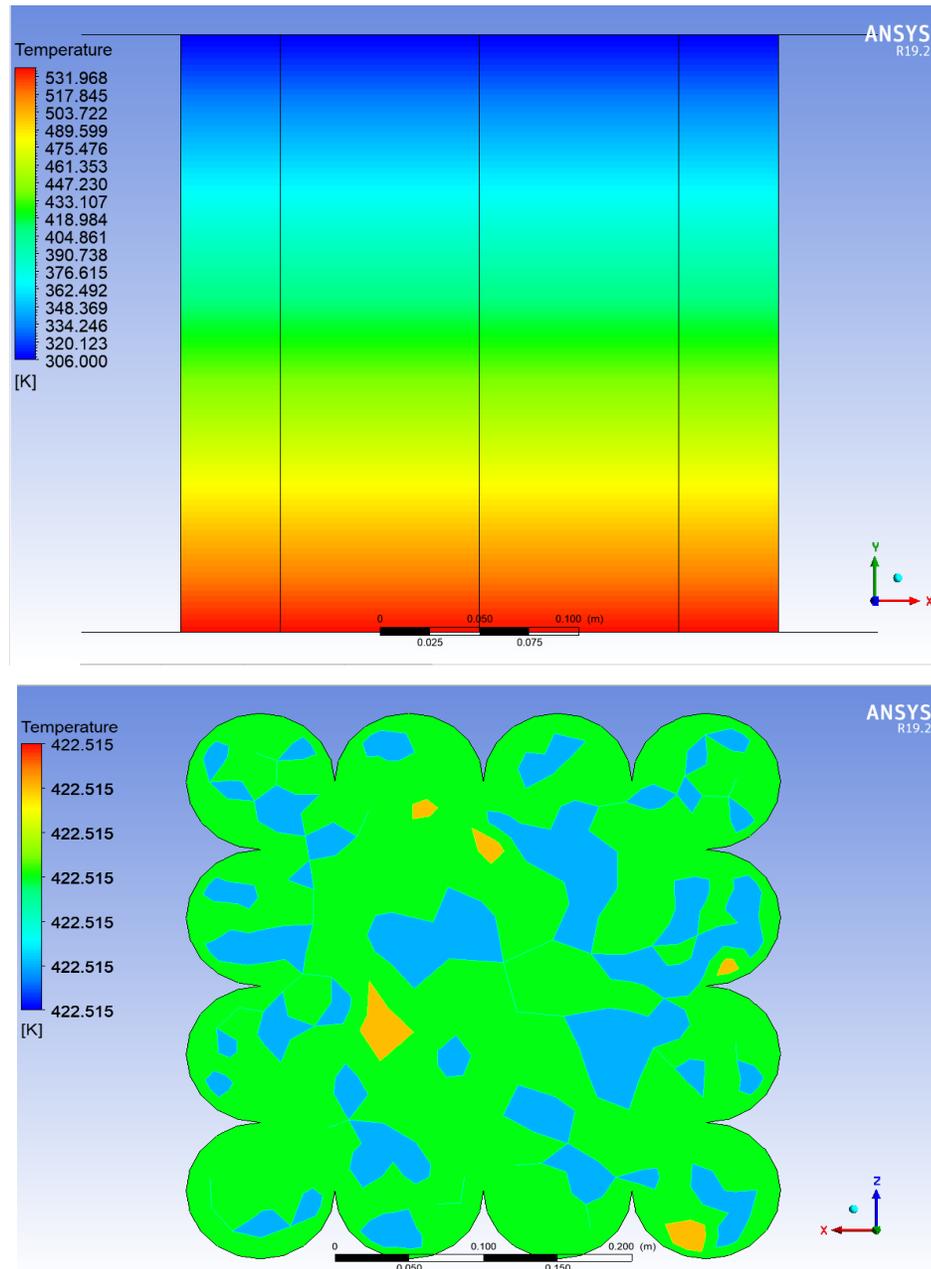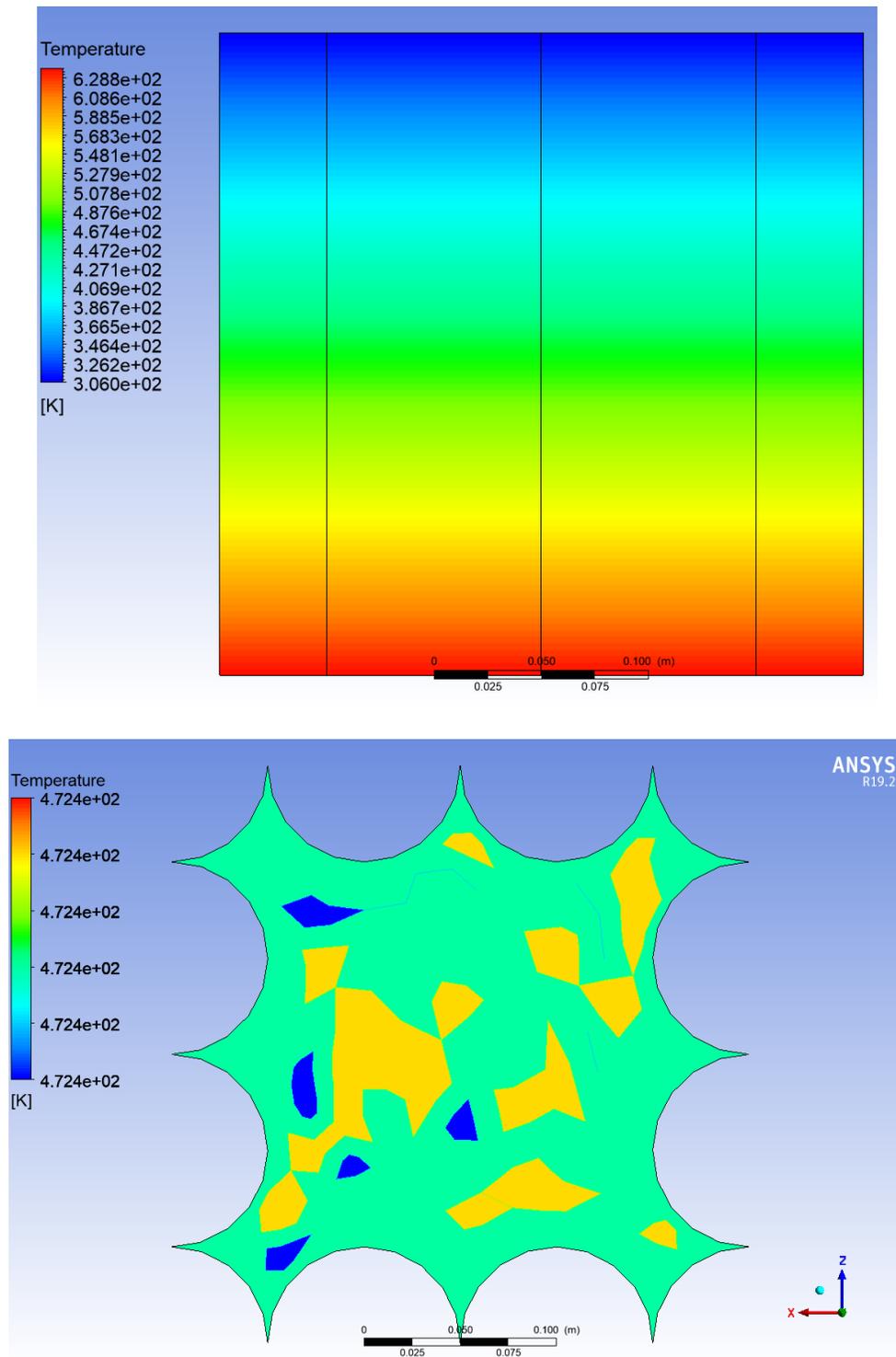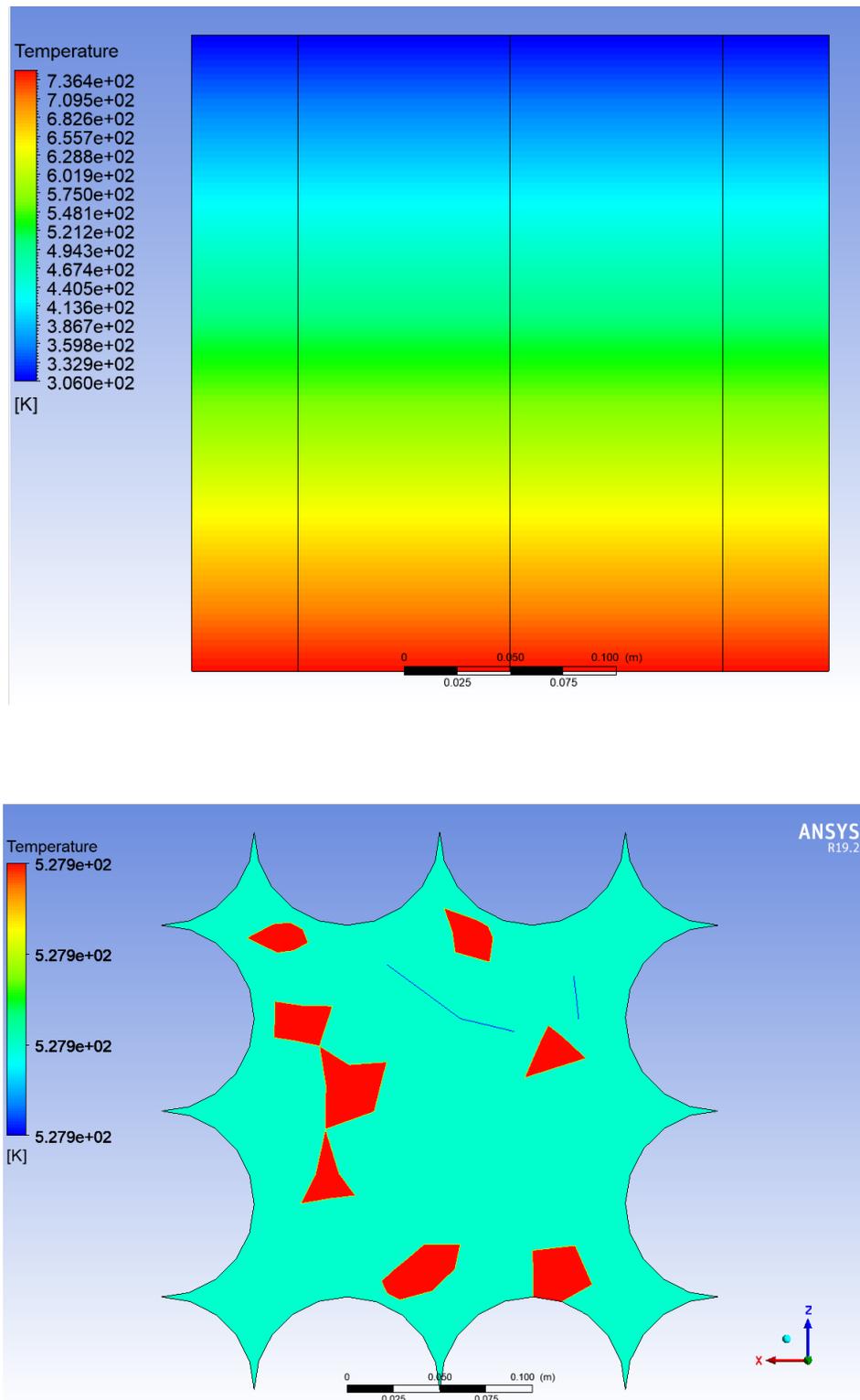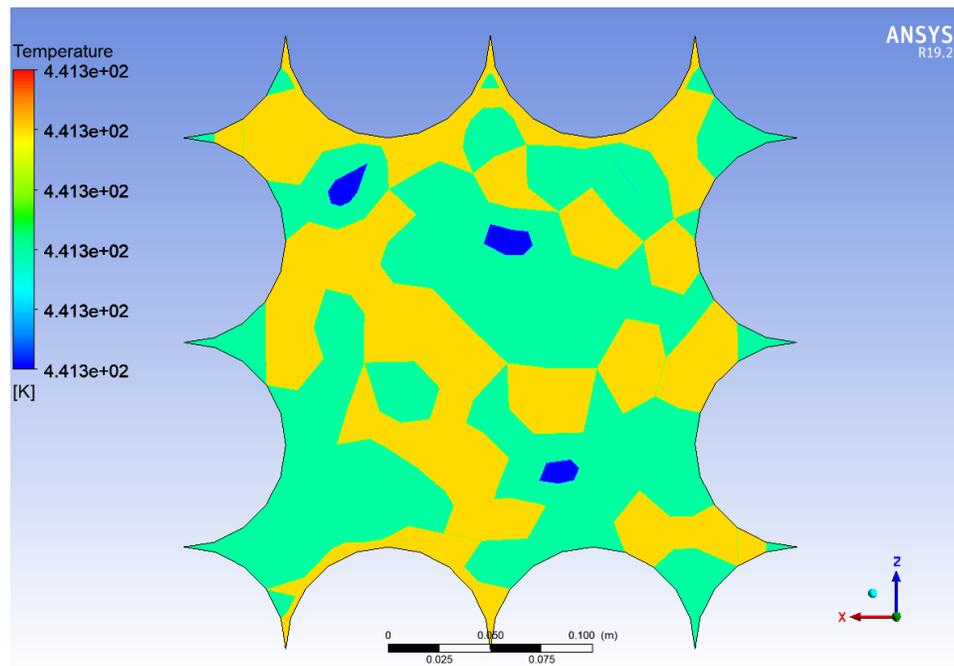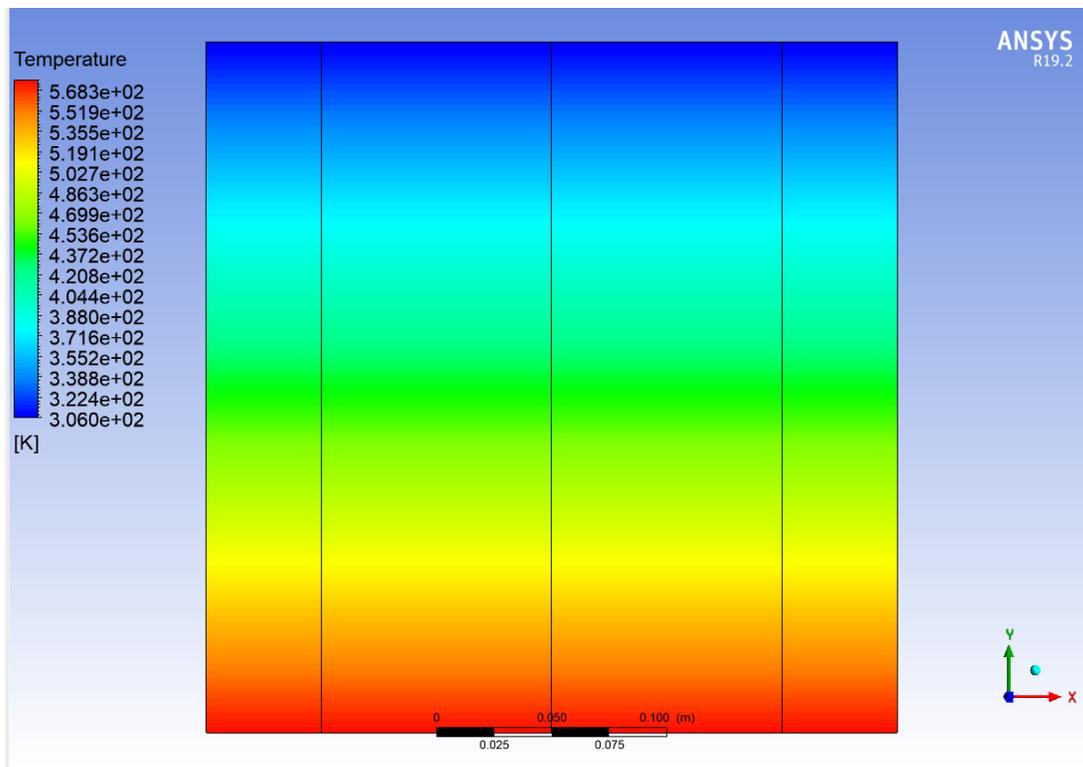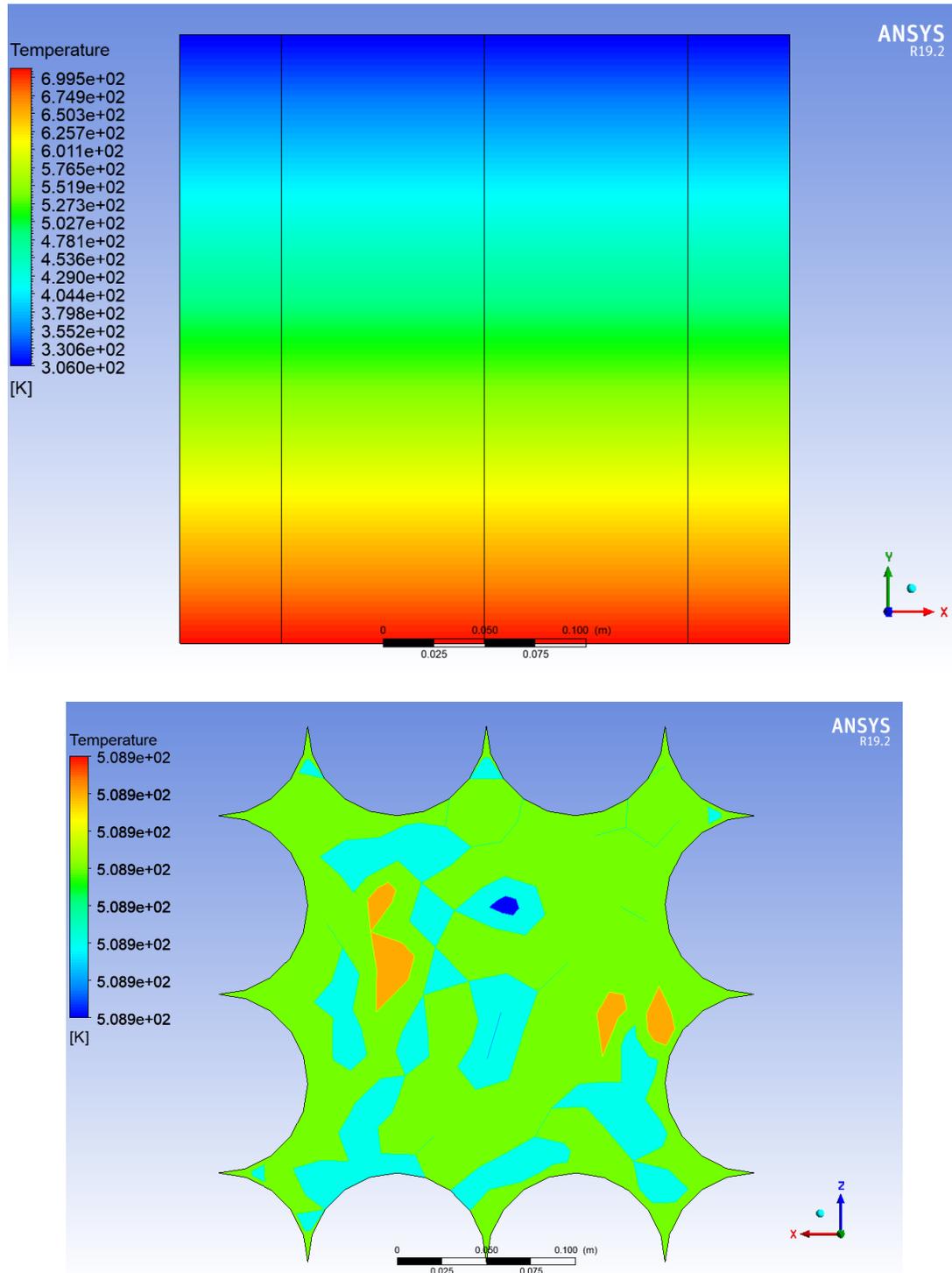

Figure (5-3). Temperature distribution for sand porous media with heat flux 1000 W/m^2 and porosity 0.36(outward sinusoidal walls).
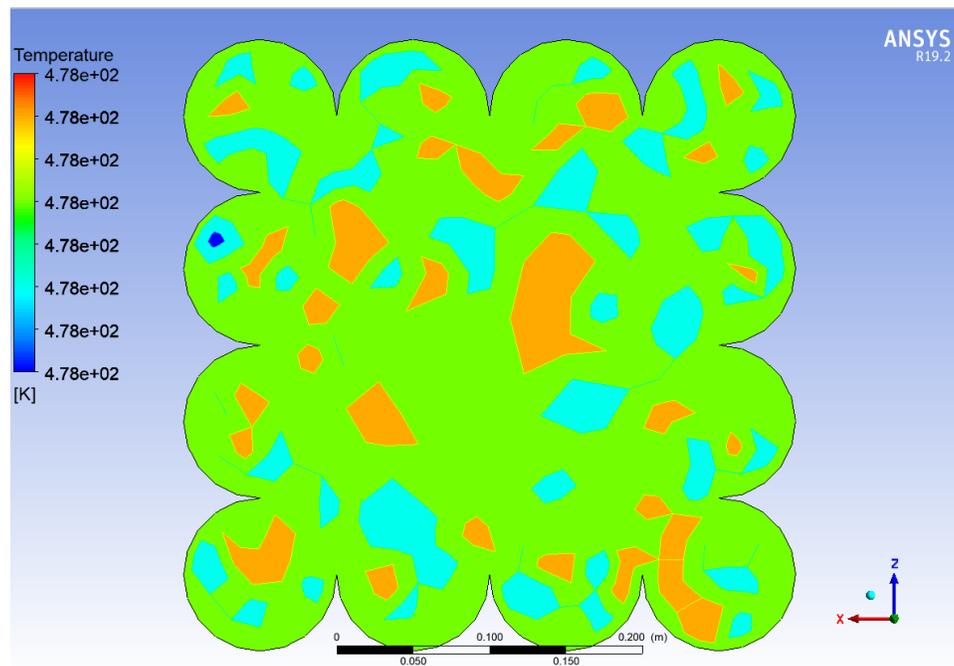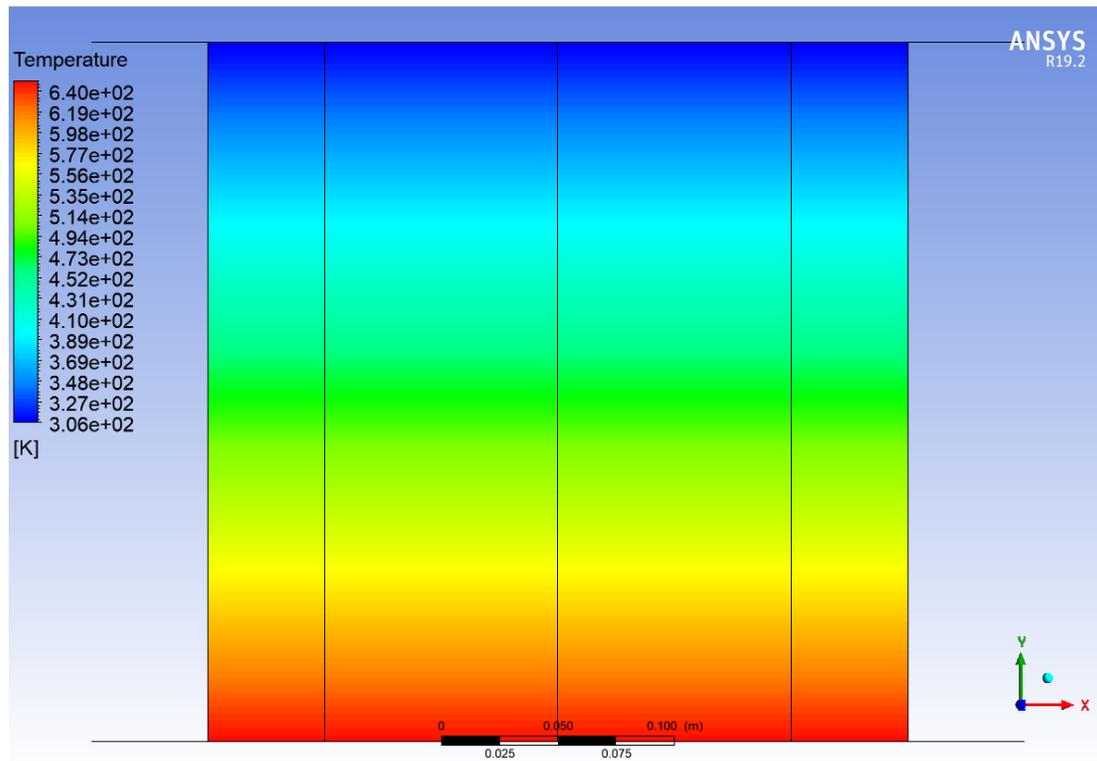
Figure (5-4). Temperature distribution for sand porous media with heat flux

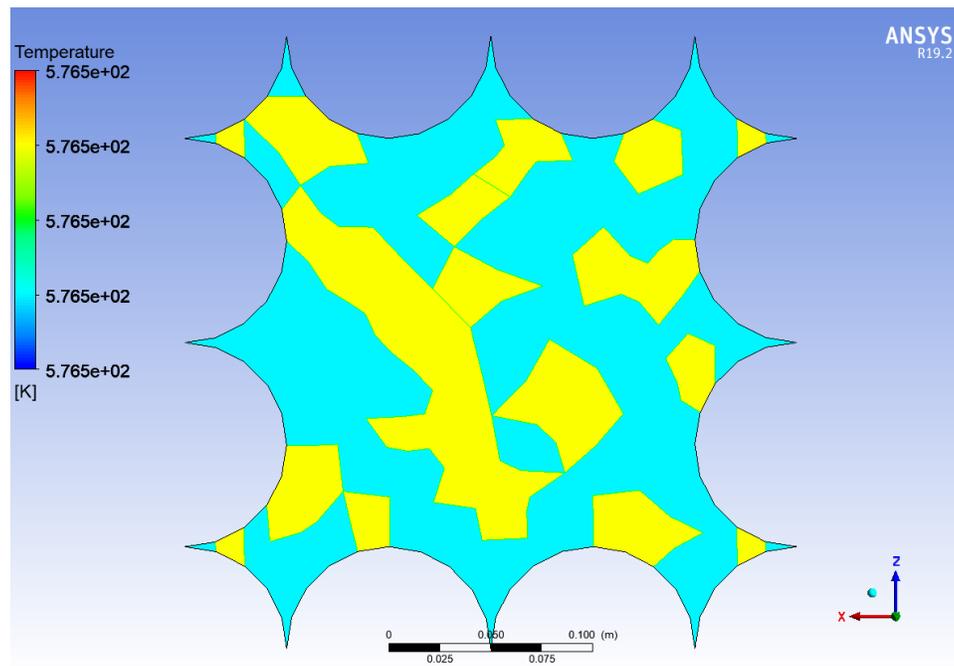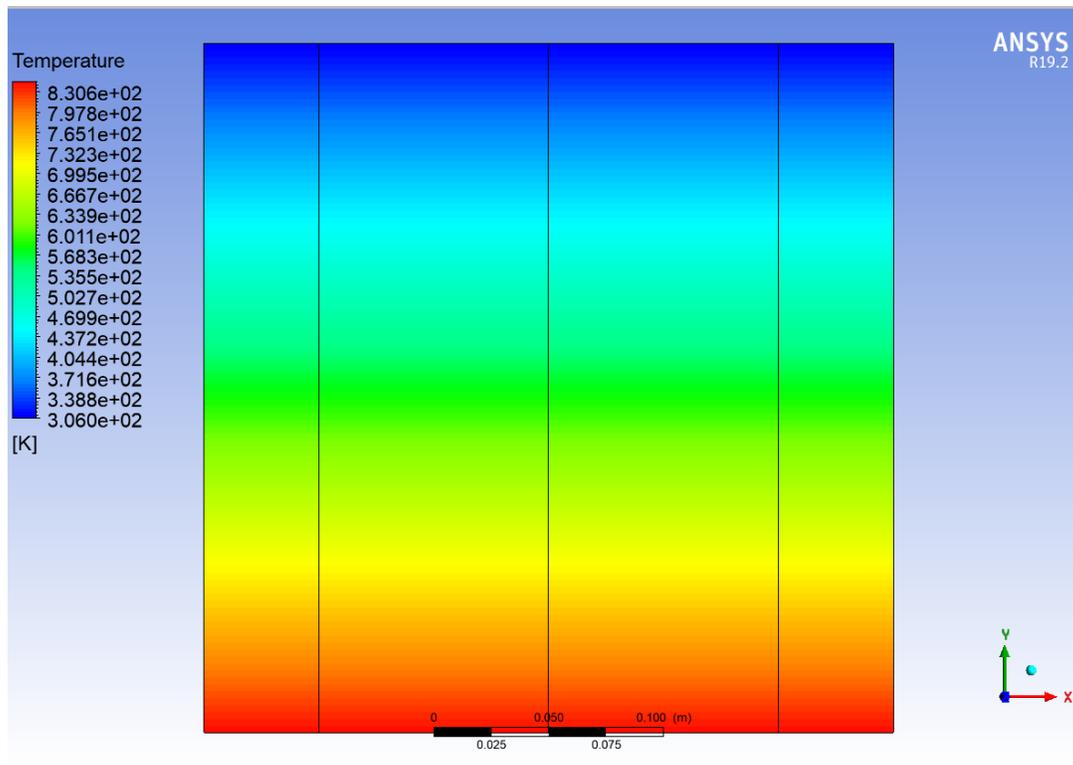$1500 \, W/m^2$ and porosity 0.36 (outward sinusoidal walls).
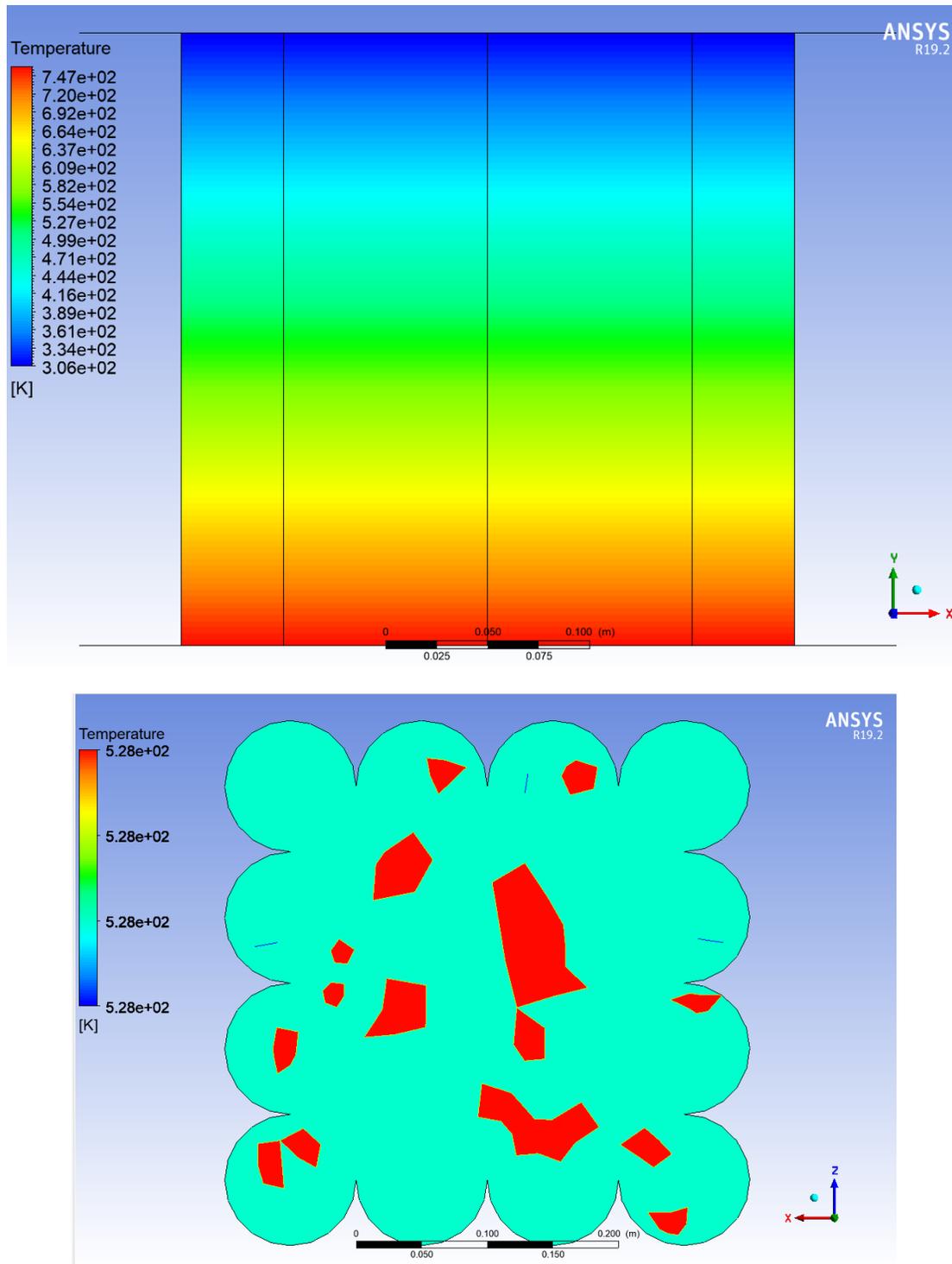
Figure (5-5). Temperature distribution for sand porous media with heat flux $2000\ W/m^2$ and porosity 0.36(outward sinusoidal walls).
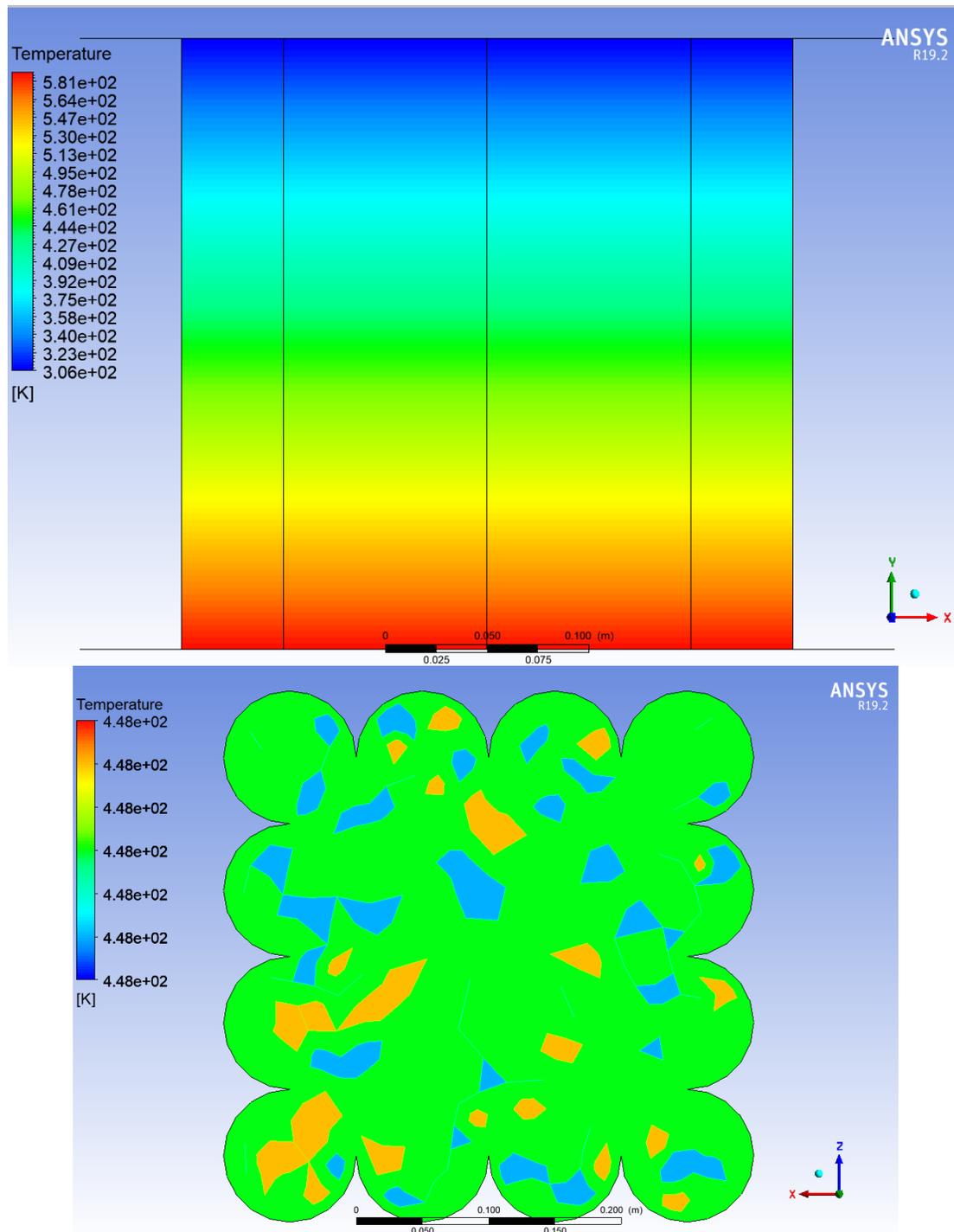
Figure (5-6). Temperature distribution for sand porous media with heat flux

$1000\ W/m^2$ and porosity 0.38(outward sinusoidal walls).
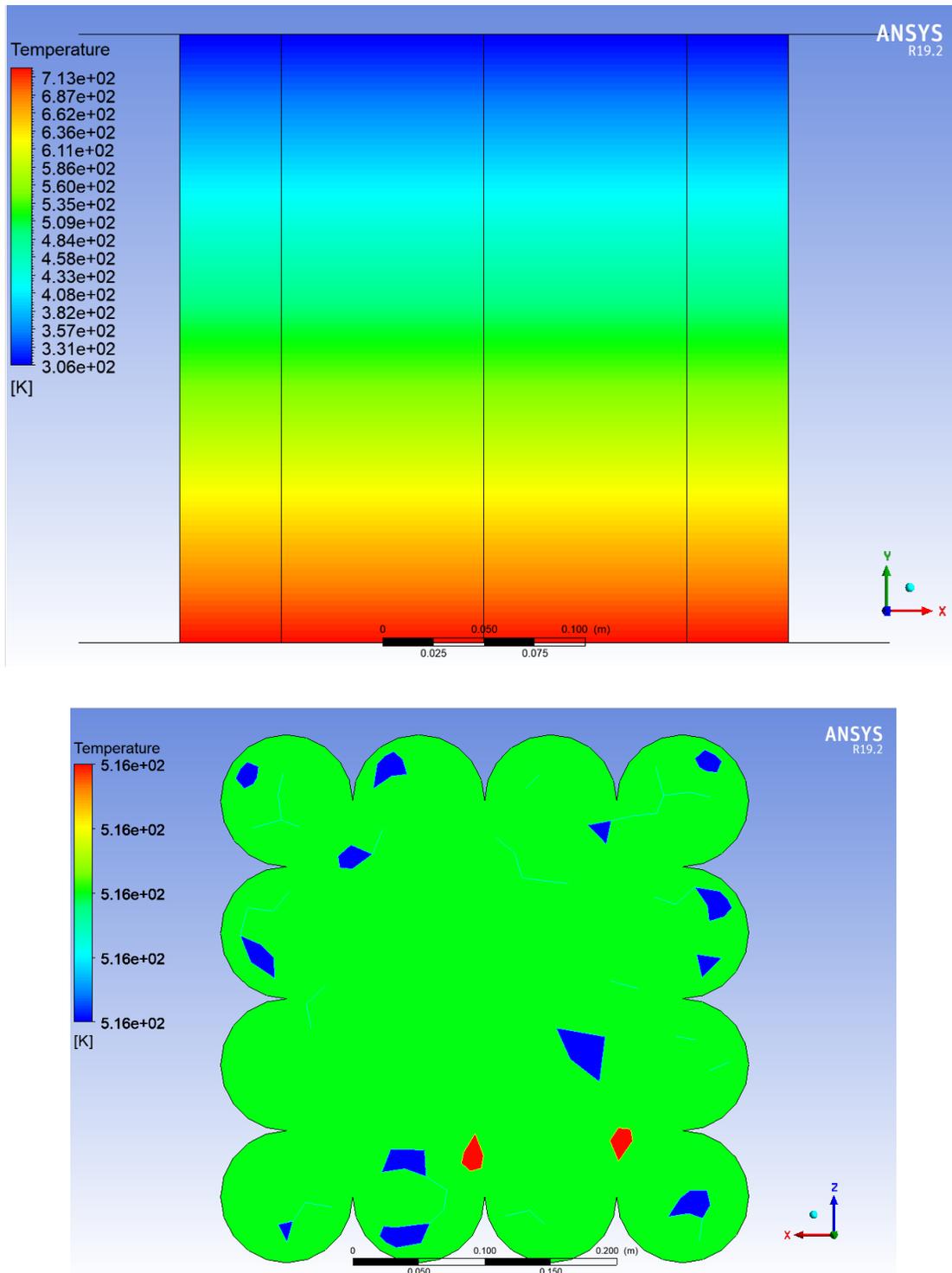
Figure (5-7). Temperature distribution for sand porous media with heat flux $1500 \, W/m^2$ and porosity 0.38(outward sinusoidal walls).
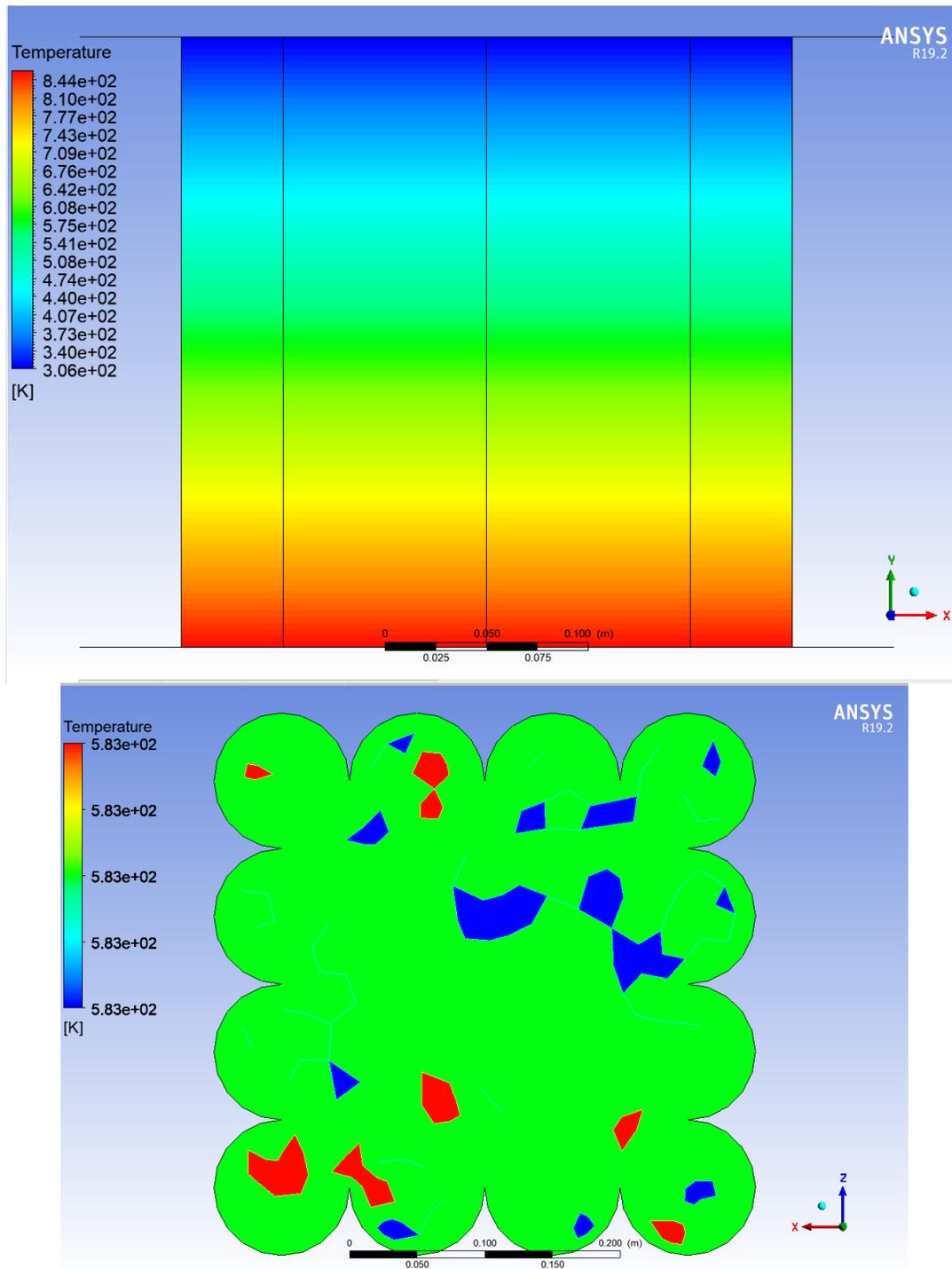
Figure (5-8).Temperature distribution for sand porous media with heat flux

$2000 \, W/m^2$ and porosity 0.38(outward sinusoidal walls).

Now it is noticed in the following figures (5-9)to ,(5-14) the temperature distribution of a porous cavity with sinusoidal walls directed inwards for different heat flux values(1000,1500,2000) W/m^2 and for different porosity 0.36and 0.38. the results are represented numerically at two planes at the center of cavity ,the first cavity is represent vertically at(x,y) plane and the second plane represent horizontaly at (x,z)plane.These results are take for distribution of temperatures at three different values of heat flux(that was shed on the bottom surface of the cavity) and for two different values of porosity   .These results indicate that the temperature variation increase with increasing the values of heat flux.Figures(5-9),(5-10)and(5-11) represent   the temperature distribution of the silica sand at(0.36) porosity and at different heat flux values(1000,1500,2000) W/m^2 while figures(5-12),(5-13)and (5-14) represent   the temperature distribution of sand at(0.38) porosity and at different heat flux values(1000,1500,2000) W/m^2.It is observed that even by increasing the heat flux. High temperature distribution is illustrated at the baser of the container while low temperature distribution is illustrated at the top of the container, which means that the temperature distribution of porous cavity with inward sinsoidal walls is parall.It is noticed that the increase in thermal flux leads to an increase in the growth of the thermal layer, which in turn causes increasing in the buoyancy strength.It is also observed when changing the porosity of the porous medium to(0.38) in porous cavity with inward sinsoidal walls as showen in figures (5-12),(5-13)and (5-14) that the increase in thermal flux leads to an increase in the growth of the thermal layer,which means that the temperature distribution when used(0.38) porosity is higher than (0.36)porosity at the same cavity and same heat flux. as shown in figures (5-9)(5-12) or for figures(5-10)(5-13)and for figures (5-11)(5-14) When the porosity of the medium increasead in porous cavity with inward sinsoidal walls the hot fluid rise up from the hot surface to the upper wall and lays down beside

the cold side walls .In other words, when porosity of the medium increased the flow intensity increased and thus, the convection heat transfer has been enhanced.This due to porosity effect in enchancing convection heat transfer.

When compare between two cavities it is notice that The distribution for the temperature did not change much as the shapes of the cavity change.but its change when porosity changed, when porosity of the medium increased the flow intensity increased and thus, the convection heat transfer has been enhanced.This due to porosity effect in enchancing convection heat transfer.The maximum value of average Nusselt number is observed to be more for higher medium porosity.
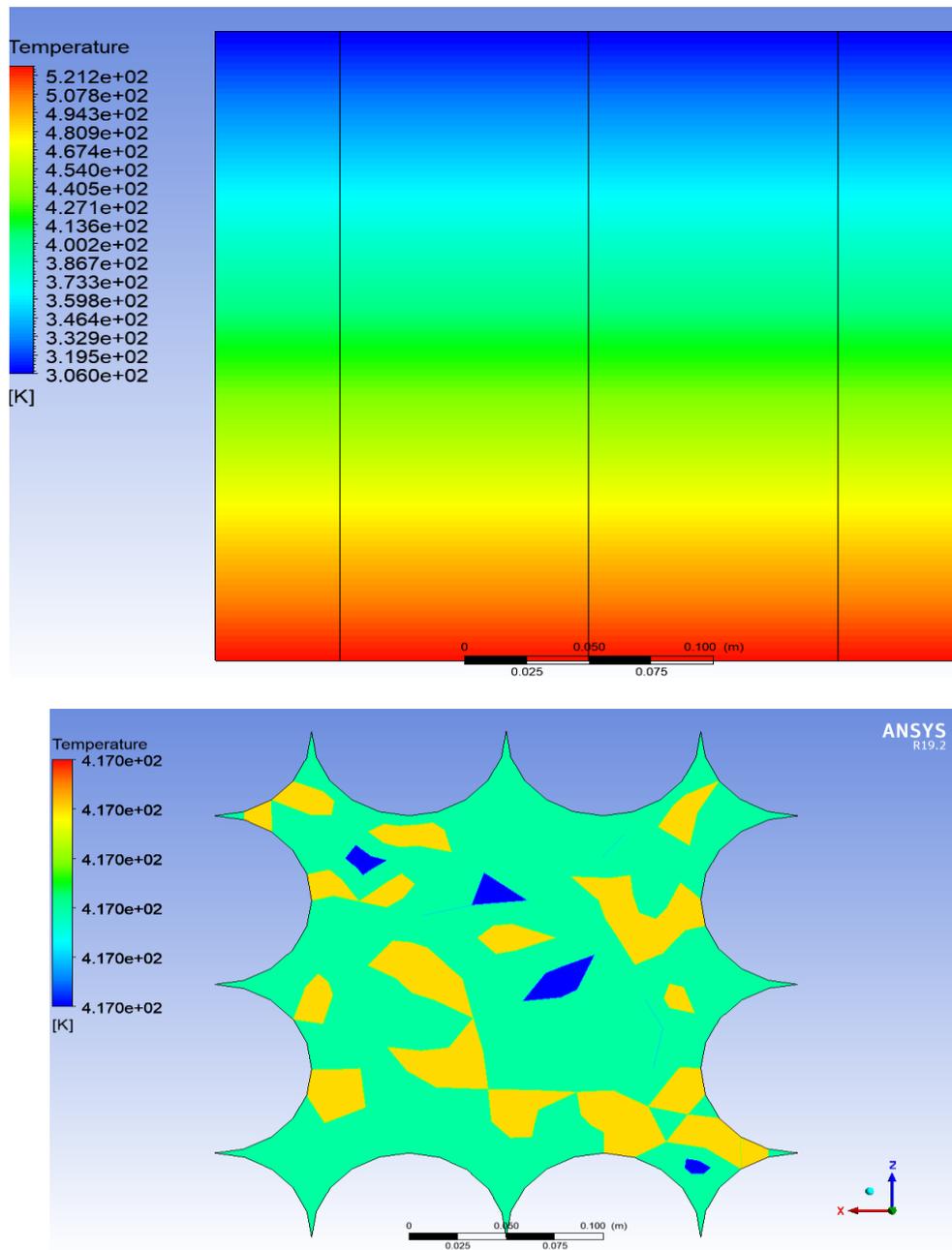
Figure (5-9). Temperature distribution for sand porous media with heat flux $1000\ W/m^2$ and porosity 0.36 (inward sinusoidal walls).

Figure (5-10) .Temperature distribution for sand porous media with heat flux
1500 W/m^2 and porosity 0.36(inward sinusoidal walls).

Figure (5-11). Temperature distribution for sand porous media with heat flux 2000 W/m^2 and porosity 0.36(inward sinusoidal walls).

Figure (5-12) .Temperature distribution for sand porous media with heat flux $1000\ W/m^2$ and porosity 0.38(inwards inusoidal walls).

Figure (5-13). Temperature distribution for sand porous media with heat flux

$1500\ W/m^2$ and porosity 0.38 (inward sinusoidal walls).

Figure (5-14). Temperature distribution for sand porous media with heat flux 2000 W/m^2 and porosity 0.38(inward sinusoidal walls).

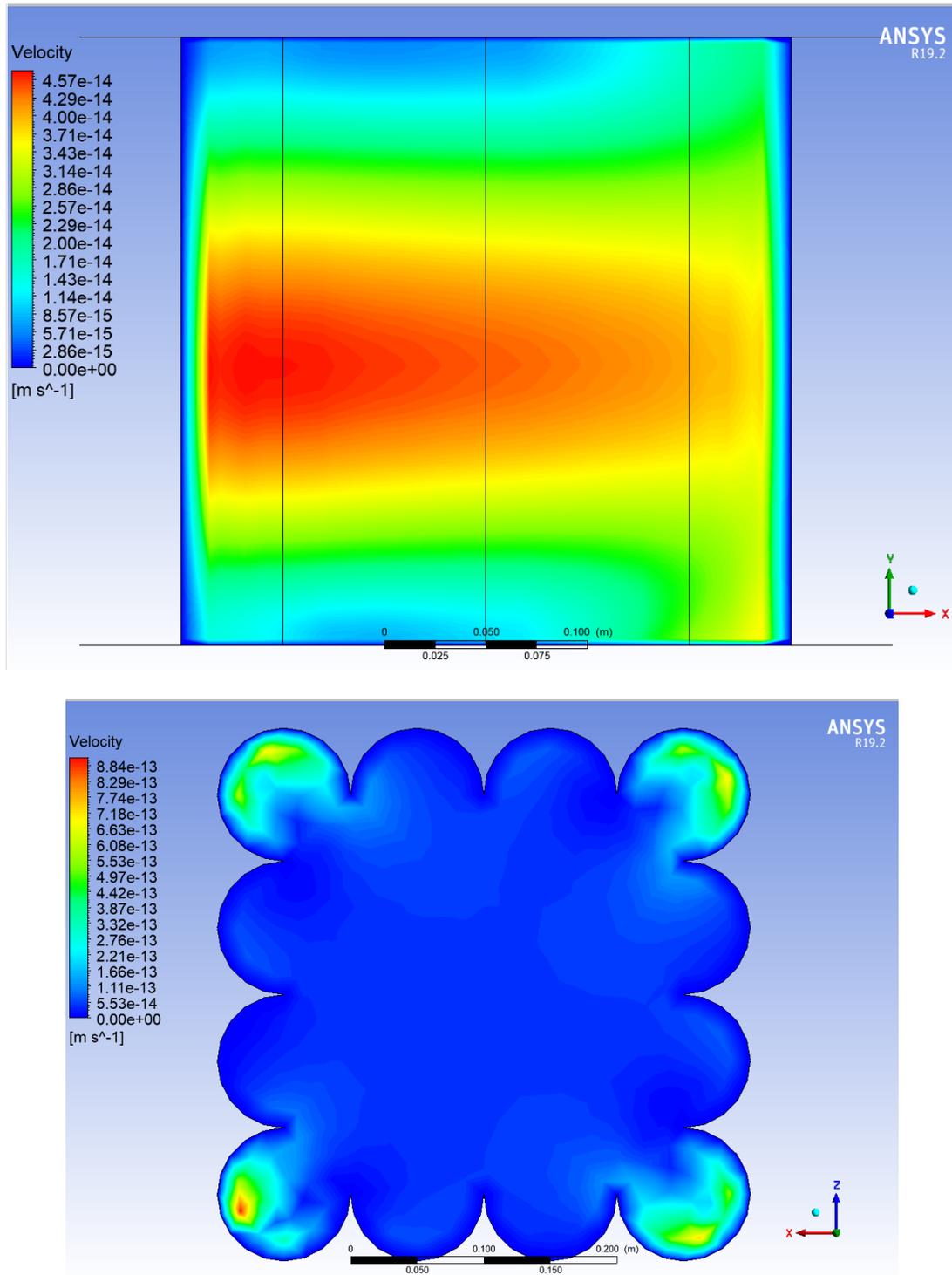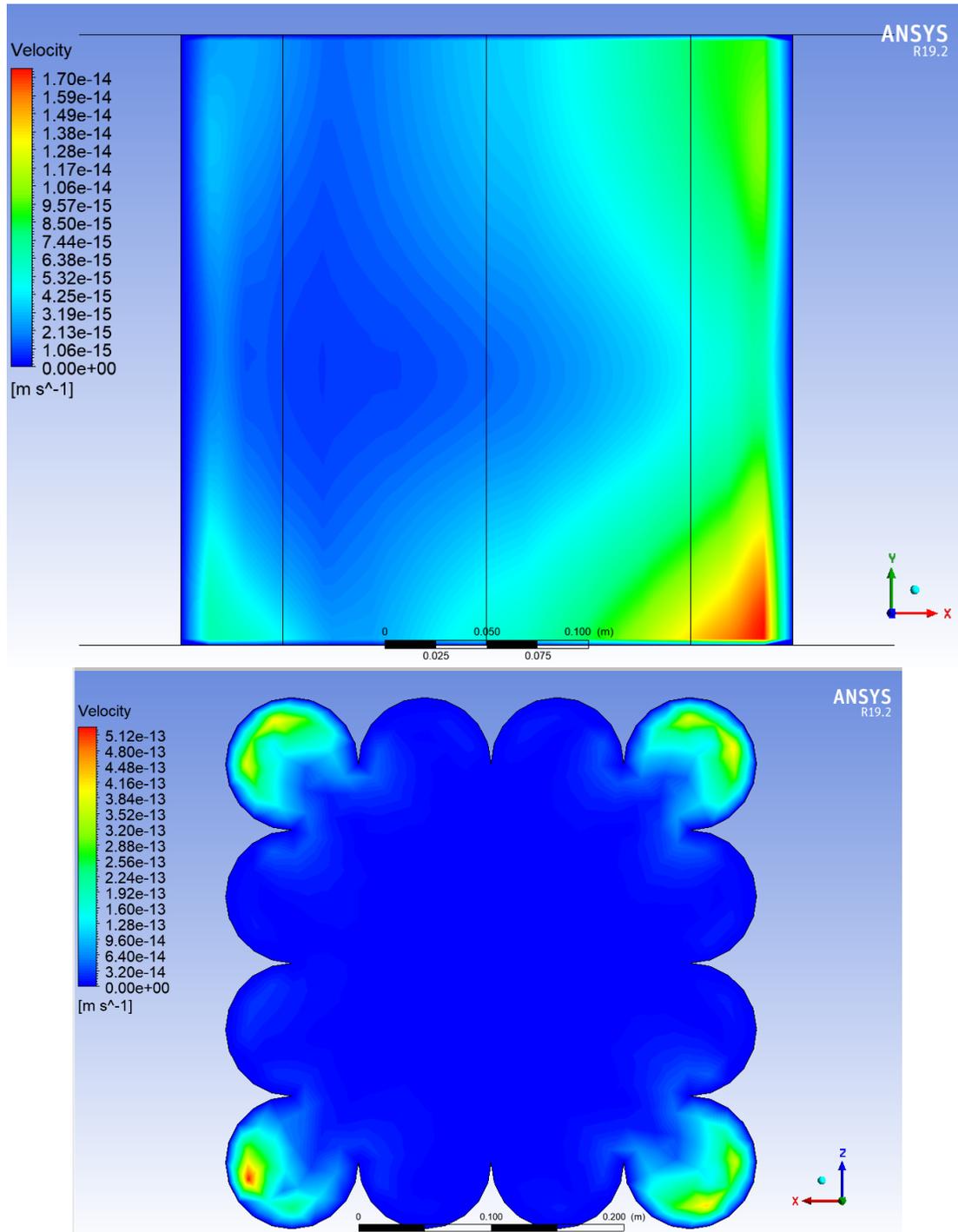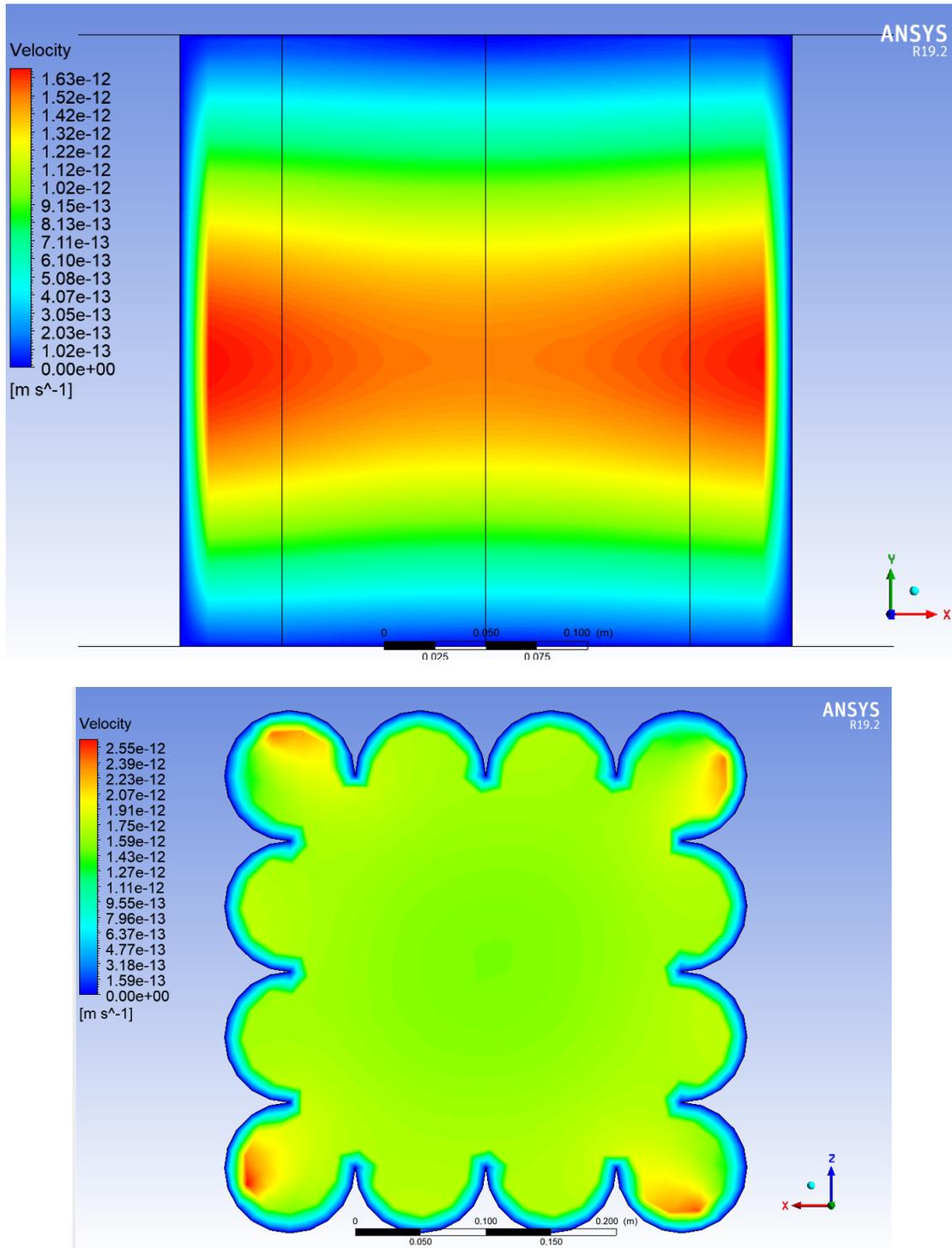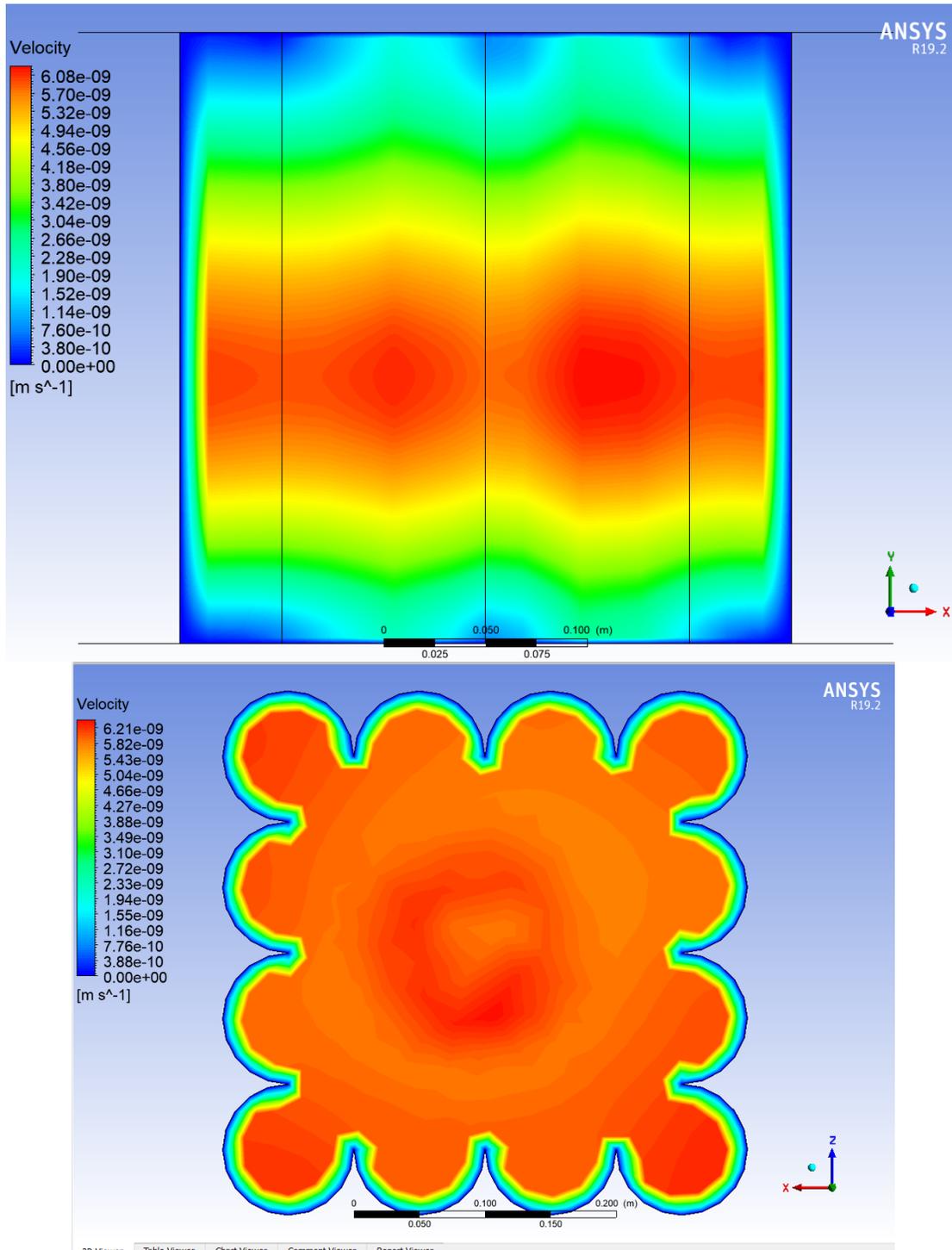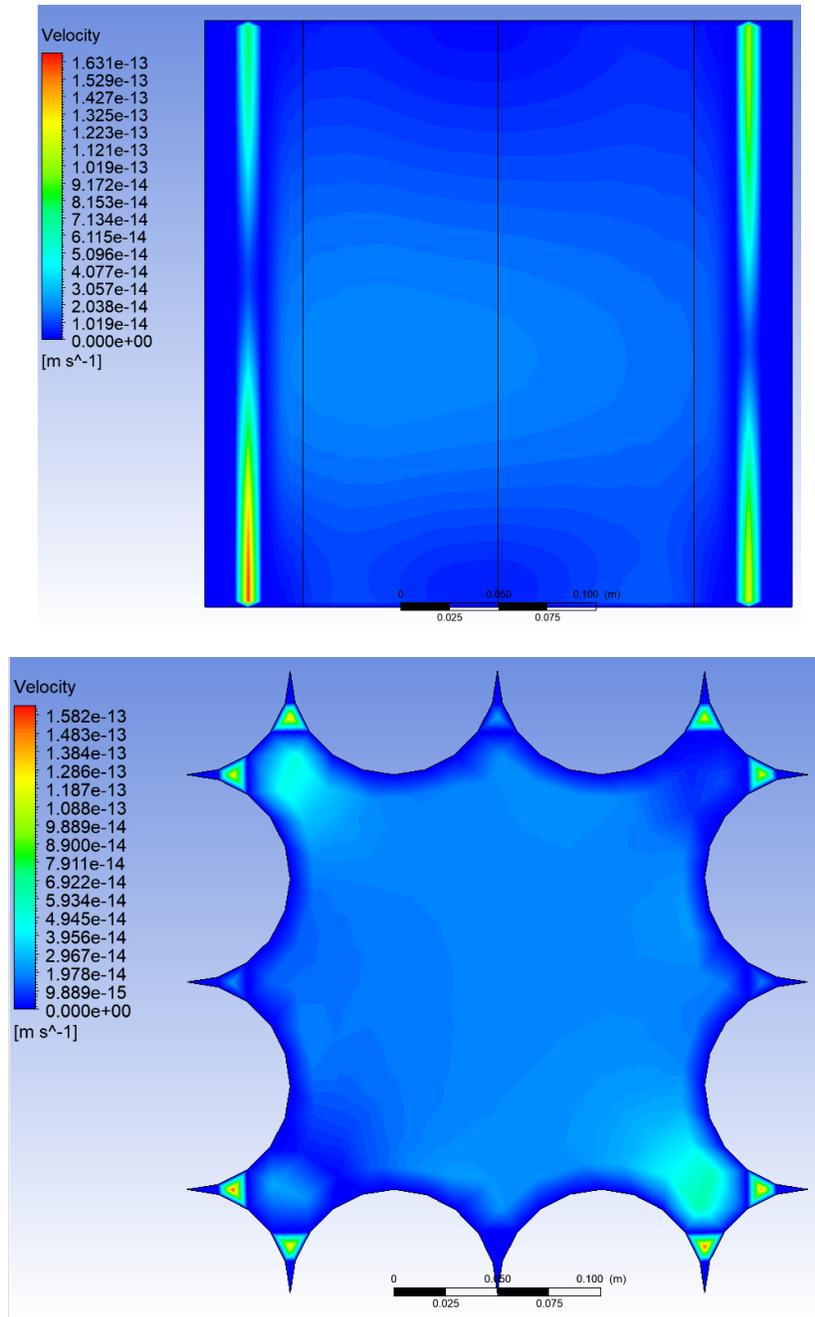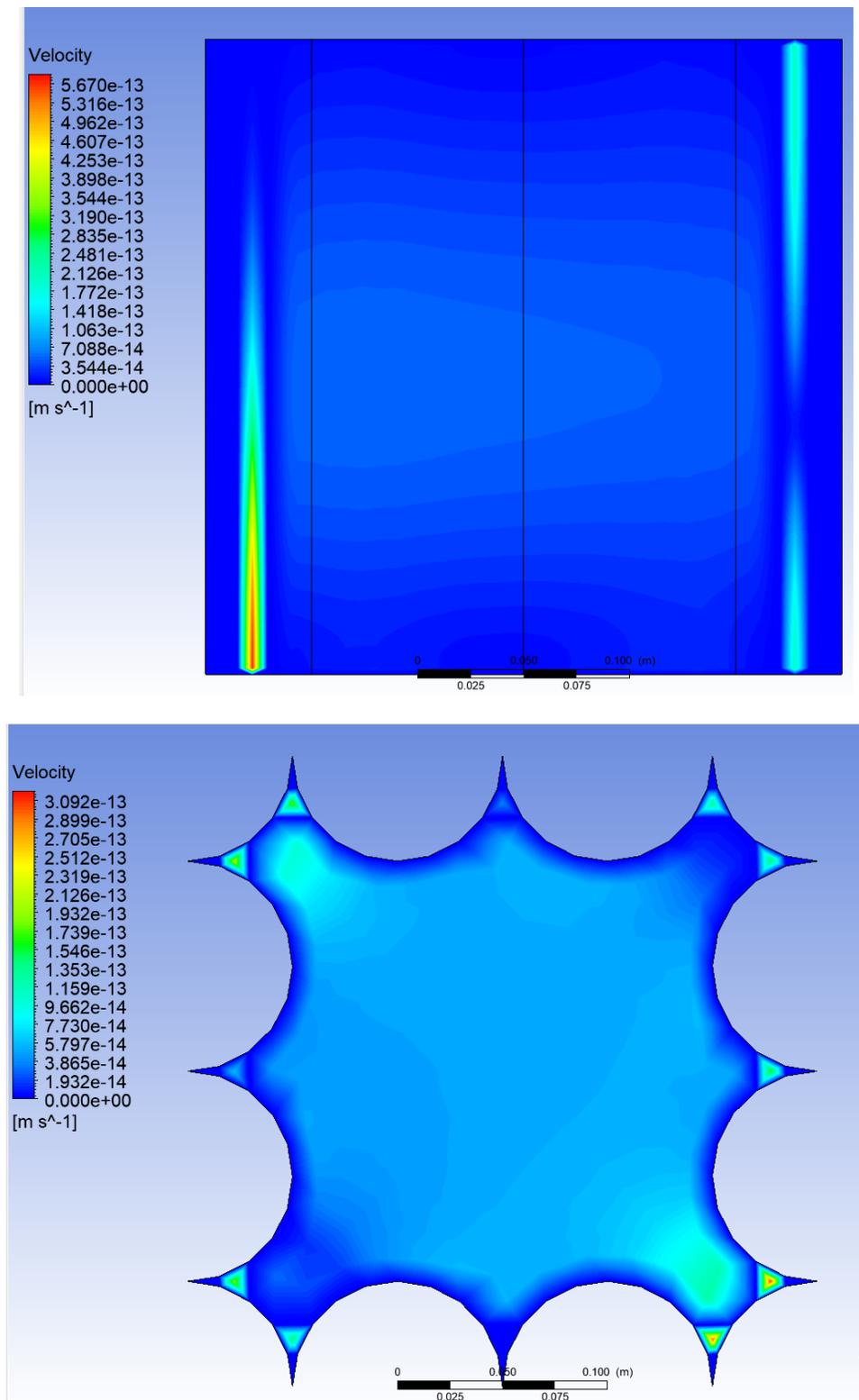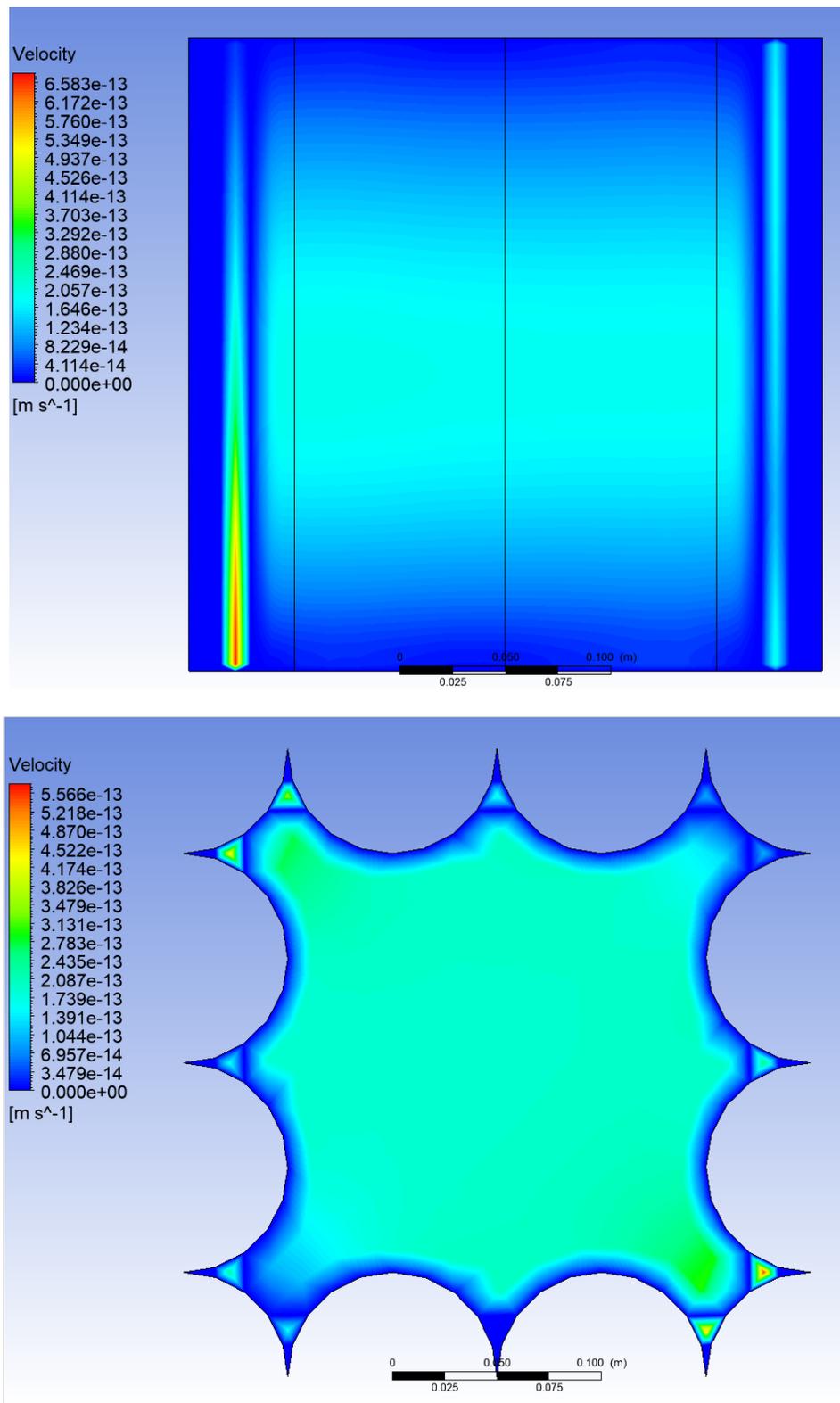## 5.2.3 Velocity Distribution

Figures (5-15) to (5-20) show the prediction results of velocity distribution for prous media with out ward sinusoidal walls for different porosity(0.36)and(0.38) different heat flux values(1000,1500,2000) W/m^2 . From Figure (5-15) to (5-20), it is noted that the velocity of the fluid, whether when in contact with the barrier, is equal to zero because it is affected by solid boundaries, that the velocity at the upper horizontal surface of the cavity is equal to zero and after a small distance a significant rise in velocity is observed up to the highest value, and the same behavior at the lower horizontal wall, but the fluid velocity in this area is higher than the layer near the upper horizontal surface, as can be seen from the figures above that the greater The value of the thermal flux applied below the cavity increased the fluid velocity due to the effects of the buoyancy force. That is, in hot regions, the velocity of the fluid is higher than its velocity in cold regions due to the loss of part of the fluid of its heat near the cold surface, so the kinetic energy of the fluid will become less, as well as we note the more porosity of the porous medium, the greater the velocity.

And figures (5-20) to (5-25) represet velocity distribution for prous media with inward sinusoidal walls for different porosity (0.36) and (0.38) different heat flux values (1000, 1500, 2000) W/m^2. From these figures (5-20) to (5-25), it is noted that the velocity of the fluid, whether when in contact with the barrier, is equal to zero because it is affected by solid boundaries, that the velocity at the upper horizontal surface of the space is equal to zero and after a small distance a significant rise in velocity is observed up to the highest value, and the same behavior at the lower horizontal wall, but the fluid velocity in this area is higher than the layer near the upper horizontal surface, as can be seen from the figure above that the greater The value of the thermal flux applied below the cavity

increased the fluid velocity due to the effects of the buoyancy force. That is, in hot regions, the speed of the fluid is higher than its speed in cold regions due to the loss of part of the fluid of its heat near the cold surface, so the kinetic energy of the fluid will become less, as well as we note the more porosity of the porous medium, the greater the speed. It is observed for two cavities outward sinusoidal walls cavity and inward sinusoidal walls in cavity that there are two areas in the cavity where almost zero velocity occurs, at the top and base of the cavity, which represents the center of the cellular where the fluid flows around, and at the edge around the container which represents a die flow area of the container.Also It was observed that the maximum velocity magnitude of the flow occurs within these regions.

1-Near wavy sides; where the smooth wavy shape always helps the flow to be faster.

2. Near the upper and the lower surfaces; where the flow inverses its direction so that the region of inversion becomes more like a narrow passages.

3. In the middle of the cavity; it is an area to collect the flow from all sides which leads to raise its velocity.

The distribution of the velocity did not change much when the shapes of the cavity change and as well as when the medium of porosity changed, however, the values of the velocity changed significantly. As the container shape changed from the sinusoidal cavity out ward to sinusoidal cavity inward as shown in, the velocity increased for all porosities that were tested. Using different types of porous media changed the velocity values .silica sand with porosity (0.38) gave the maximum velocity value, This increase in the velocity is due to the increase in the heat flux

and porosity also the other reason of this increasing is due to buoyancy forces which causes an increase in the mass flow rate close to the wall and accelerate the fluid flow so as a result causes an increasing in the velocity. , it has been pointed that the values of air velocity increased when the fluid layer increased, and decreased as the solid layer increased.
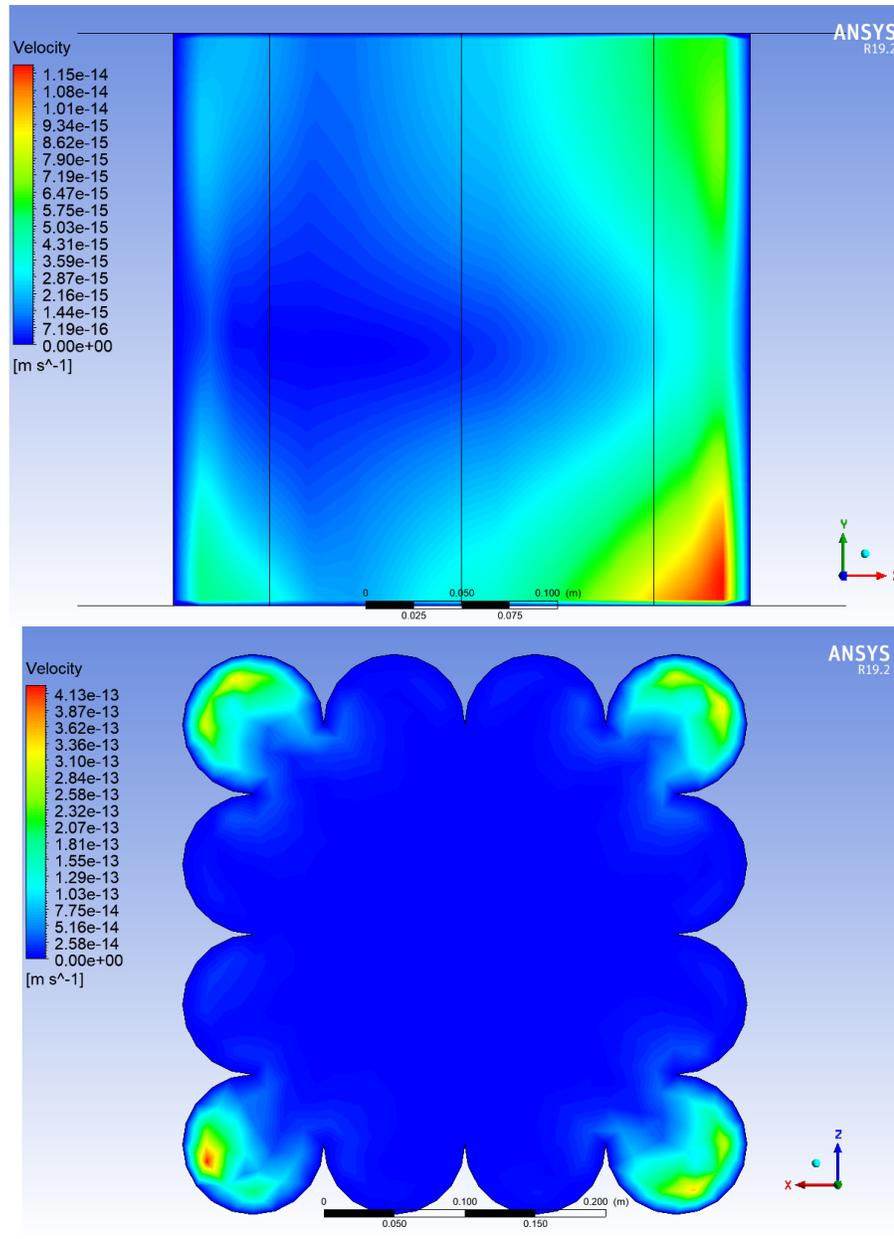
Figure (5-15). Velocity distribution for Sand porous media with heat flux $1000\,W/m^2$ and porosity 0.36(outward sinusoidal walls).
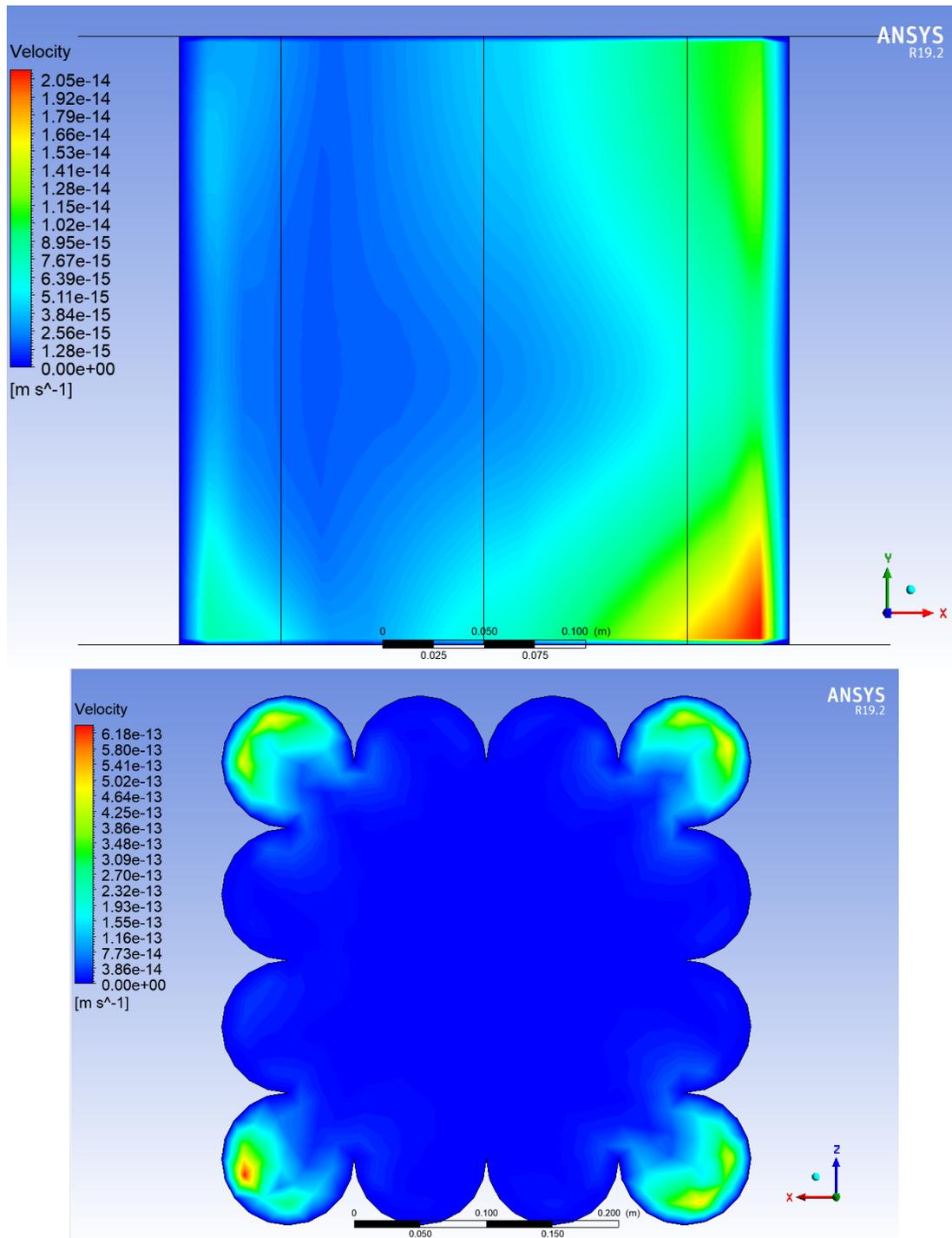
Figure (5-16). Velocity distribution for sand porous media with heat flux $1500 \, W/$ m^2 and porosity 0.36(outward sinusoidal walls).

Figure (5-17). Velocity distribution for sand porous media with heat flux $2000\,W/$ m^2 and porosity 0.36(outward sinusoidal walls).

Figure (5-18). Velocity distribution for Sand porous media with heat flux 1000 $W/$ m^2 and porosity 0.38(outward sinusoidal walls).

Figure (5-19). Velocity distribution for sand porous media with heat flux $1500\,W/$ m^2 and porosity 0.38(outward sinusoidal walls).

Figure (5-20). Velocity distribution for sand porous media with heat flux 2000 $W/$ m^2 and porosity 0.38(outward sinusoidal walls).

As for the second porous cavity with sinusoidal wave walls that are directed inward, the velocity distribution can be observed as in the figures.

Figure (5-21) .Velocity distribution for sand porous media with heat flux $1000\ W/m^2$ and porosity 0.36(inward sinusoidal walls).

Figure (5-22). Velocity distribution for sand porous media with heat flux $1500\,W/m^2$ and porosity 0.36(inward sinusoidal walls).

Figure (5-23). Velocity distribution for sand porous media with heat flux 2000 $W/$ m^2 and porosity 0.36(inward sinusoidal walls).
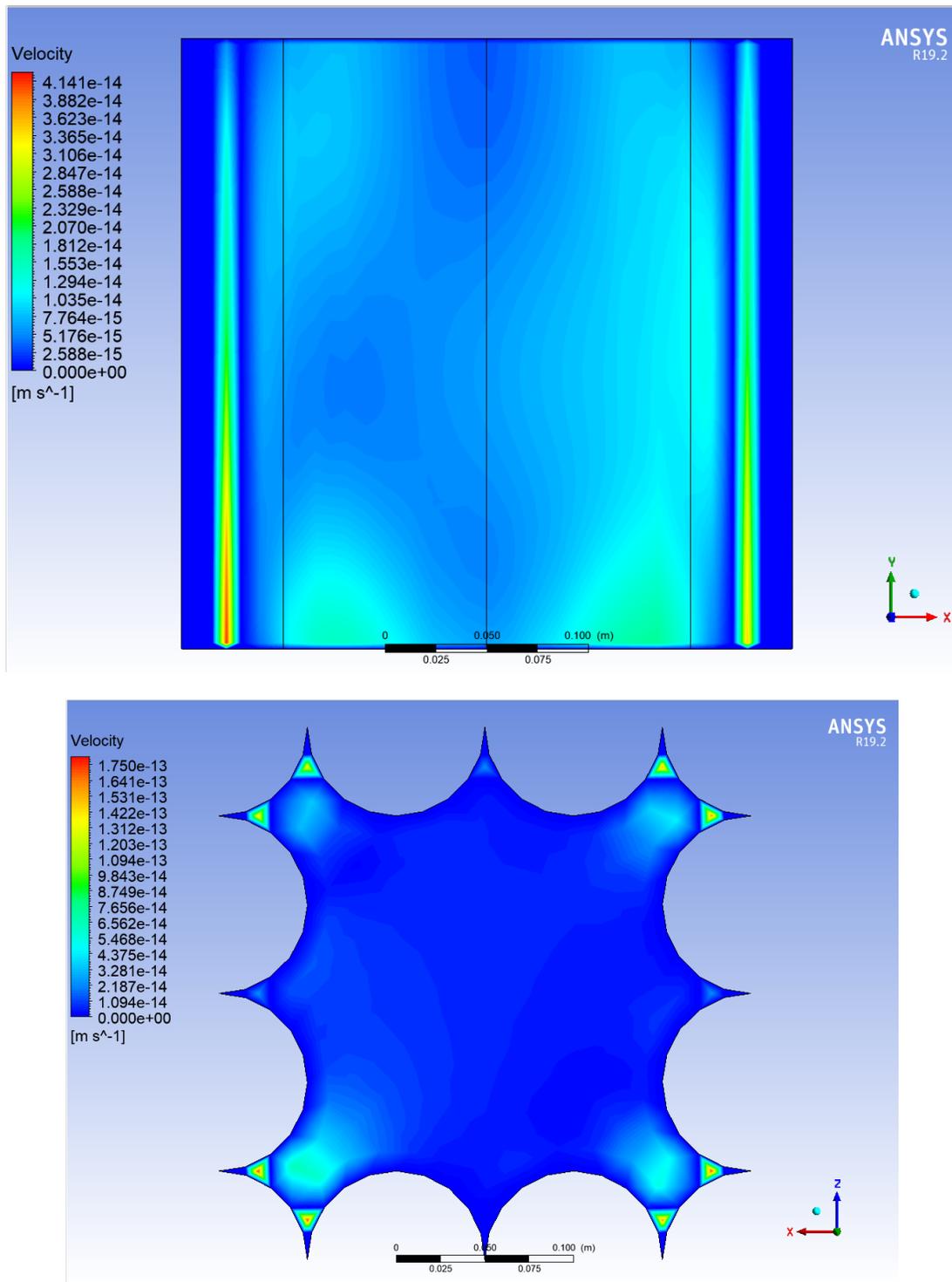
Figure (5-24). Velocity distribution for sand porous media with heat flux $1000\ W/$
m^2 and porosity 0.38(inward sinusoidal walls).
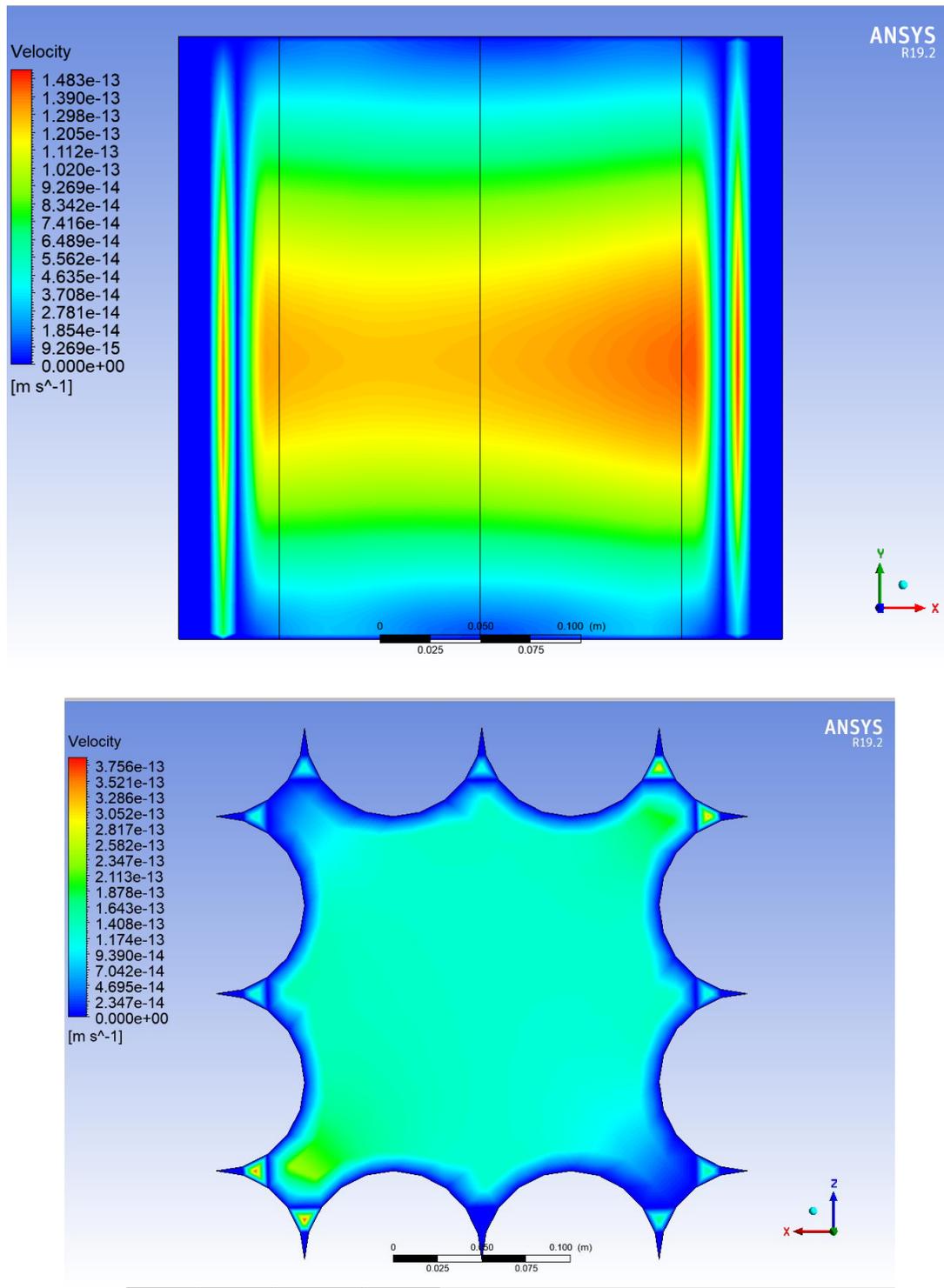
Figure (5-25) .Velocity distribution for sand porous media with heat flux 1500 $W/$ m^2 and porosity 0.38(inward sinusoidal walls).
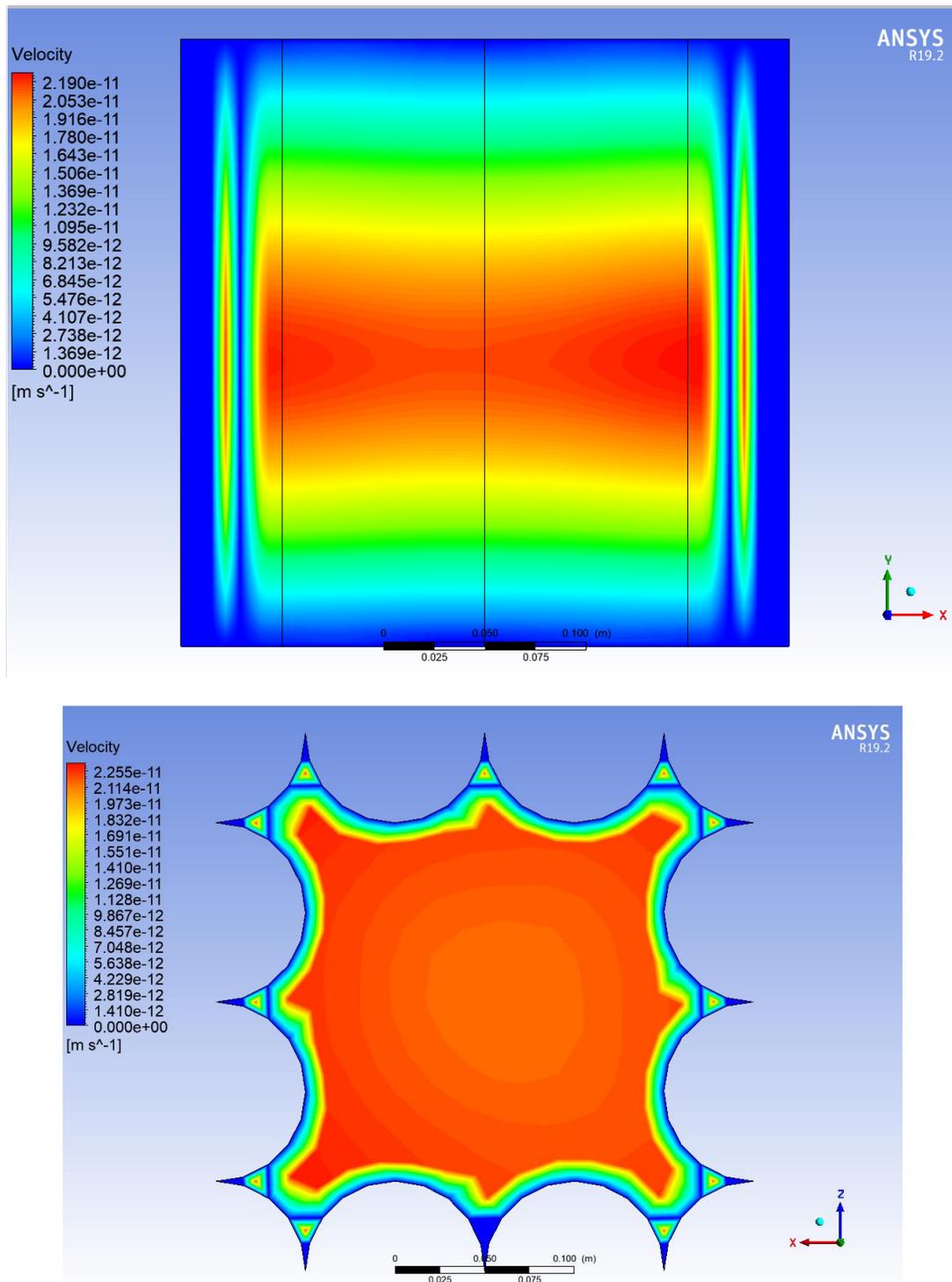
Figure (5-26). Velocity distribution for sand porous media with heat flux 2000 $W/$ m^2 and porosity 0.38(inward sinusoidal walls).

5.3 Experimental Results

5.3.1 The Effect of Cavity Shape on Temperature Distribution.

Figure (5.27), (5-28), (5-29), (5-30), (5-31), (5-32) show an isothermal contour maps for(x-y) plane of silica –air system at different heat flux (1000, 1500, 2000) W/m^2 for two cavities with inward sinusoidal walls and outward. Temperature difference increases with the increase in the thermal flux for each of the cavities for sand material as a porous medium. The amount of temperature difference for the sinusoidally wave cavity outward is slightly higher than sinusoidal cavity with inward oriented walls. This is because the increase in thermal flux leads to an increase in the growth of the thermal layer, which in turn increases the buoyancy strength for all models.
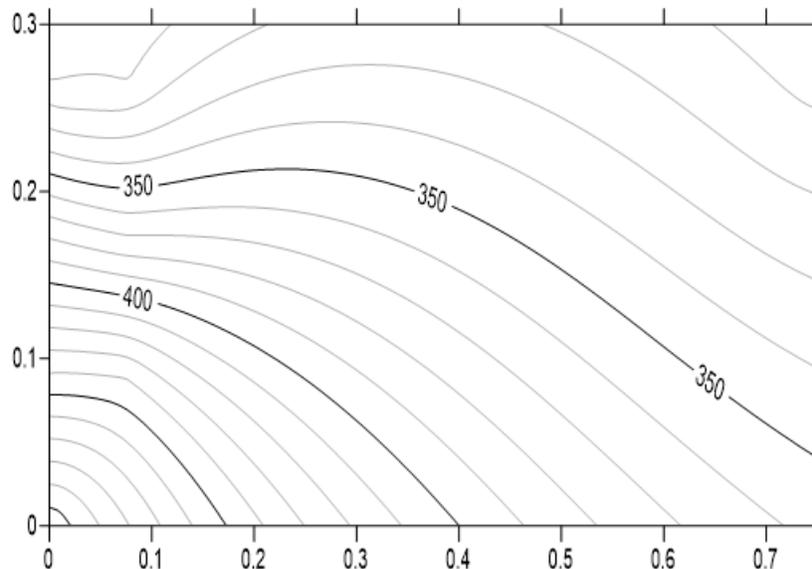

Figure (5-27).Isothermal contour map for (x-y) plane in silica -air system with
Ɛ=0.36 and heat flux of 1000 W/m^2 (outward sinusoidal walls).
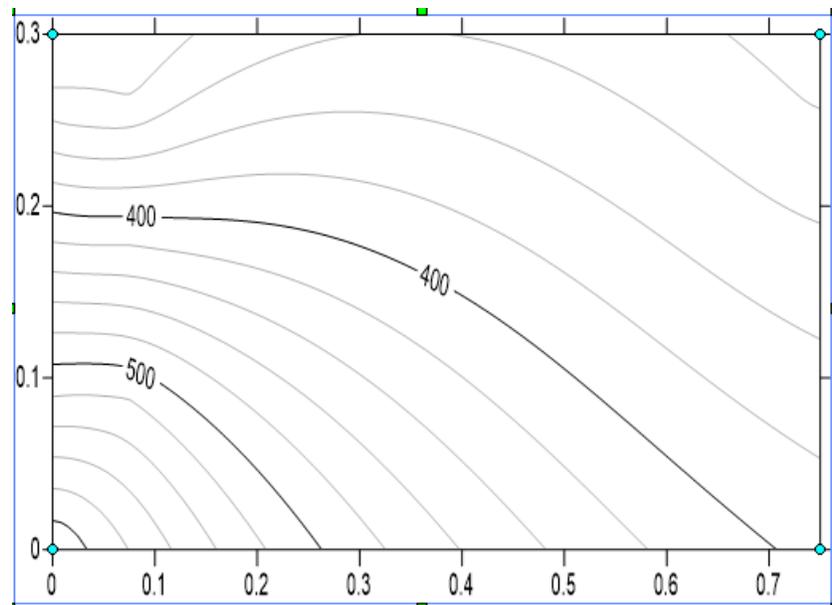
Figure (5-28).Isothermal contour map for (x-y) plane in silica -air system with $\varepsilon=$

0.36 and heat flux of 1500 W/m^2 (outward sinusoidal walls).
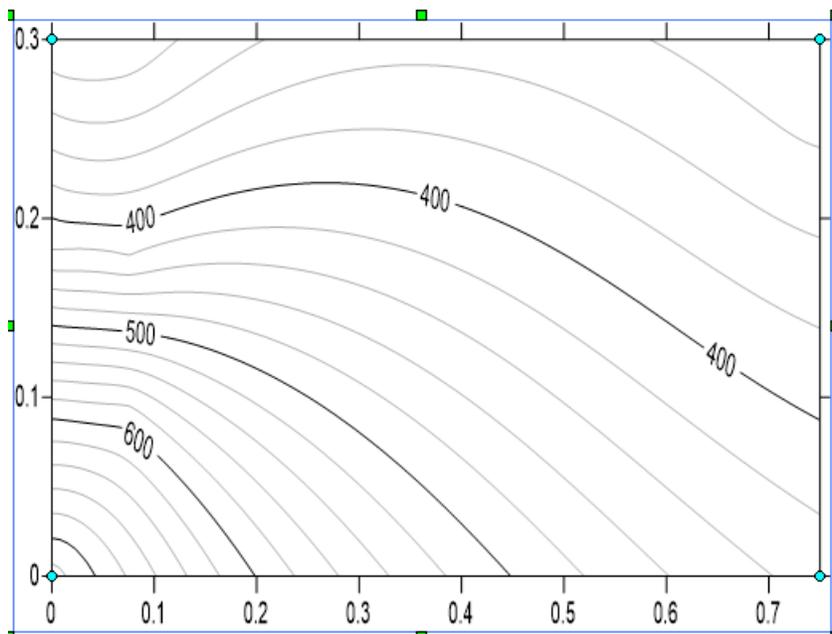
Figure (5-29).Isothermal contour map for (x-y) plane in silica -air system with
ε=0.36 and heat flux of 2000 W/m^2 (outward sinusoidal walls).
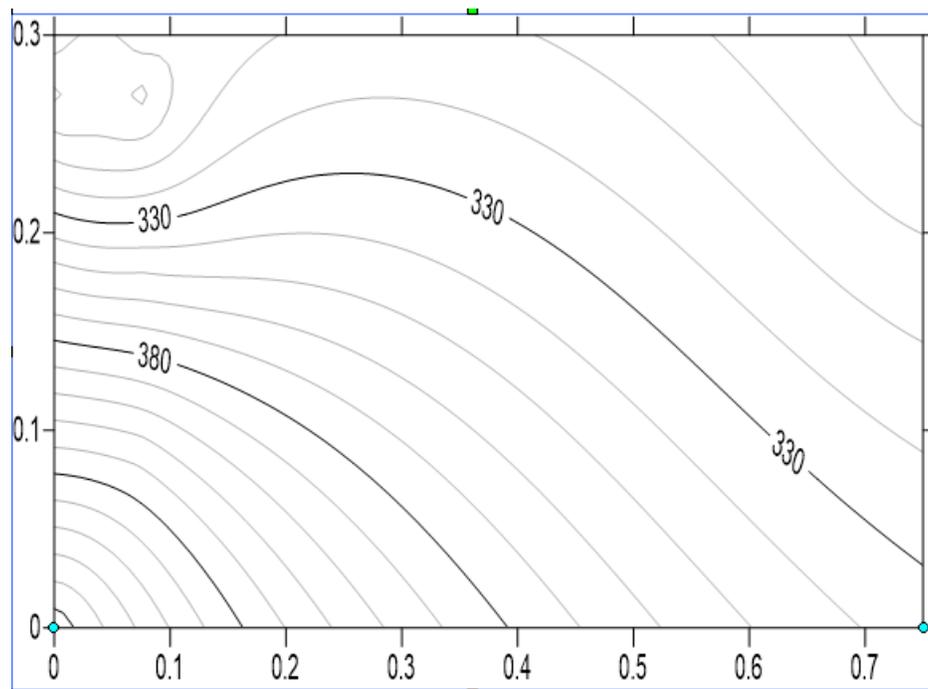
Figure (5-30).Isothermal contour map for (x-y) plane in silica -air system with
$\mathcal{E}$=0.36 and heat flux of 1000 W/m^2 (inward sinusoidal walls).
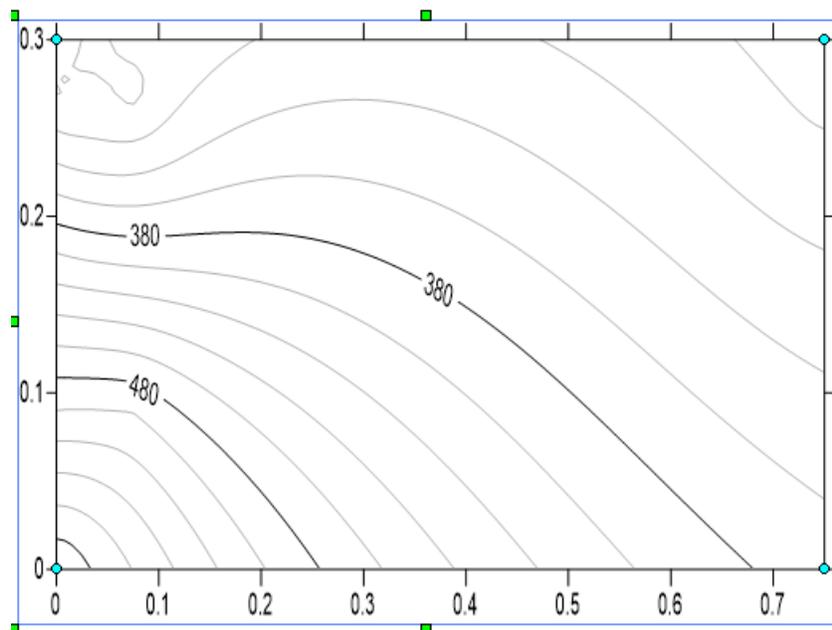
Figure (5-31).Isothermal contour map for (x-y) plane in silica -air system with
$\mathcal{E}$=0.36 and heat flux of 1500 W/m^2 (inward sinusoidal walls).
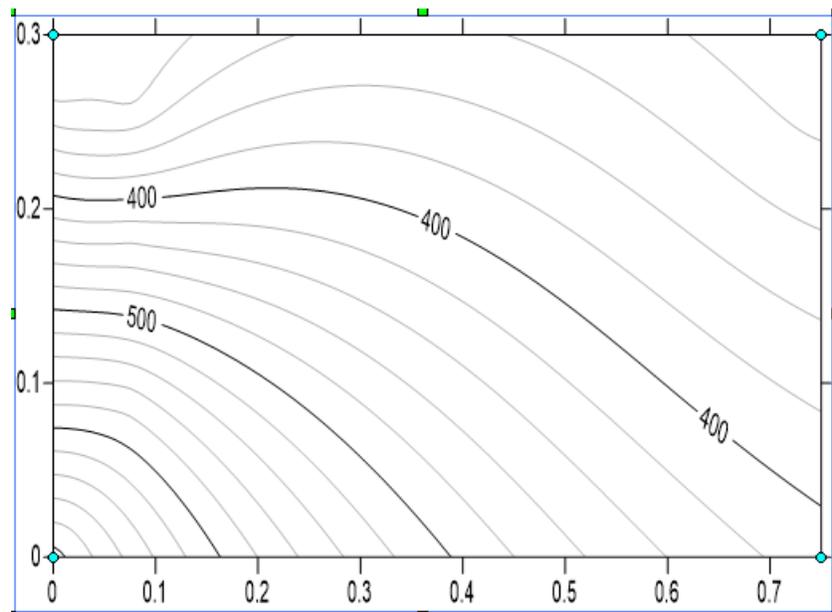
Figure (5-32).Isothermal contour map for (x-y) plane in silica -air system with
$\mathcal{E}$=0.36 and heat flux of 2000 W/m^2 (inward sinusoidal walls).

5.3.2 Effect of Heat Flux with Modified Rayleighx Number for Sand

Figure (5-33) The relationship between the amount of thermal flux
impose   on the two cavities filled   with a porous medium with the modified
Rayleigh Numberas   calculated based on the height cavity for all the models
tested. It   appears   that   the modified   Rayleigh Number increases with the
increase in the thermal   flux for two cavities.
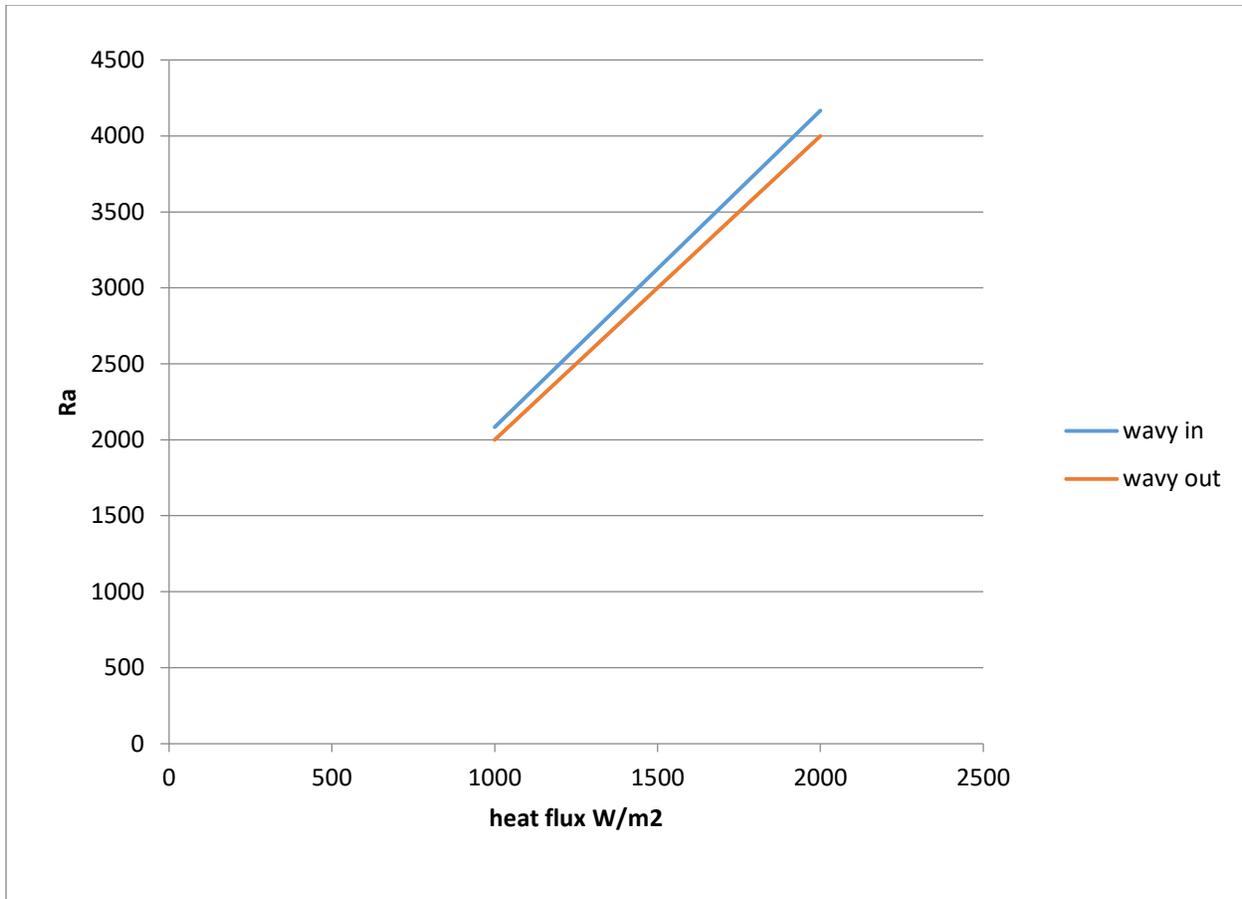
Figure(5-33) Modified Rayleigh Number against heat flux for porous cavity with outward and inward sinusoidal walls.

.*5.3.3 Effect of Heat Flux on the Nusselt Number*

The relationship between the amount of thermal flux impose on the two cavities filled with porous medium(silica_ sand) with the Nusselt number calculated for all the models of cavities(out ward wavy cavity and inward wavy cavity). It appears as shown in figure (5-34) that the Nusselt number increases with the increase in the thermal flux for two cavities, and it is the highest value at the wave walls cavity inward. This is due to the fact that the increase in thermal flux leads to an increase in the growth of the thermal layer, which in turn causes increasing in the buoyancy strength.
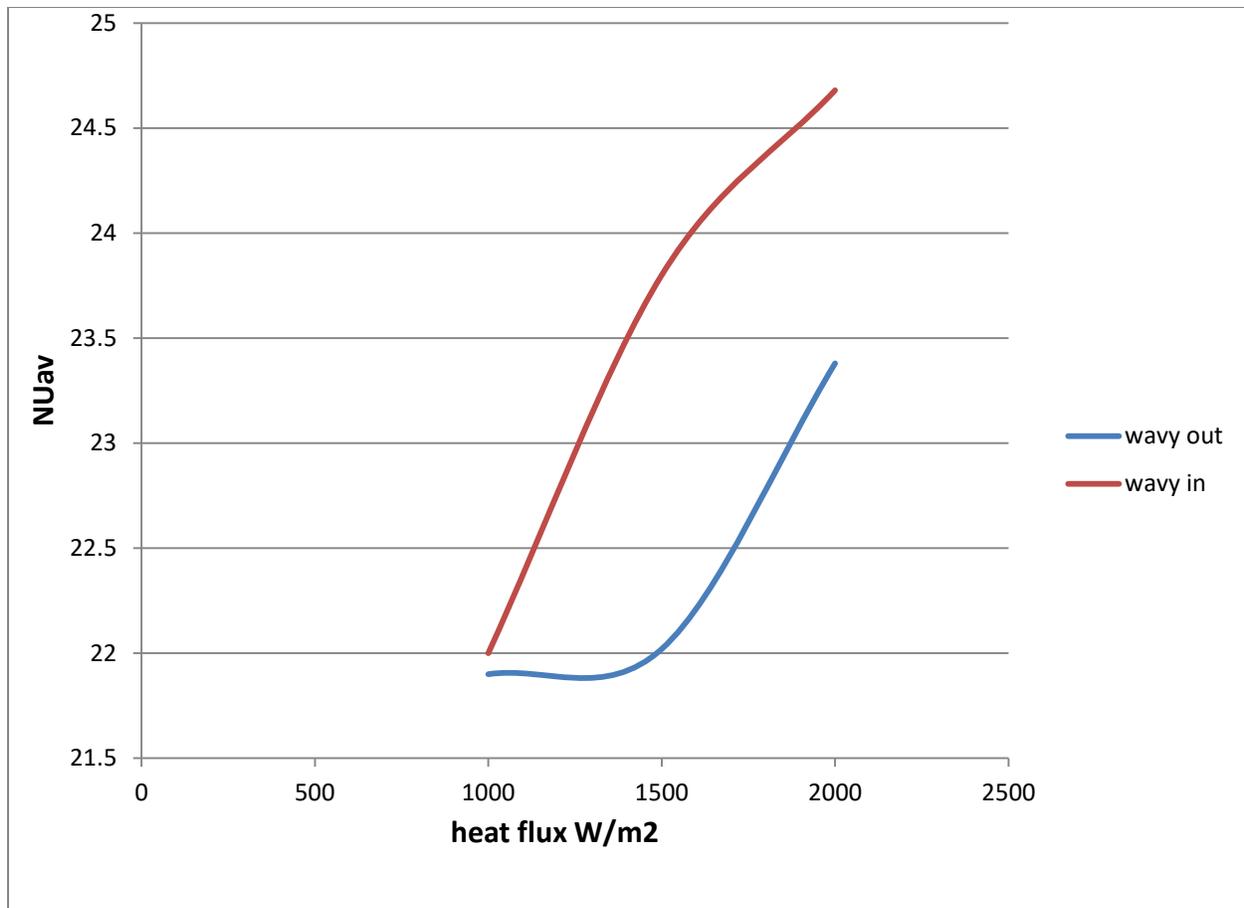
Figure (5-34) Effect of heat flux on Nu_{av} for sand porous media with the two porous cavities with outward and inwad sinusoidal walls.

5.3.4 Effect of Modified Rayleigh Number on the Nusselt   Number

The effect of the shape of porous cavity with sinusoidal walls inward and outward on the Nusselt number with different modified Rayleigh number for all these cavities   are studied. We notice from figure (5-35) that the values of the Nusselt number, in general, increase with the increase in the Rayleigh number values for all the models tested. However, the wave inward cavity gave the highest values of the Nusselt number and the lowest values obtained in the opposite wave cavity (for out ward wavy cavity). This is because the temperature difference in the

outward wave cavity gives the lowest values of the heat transfer coefficient, which in turn is directly proportional to the Nusselt number increase.
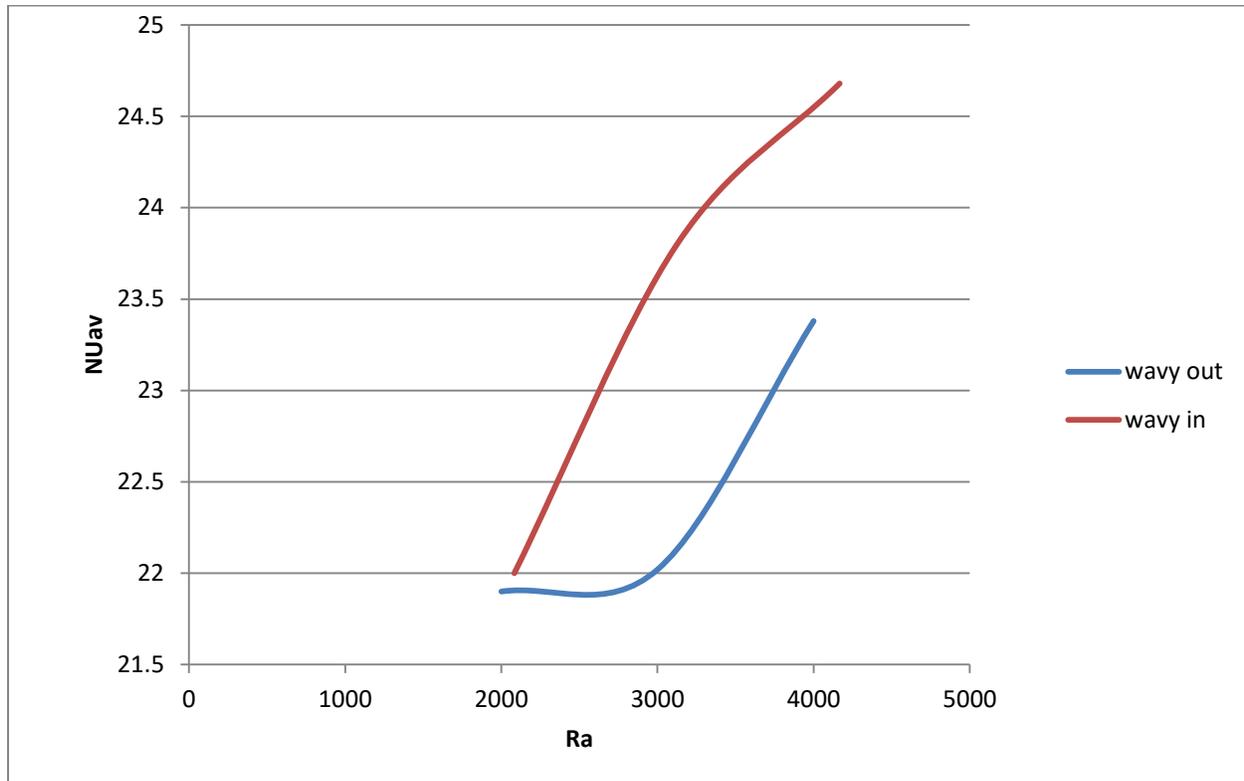
Figure (5-35) Effect   of modified   Rayleigh   Ram on Nu_{av} for sand porous   with the two porous cavities with outward and inwad sinusoidal walls.

5.4 Comparison of Experimental and Numerical Results

To verify the simulation (CFD) model, the tests of experimental results are compared with theoretical results under the same organizational and technological conditions, and by comparison with the theoretical results, a good match is obtained where The mean percentage error in the temperature distribution of the experimental values with respect to the theoretical values is (14.05%) for all states. This done by using of the standard percentage error formula which takes

here the form (percentage error = [$(\Delta T_{num} - \Delta T_{exp})/\Delta T_{num}$]*100) and then it is taken the average as a mean (total) percentage error all states.The comparisons between the experimental and theoretical results of the temperature difference between the hot and bluck Temperature, where the bulk temperature is estimated to be equal to.

[(T1+T2+T3+T4+T5+T6+T7+T8+T9+T10+T11+T12+T13+T14+T15+T16+T17+ T18+T19+T20+T21+T22) /22]. While the base temperature is taken to be equal to [(T23+ T24)/2].

The mismatch between the experimental and theoretical results can be traced back to the following reasons:

1. Losses in the supplied heat flux due to non-perfectly insulation.
2. Roughness of the inside curvy walls.
3. Instability of electricity.
4. Errors in measurement devices due to the accuracy of the instruments.

Chapter six

CONCLUSIONS AND

RECOMENATIONS

CHAPTER SIX

CONCLUSIONS AND RECOMENATIONS

6.1. Introduction

The current study has been based essentially on the numerical solution to investigate the natural convection inside a porous cavity with sinusoidal walls heated from below by constant heat flux and also to find how the sinusoidal curvy shapes of the cavity act upon porous media too. The experimental part was accomplished for two model (porous cavity with sinusoidal walls outward and porous cavity with inward sinusoidal walls), as a numerical study in which two different porosities are take as porous materials inside these two. In this chapter, both the conclusions and the recommendations for future similar studies will be viewed as follows.

6.2. Conclusion

Several variables were studied to obtain different results to reach the best heat transfer case. The following is a detailed explanation of the main conclusions:

1. The temperature difference is extracted from the difference in the average temperature of the base and the rate of the temperatures of the cavity. In both the theoretical and practical studies, it was concluded that the cavity with outward sinusoidal walls gives a higher temperature difference than the porous cavity with inward sinusoidal walls.

2. The heat transfer coefficient in the cavity with inward sinusoidal walls is higher than porous cavity with outward sinusoidal walls for theoretical and experimental study.

3. From numerical study the temperature difference is directly proportional to the porosity of porous materials, as the difference increase with the increase in the porosity of the porous materials.

4. The modified Rayleigh number increases with the increase in the thermal flux. Through the porous sand medium with porosity (0.38), the values of the modified Rayleigh number are higher than the porous medium with porosity (0.36), due to the influence of both the permeability and porosity of medium.

5. The Nusselt Number in general increases with the increase in the Rayleigh number values for all the models tested.

6. From the numerical investigation, it was noticed that there are two areas in the cavity where almost zero velocity occurs, at the top and base of the container, which represents the center of the cellular where the fluid flows around, and at the edge around the container which represents the die flow areas of the container

6.3. Recommendations

Some recommendations help to reach the main goal of the research that does not allow the opportunity to be covered in this study, which is as follows:

1- Studying other shapes of the cavity to demonstrate their effect more broadly.

2- Using different boundary conditions of the cavity, such as imposing the heat flux on asinsiodal walls cavity and insulating the upper and bottom surfaces.

3 - Using other forms of porous materials.

4 -Using a different fluid with the porous medium ,such as water.

5 -Using different aspect ratio of cavities.

References

<u>REFERENCES</u>

[1]   D. A. Nield and A. Bejan, "*Heat Transfer Through a Porous Medium,*" in *Convection in Porous Media*New York, NY: Springer New York, 1999, pp. 23-31.

[2]   D. A. Nield and A. Bejan, *Convection in porous media*. Springer, 2006.

[3]   Y. Deng, "*Thermal properties of porous media with applications in multilayer ground-coupled heat pumps*," Ph.D Thesis, Texas Tech University, 1990.

[4]   M. Kaviany, *Principles of Convective Heat Transfer*, 2 ed. Springer New York, 2001.

[5]   M. ALTimemy, "*Numerical study of natural convection in porous enclosure with multi*," University of Mosul, 2003.

[6]   B. R. Kumar, "*A study of free convection induced by a vertical wavy surface with heat flux in a porous enclosure*," Numerical Heat Transfer: Part A: Applications, vol. 37, no. 5, pp. 493-510, 2000.

[7]   B. Rathish Kumar and Shalini, "*Natural convection in a thermally stratified wavy vertical porous enclosure*," Numerical Heat Transfer: Part A: Applications, vol. 43, no. 7, pp. 753-776, 2003.

[8]   B. R. Kumar, "*Free convection in a non-Darcian wavy porous enclosure*," International Journal of Engineering Science, vol. 41, no. 16, pp. 1827-1848, 2003.

References

[9]   T. Jue, "*Analysis of thermal convection in a fluid-saturated porous cavity with internal heat generation*," Heat Mass Transfer, vol. 40, pp. 83-89, 2003.

[10]   P. K. Das, S. Mahmud, S. Humaira Tasnim, and A. Sadrul Islam, "*Effect of surface waviness and aspect ratio on heat transfer inside a wavy enclosure*," International Journal of Numerical Methods for Heat Fluid Flow, vol. 13, no. 8, pp. 1097-1122, 2003.

[11]   A. Dalal and M. K. Das, "*Laminar natural convection in an inclined complicated cavity with spatially variable wall temperature*," International Journal of Heat Mass Transfer, vol. 48, no. 18, pp. 3833-3854, 2005.

[12]   A. Misirlioglu, A. C. Baytas, and I. Pop, "*Free convection in a wavy cavity filled with a porous medium*," International journal of heat mass transfer, vol. 48, no. 9, pp. 1840-1850, 2005.

[13]   A. Dalal and M. K. Das, "*Natural convection in a cavity with a wavy wall heated from below and uniformly cooled from the top and both sides*," J. Heat Transfer, vol. 128, no. 7, pp. 717-725, 2006.

[14]   S. M. Salih, M. H. Majeed, and A. M. Ala'a, "*Numerical Investigation of Laminar Natural Convection in Rectangular Enclosures of Porous Media*," Journal of Engineering, vol. 13, no. 3, 2007.

[15]   M. H. Ali, A. T. Ahmed, and K. I. Hamada, "*Numerical Study of Non-Darcian Natural Convection Heat Transfer in a Rectangular Enclosure Filled with Porous Medium Saturated with Viscous Fluid*," Tikrit Journal of Engineering Science, vol. 15, no. 2, pp. 15-16, 2008.

References

[16]   K. Khanafer, B. Al-Azmi, A. Marafie, and I. Pop, "*Non-Darcian effects on natural convection heat transfer in a wavy porous enclosure*," International Journal of Heat Mass Transfer, vol. 52, no. 7-8, pp. 1887-1896, 2009.

[17]   A. K. Hussein, "*Numerical Prediction of Free Convection Phenomena Through a Rectangular Inclined Cavity Filled with a Porous Media*," The Iraqi Journal for Mechanical Material Engineering, vol. 10, no. 1, 2010.

[18]   K. S. Mushate, "*CFD prediction of natural convection in a wavy cavity filled with porous medium*," Glob. J. Res. Eng, vol. 11, pp. 29-45, 2011.

[19]   M. Young Kim and S. W. Baek, "*Numerical analysis of conduction. Convection, and radiation in a gradually expanding channel*," Numerical Heat Transfer, Part A Applications, vol. 29, no. 7, pp. 725-740, 1996.

[20]   M. Bhuvaneswari, S. Sivasankaran, and Y.-J. Kim, "*Effect of aspect ratio on convection in a porous enclosure with partially active thermal walls*," Computers Mathematics with Applications, vol. 62, no. 10, pp. 3844-3856, 2011.

[21]   F. A. Abood, "*Numerical analysis of free convection in a square and in a right-angle trapezoidal enclosure filled with porous medium*," Al-Qadisiya J Eng Sci, vol. 4, no. 3, pp. 1-11, 2011.

[22]   M. M. Saleh and I. Y. Hussain, "*Natural Convection in Confined Cylindrical Enclosure of Porous Media with Constant and Periodic Wall Temperature Boundary Conditions*," Journal of engineering, vol. 17, no. 2, 2011.

References

[23]   M. A. Ismael, "*Natural convection in a wavy porous enclosure heated by an internal circular cylinder*," Al-Qadisiyah Journal for Engineering Sciences, vol. 4, no. 3, pp. 204-220, 2011.

[24]   G. Nardini, M. Paroncini, and R. Vitali, "*Natural convection in square cavities with three active source configurations*," Int. J. Mech, vol. 7, no. 4, pp. 534-542, 2013.

[25]   A. R. Tahavvor, S. Hosseini, and A. K. Fard, "*Numerical investigation of the effect of number of waves on heat transfer in a wavy wall enclosure*," International Journal of Aerospace mechanical engineering, vol. 8, no. 11, pp. 1862-1866, 2014.

[26]   P. Sompong and S. Witayangkurn, "*Numerical Study of Natural Convection in a Heated Enclosure with Two Wavy Vertical Walls Using Finite Element Method*," Journal of Applied Mathematics, vol. 2014, p. 853231, 2014/05/04 2014.

[27]   W. Kalaoka and S. Witayangkurn, "*Numerical simulation of natural convection in a partially cooled square enclosure filled with porous medium*," Int. J. Pure Appl. Math, vol. 96, pp. 507-522, 2014.

[28]   M. Yousaf and S. Usman, "*Natural convection heat transfer in a square cavity with sinusoidal roughness elements*," International Journal of Heat Mass Transfer, vol. 90, pp. 180-190, 2015.

[29]   A. M. Gati'a, Z. K. Kadhim, and A. K. Al-Shara, "*Numerical Study of Laminar Free Convection Heat Transfer Inside a Curvy Porous Cavity Heated from Below*," Engineering Science, vol. 2, no. 2, pp. 14-25, 2017.

References

[30]   A. Dalal and M. K. Das, "*Laminar Natural Convection Inside a Wavy Enclosure Heated from Top and Uniformly Cooled from the Bottom and Both Sides*," in ASME International Mechanical Engineering Congress and Exposition, 2005, vol. 42215, pp. 123-131.

[31]   H. T. Cheong, S. Sivasankaran, and M. Bhuvaneswari, "*Natural convection in a wavy porous cavity with sinusoidal heating and internal heat generation*," International Journal of Numerical Methods for Heat Fluid Flow, vol. 27, no. 2, pp. 287-309, 2017.

[32]   H. T. Cheong, S. Sivasankaran, and M. Bhuvaneswari, "*Effect of aspect ratio on natural convection in a porous wavy cavity*," Arabian Journal for Science Engineering Science, vol. 43, pp. 1409-1421, 2018.

[33]   A. Abdulkadhim, A. M. Abed, A. Mohsen, and K. Al-Farhany, "*Effect of partially thermally active wall on natural convection in porous enclosure*," Mathematical Modelling of Engineering Problems, vol. 5, no. 4, pp. 395-406, 2018.

[34]   M. Saglam, B. Sarper, and O. Aydin, "*Natural convection in an enclosure with a discretely heated sidewall: Heatlines and flow visualization*," Journal of Applied Fluid Mechanics, vol. 11, no. 1, pp. 271-284, 2018.

[35]   M. S. Sadeq and Z. K. Kadhim, "*The effect of container shape and porous media on heat transfer*," J. Mech. Eng. res Developments CODEN: JERDFO, vol. 6, no. 43, pp. 197-206.

[36]   A. A. Mohammed, H. S. Majdi, and M. S. Alwan, "*Effect of thermal conductivity of porous media on thermo-fluid fields of free convective flow*

around a circular cylinder inside a square cavity," Journal of Mechanical Engineering Research Developments*, vol. 43, no. 6, pp. 440-455, 2020.

[37]   H. Moria, "*Natural convection in an L-shape cavity equipped with heating blocks and porous layers*," International Communications in Heat Mass Transfer*, vol. 126, p. 105375, 2021.

[38]   P. Rao and P. Barman, "*Natural convection in a wavy porous cavity subjected to a partial heat source*," International Communications in Heat Mass Transfer*, vol. 120, p. 105007, 2021.

[39]   P. Barman and P. Rao, "*Natural convection inside a heat source embedded wavy porous cavity containing an insulated obstacle*," Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 235, no. 5, pp. 1694-1704, 2021.

[40]   P. Barman and P. Rao, "*Effect of aspect ratio on natural convection in a wavy porous cavity submitted to a partial heat source*," International Communications in Heat Mass Transfer*, vol. 126, p. 105453, 2021.

[41]   F. J. Zachi and L. F. Ali, "*Numerical investigation of natural convection heat transfer in partially filled porous enclosure subjected to constant heat flux*," J Mech Eng Res Dev*, vol. 44, pp. 382-394, 2021.

[42]   M. A. Nima, S. A. A. Hussein, and S. S. Hameed, "*Mixed Convection Heat Transfer in a Vertical Saturated Concentric Annulus Packed with a Metallic Porous Media*," Journal of Engineering*, vol. 21, no. 9, pp. 85-104, 2015.

[43]   C. Grobler, M. Sharifpur, H. Ghodsinezhad, R. Capitani, and J. P. Meyer, "*Experimental study on cavity flow natural convection in porous*

References

medium, saturated with an AL_2O_3 60% EG-40% water nanofluid," in 11th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, Kruger National Park, South Africa, 2015, pp. 828-832.

[44] A. A. Alwan, M. T. Mohammed, and E. Mohammed, "*Experimental Investigation of Natural Convective Heat Transfer through Porous Media*," Journal of Babylon University/Engineering Sciences*, vol. 25, no. 2, pp. 570-584, 2017.

[45] A. M. Gati'a, Z. K. Kadhim, and A. K. Al-Shara, "*Experimental Study of Free Convection Inside Curvy Surfaces Porous Cavity*," Engineering Science*, vol. 2, no. 4, pp. 85-92, 2017.

[46] N. M. Salih, S. B. Ezzat, A. A. Hassan, and Q. K. Jasim, "*Natural Convection in a Square Cavity Filled with Saturated Porous Media and Partially Heated from Below*," in IOP Conference Series: Materials Science and Engineering, 2021, vol. 1094, no. 1, p. 012059: IOP Publishing.

[47] A. Fluent, "Ansys Fluent 19.2 User's Guide," ed. Canonsburg, PA: ANSYS, Inc., 2019.

[48] Bakker A., "*Applied Computational Fluid Dynamics, Mesh Generation*," Computational fluid dynamics lectures 2006, Available: www.bakker.org.

[49] M. N. Panda and L. W. Lake, "*Estimation of single-phase permeability from parameters of particle-size distribution*," AAPG bulletin*, vol. 78, no. 7, pp. 1028-1039, 1994.

[50] J. Holman, *Heat transfer*, 9 ed. McGraw Hill, 2002.

References

[51]   A. Al-Meiyahi, "*Experimental and Numerical Study of Free Convection Inside Curvy Surfaces Porous Cavity*," M.Sc thesis, collage of Engineering, Wasit University, 2017.

Appendix

Appendix: An ANSYS steps

Draw the cavity using solid work
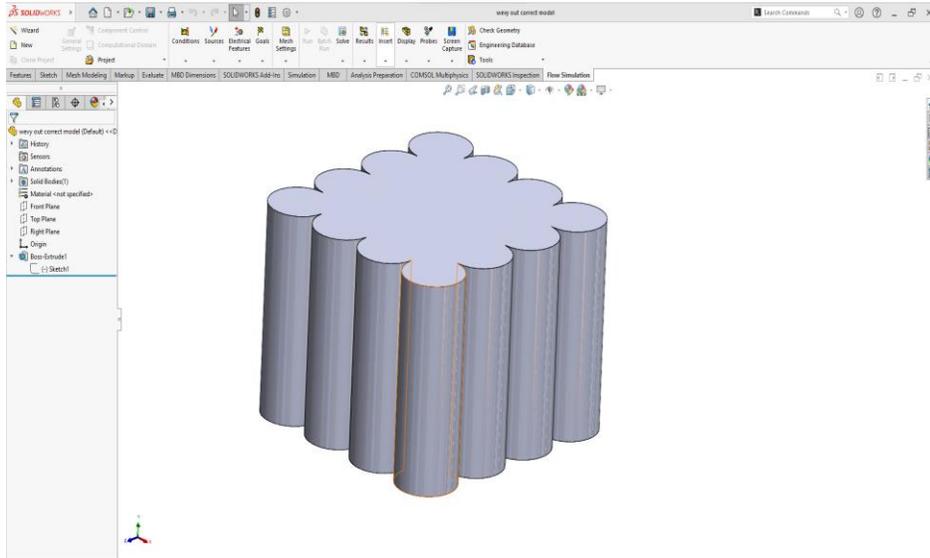
Save the drawing sat format to be included in the ANSYS program.
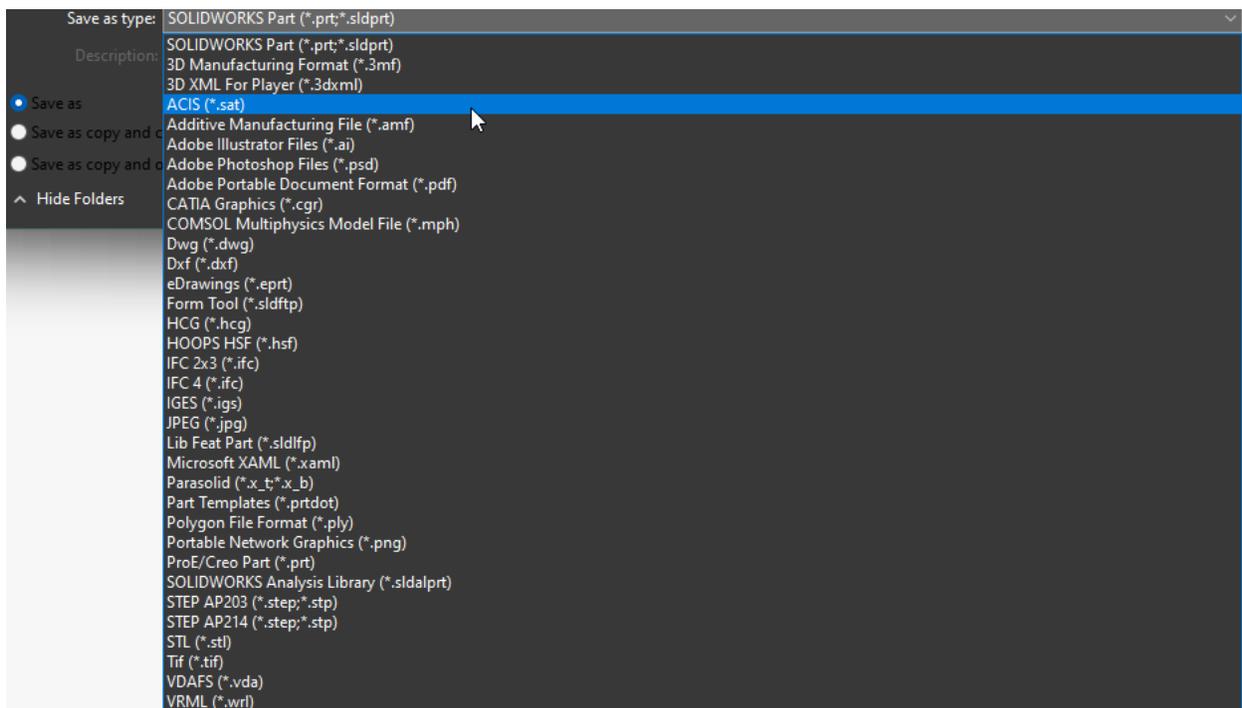
Appendix

Insert the drawing cavity into the ANSYS.
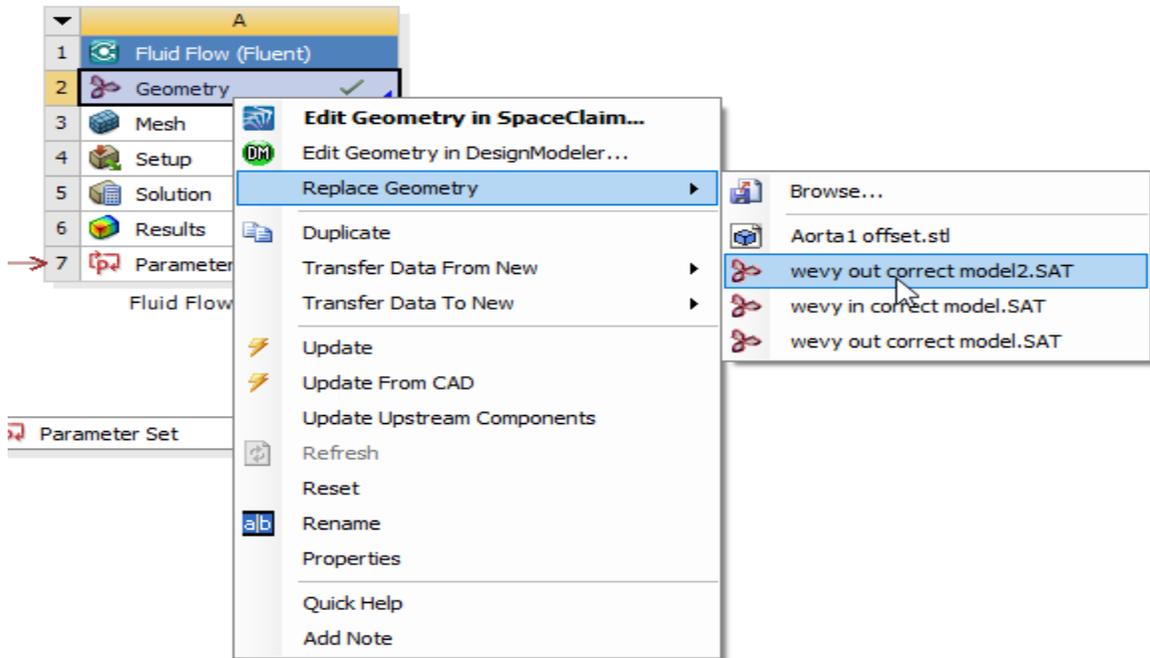
Carry out the Mesh generation.
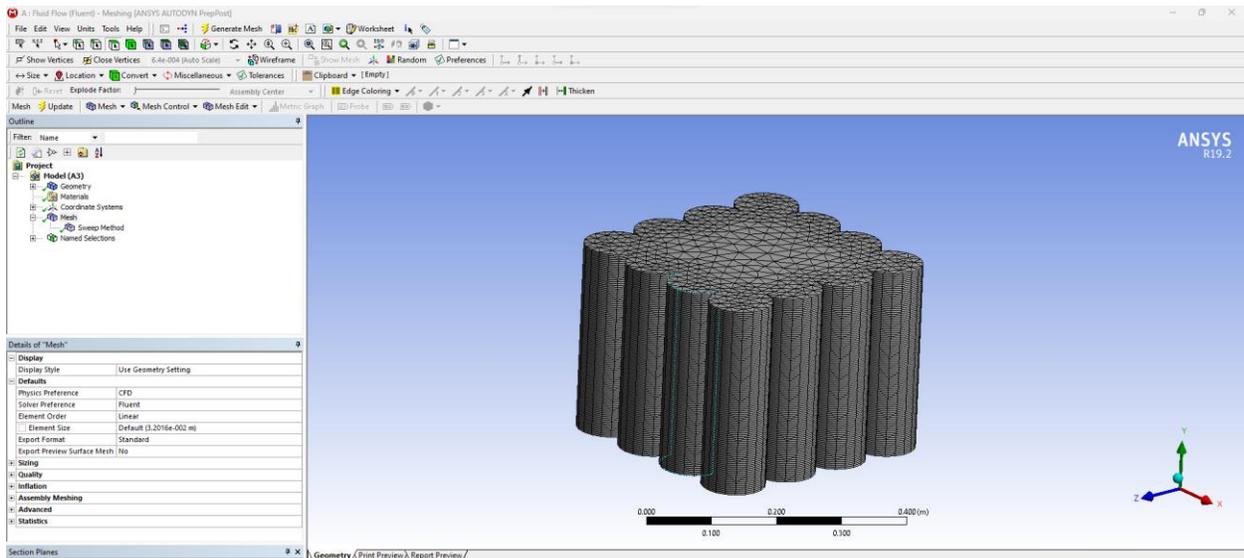
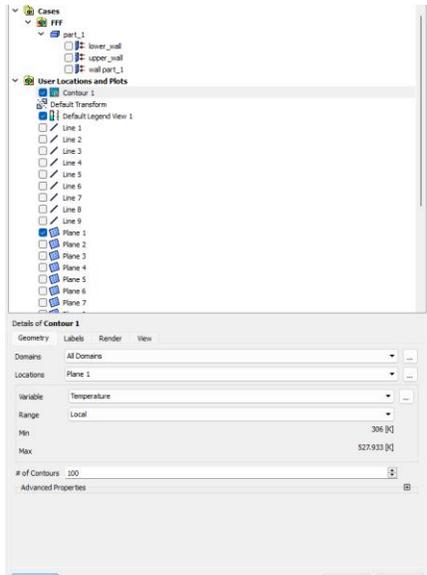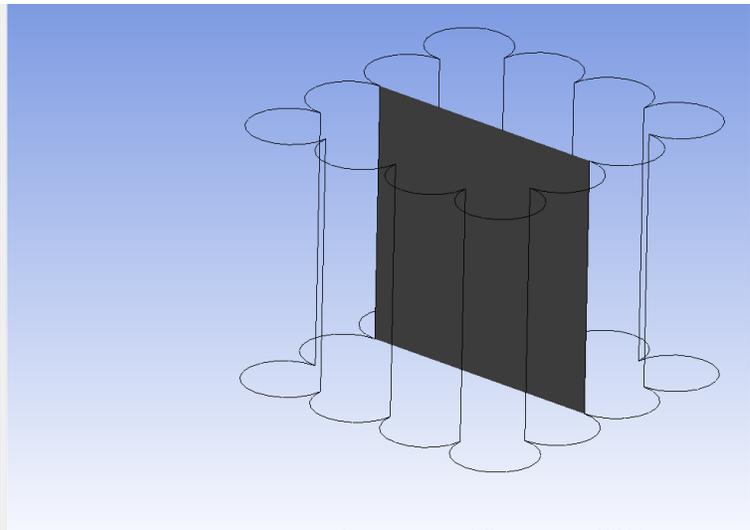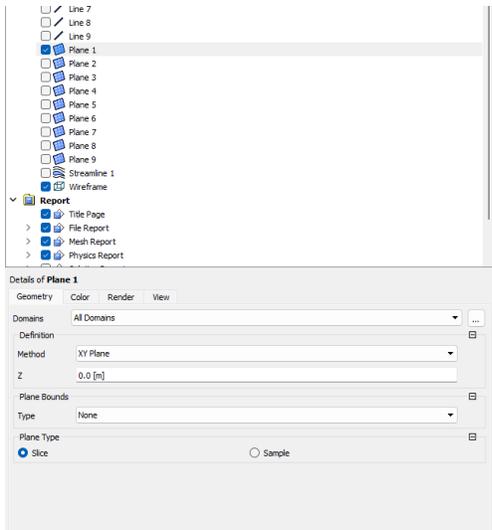Login to Flunt and adjust the following settings.
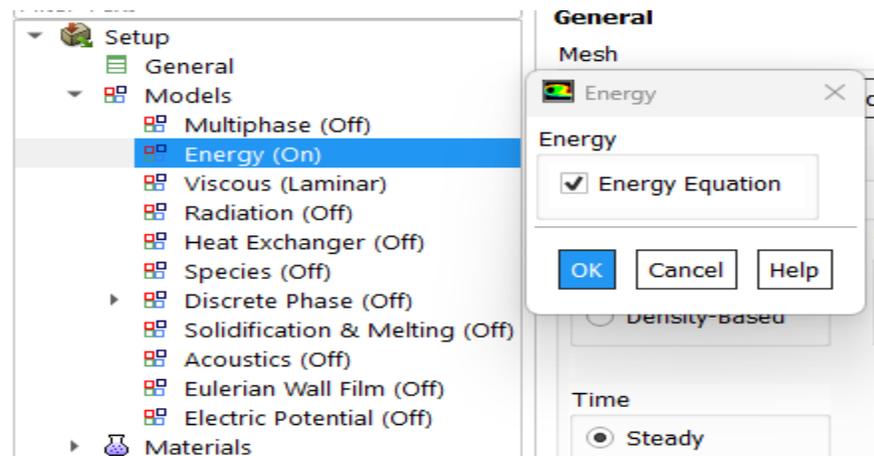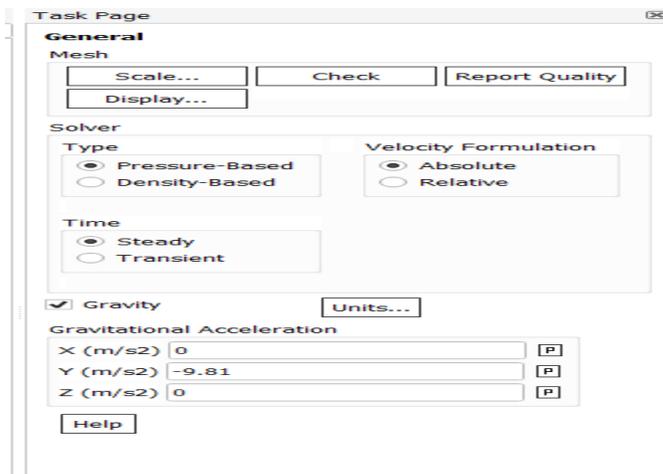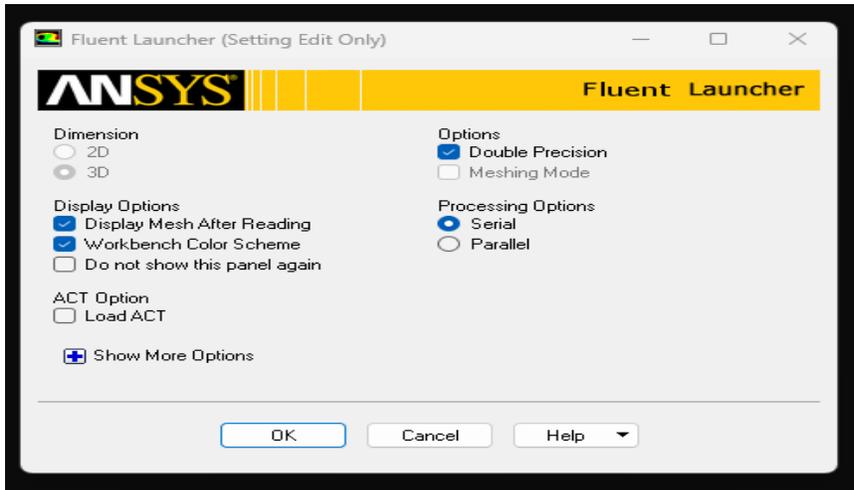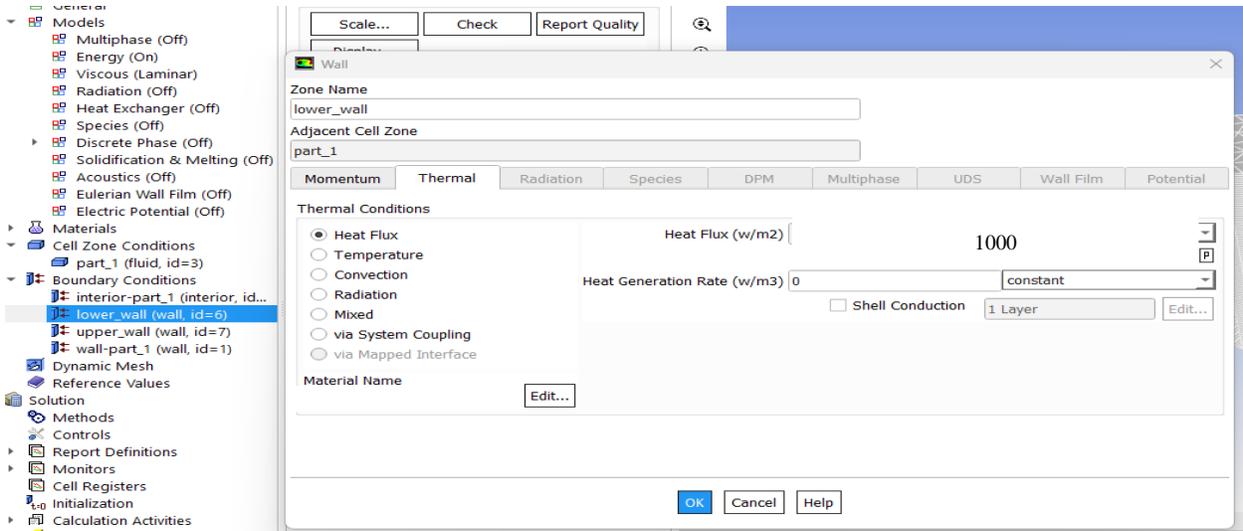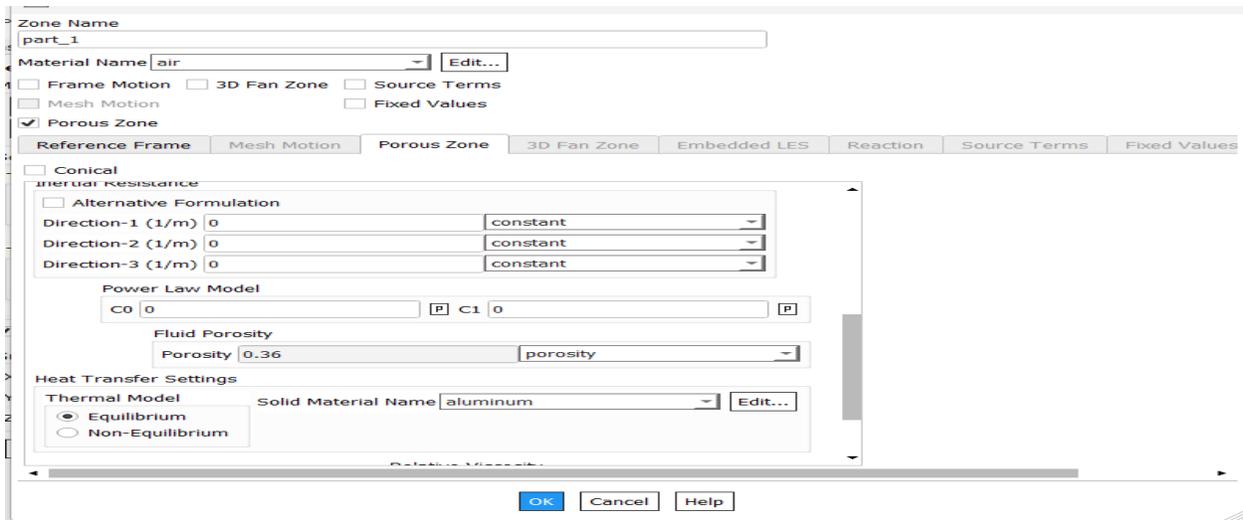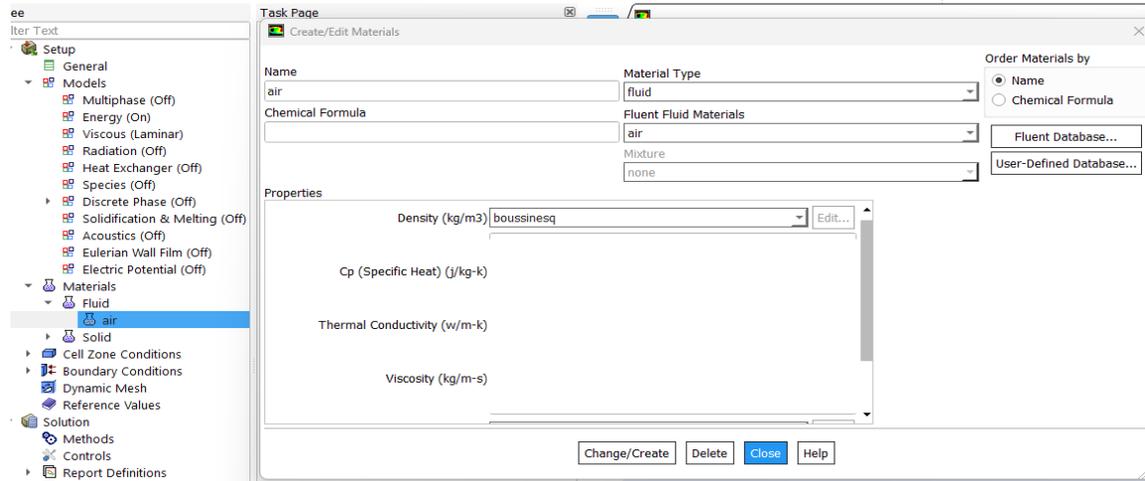
Appendix
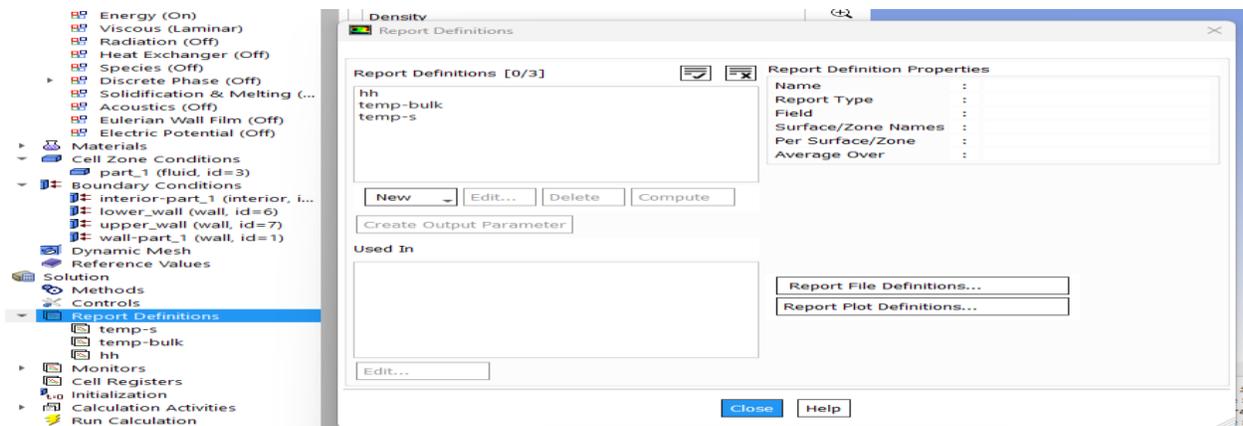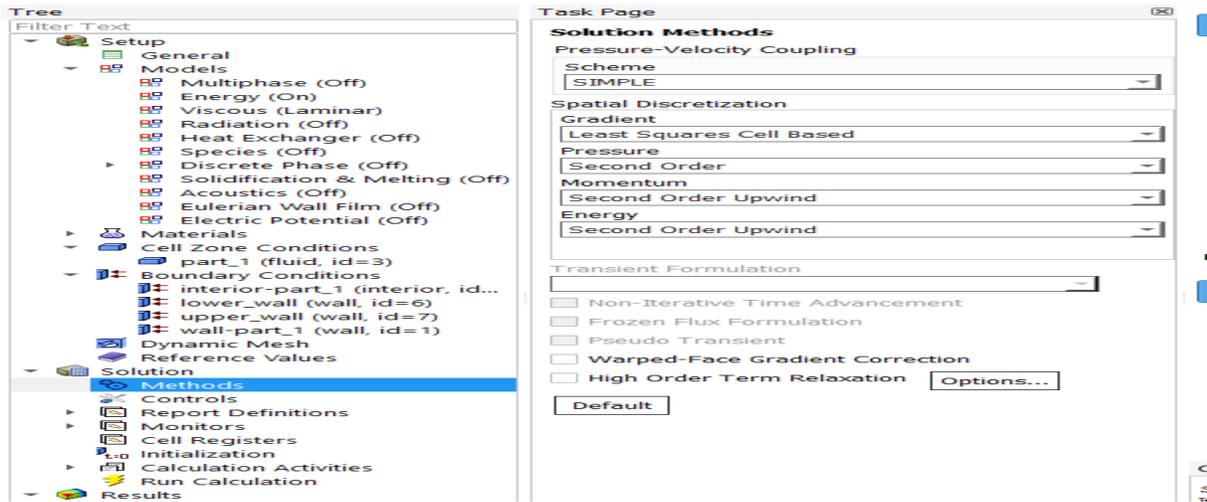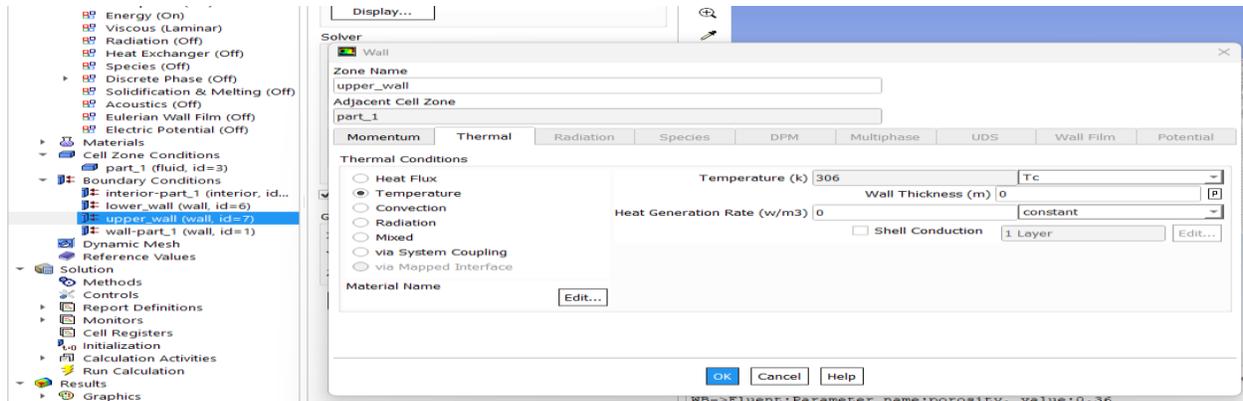
Appendix
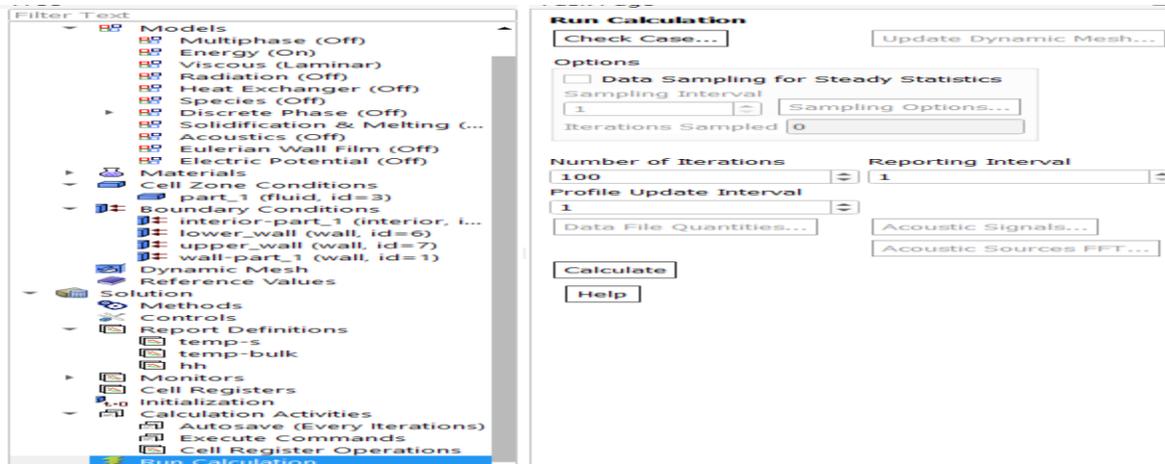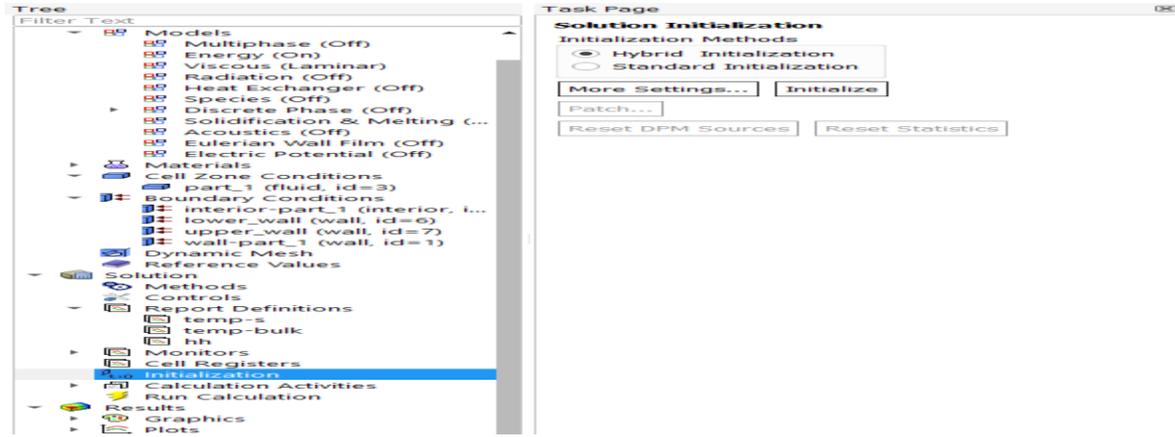
After completing the solution, it is extract the results.
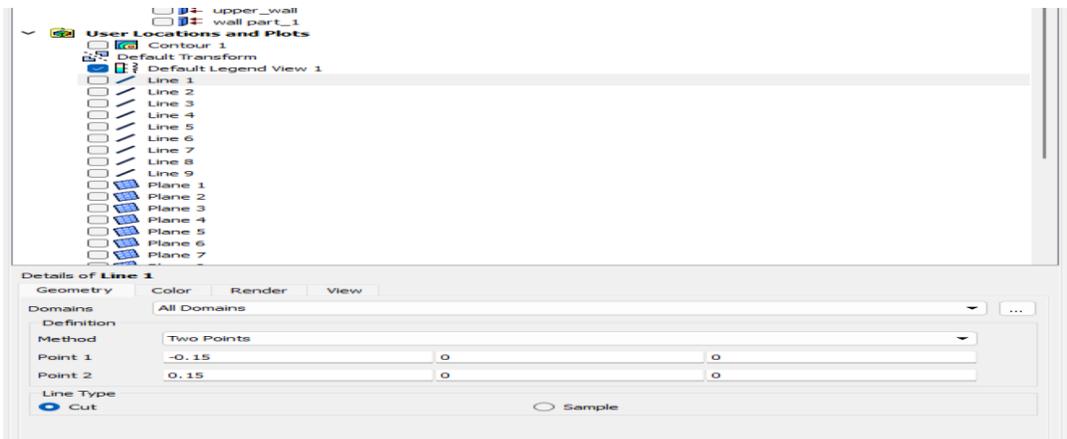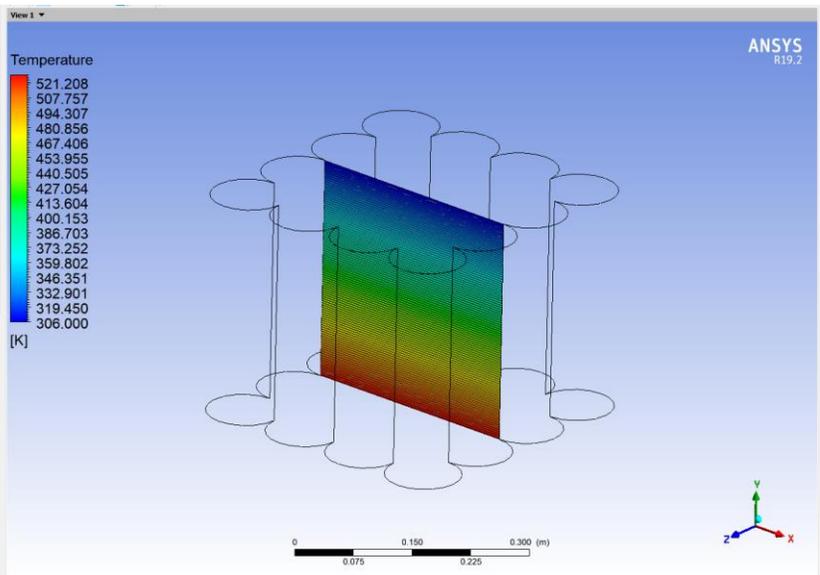
الخلاصة

في العمل الحالي تم دراسه انتقال الحراره بالحمل الحراري الطبيعي في تجويف مملوء بوسط مسامي عدديا وتجريبيا.اجريت هذه الدراستيين على شكلين من التجاويف (التجويف الاول بجدران متموجه الى الخارج والتجويف الثاني بجدران متموجه الى الداخل).تم اختيار الوسط المسامي الذي يملى هذه التجاويف (رمال السيلكا) وتم اعتبار الهواء مائع العمل . وتم تمثيل العمل النظري بأستخدام برنامج ANSYS-FLUNT 19.2ان المادة التي تم اخذها كوسط مسامي (هي رمال السيلكا) بمساميتيين مختلفتين (0.36) وكذلك (0.38) .وايضا تم دراسه العمل تجريبيا وبنفس الظروف حيث ان الفيض الحراري المسلط من الاسفل تتراوح قيميه (100- 2000) واط/ م^2 وان الجدران المتموجه ذات الموجه الجيبيه معزوله بالكامل كما ان السطح الاعلى من التجويف يكون عند درجه حراره ثابتة .تم قياس مسامية رمال السيلكا عمليا وتم اعتماد قيمه المسامية المستخدمة عمليا هي 0.36. وتم تثبيت اربع وعشرون ثرموكوبل نوع(ك) في اماكن مختلفه من التجويف المسامي.لقد تم تمثيل النتائج على شكل خطوط السرعة والحرارة وعدد نسلت .   لقد اظهرت النتائج العملية والنظرية لكلا التجويفين ان عدد نسلت يزداد بزيادة الفيض الحراري المسلط من الاسفل.وكذلك اظهرت الدراسة النظرية ان عدد نسلت يزداد بزياة المسامية للوسط المسامي ولكلا التجويفيين.تم   مقارنة النتائج العملية والنظرية وأظهرت تقربا جيدا بنسبة 86%.وقد أظهرت الدراسة النتائج التالية:

من بين اشكال التجاويف التي تمت دراستها يعطي التجويف ذو الجدران المتموجة للخارج أكبر فرق في درجة الحرارة حيث أن هذا الاختلاف هو الاساس في دراسة الخواص الاخرى.

عندما تزداد المسامية سوف يقل الفرق في درجات الحرارة وبالتالي يزداد معامل نقل الحرارة للحمل الحراري وهذا يؤدي الى زيادة في عدد نسلت.

وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة
قسم الهندسة الميكانيكية

دراسة تجريبية وعددية لحمل طبيعي داخل تجويف مسامي مع جدران جيبية مملوء بمائع

رسالة

مقدمة لكلية الهندسة جامعة بابل استيفاء جزئي لمتطلبات درجة الماجستير في الهندسة / الهندسة الميكانيكية / قدرة

أعدت من قبل

رقية نصر جواد

بأشراف

أ.م. د. حسين محمود جاسم

1444 هـ
2023 م