THEORETICAL INVESTIGATIONS INTO POTENTIAL OPTICALLY TRANSPARENT INSULATING MATERIALS FOR EFFICIENT SOLAR THERMAL ENERGY CONVERSION

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING

IN THERMAL ENGINEERING

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CERTIFICATE

I hereby declare that the dissertation entitled "**Theoretical Investigations into Potential Optically Transparent Insulating Materials for Efficient Solar Thermal Energy Conversion**" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Thermal Engineering** at **Thapar Institute of Engineering and Technology, Patiala** under the supervision of **Dr. Vikrant Khullar (Associate Professor, Mechanical Engineering Department)** and **Dr. Sayan Sadhu (Assistant Professor, Mechanical Engineering Department).** No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

As concentrating solar collectors are very expensive and also concentrating solar collectors have low optical efficiency at higher concentration ratios so due to this reason an alternative method of solar collection which is economical and also can be used to attain higher temperatures of the receiver or absorber plate is required. Therefore, to achieve this optically transparent insulating materials are used. By using optically transparent insulating materials intermediately high temperatures could be achieved at low optical solar concentration ratio. If we use an aerogel as an optically transparent insulating material then the maximum percentage increase of 5.5 percent was observed in case of pure scattering medium with respect to the case of pure absorbing medium but this maximum percentage increase of 5.5 percent in the absorber or receiver temperature was found when the optical depth in the solar region is 1 and the thickness of an aerogel medium is 30 mm. So, by varying the conditions of the medium, by varying the thermophysical properties of the medium and also by varying the physical properties like thickness of the medium absorber or receiver plate temperature variation was found out and analyzed.

ACKNOWLEDGEMENT

I would like to express my special thanks and sense of gratitude to my supervisors, Dr Vikrant Khullar and Dr Sayan Sadhu for their guidance. I have been extremely lucky to have both of them as my supervisors who have helped me in my work and I came to know about a lot of new things and my knowledge has drastically increased. They provided me the technical support and skills that really helped me during the work. They cared so much about my work over the year. Their patience, the adjustments they made, and the trust and confidence they had in me really helped me to finish my work.

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NOMENCLATURE

English Symbols

G	Incident Solar Energy [W/m^2]
H	Thickness [mm]
T_B	Bottom Surface temperature [K]
Tt	Top Surface temperature [K]
k	Thermal Conductivity [W/m K]
h	Convection heat transfer coefficient [W/m^2 K]
T_{amb}	Ambient temperature [K]
T_{sky}	Sky Temperature [K]
p	Static Pressure [Pa]
g	Acceleration due to gravity [m/s^2]
F	Source term
J_j	Diffusion flux of species j
E	Total Energy
k_{eff}	Effective thermal conductivity
T	Temperature
h_j	Sensible enthalapy of species j
S_h	Volumetric heat source
n	Refractive Index
$I(r,s)$	Total intensity in each direction s at position r
s	Any arbitrary direction
r	Any arbitrary position
C	Scattering Phase function

Greek Letters

ρ	Density
ϑ	Kinematic Viscousity
τ	Stress Tensor
α	Absorption Coefficient

σ_s	Scattering Coefficient
σ	Stefan Boltzmann Constant
ω	Scattering Albedo
β_{solar}	Optical Depth in Solar region
β_{IR}	Optical Depth in Infrared region
ε_{IR}	Emissivity in Infrared region
τ_{total}	Total Transmittance
λ_{cutoff}	Cutoff Wavelength
ε	Emissivity

Subscripts

amb	Ambient
IR	Infrared region
solar	Solar region
j	Number of species

Abbreviations

OTIM	Optically Transparent Insulating Materials
TIM	Transparent Insulating Materials
IR	Infrared region

CHAPTER 1

INTRODUCTION

1.1. MOTIVATION

In these days the solar thermal systems are coming in trend as they are very much beneficial in converting the sun energy into the electricity. There are many types of solar thermal system available but every solar thermal system have its own advantages and disadvantages. In case of flat plate solar collector not having its own tracking system the temperatures that are achieved are not very high or losses are high , in case of concentrating solar collector having its own tracking system the temperatures achieved will be significantly high and hence losses will also be less as these type of solar thermal systems concentrate the sunlight to a localized area or to a very small area resulting in higher temperatures but the concentrating collectors having its own tracking system are very costly so there is a need of such a solar collector in which losses are less as well as the cost is also less. Development of highly efficient solar thermal system at a lower cost will be very beneficial. Highly efficient solar thermal system refers to that solar thermal system which uses the same amount of incident radiation from the sun but produces the higher temperatures of the intended plate or absorber plate or in other words its losses are very less and its efficiency is high. So this is required to devise a solar system by whom we can solve both of these problems or limitations.

1.2 OPTICAL TRANSPARENT INSULATING MATERIALS

Optical Transparent Insulating Materials are a special type of materials that have certain characteristics which makes it suitable for its use in solar thermal system. Optical Transparent Insulating Materials works on the same principle as that of the Greenhouse Effect. Optical Transparent Insulating Materials basically allows most of the incident solar energy to pass through it without any absorption in it so that much amount of incident radiation energy passes on to intended plate or receiver present at bottom but on the other hand Optical Transparent Insulating Materials does not allow the radiation emitted by the absorber or receiver plate to pass through it and due to this reason most of the energy gets trapped inside the medium or in other words losses are minimized and reduced to a great extent. Most of the energy will be trapped inside the Optical Transparent Insulating Materials and due to this trapped energy the temperature of the intended plate or receiver will reach upto very high magnitude indicating less losses or higher efficiency. Optical Transparent Insulating Materials allows the solar energy to pass through it i.e it acts as an insulating material for sun radiation and on the other hand it behaves like an opaque material for energy released by absorber or receiver plate i.e it behaves like an opaque material for energy released in infrared region. Due to this special characteristic which Optical Transparent Insulating Materials possess these can be used in the solar thermal system to reduce the losses and hence to increase its effectiveness.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Although we can obtain high value of temperatures by using different types of solar collectors but using Optical Transparent Insulating material is one another way of obtaining high temperatures in solar collectors and that too in an economical way. The higher temperatures are required in the industry since most of the processes in the industry require high temperature for their operation. Different types of studies and researches have been done and are being continuously done in the current time on the Optical Transparent Insulating materials to test its efficiency and to check that under what conditions these Optical Transparent Insulating materials work the best or what are the optimal conditions under which Optical Transparent Insulating materials function the best. Different modifications or variability of structure of working material is being done to obtain the desired properties of the working medium.

Table 1 below shows the notable researchers along with their affiliation who have conducted research in this regard

S. No.	Title of the research paper	Institute/ University/ Laboratory	Researcher(s)
1.	Plasmon-Enhanced Greenhouse Selectivity for High-Temperature Solar Thermal Energy Conversion	University of Michigan, Ann Arbor, Michigan, United States	Zachary J. Berquist, Kevin K. Turaczy, Andrej Lenert
2.	Harnessing heat beyond 200℃ from Unconcentrated Sunlight with Non evacuated Transparent Aerogels	Massachusetts Institute of Technology, Massachusetts, United States	Lin Zhao, Bikram Bhatia, Sungwoo Yang, Elise Strobach, Lee A. Weinstein, Thomas A. Cooper, Gang Chen and Evelyn N. Wang
3.	Theoretical and experimental investigation of haze in transparent aerogels	Massachusetts Institute of Technology, Massachusetts, United States	Lin Zhao, Elise Strobach, Bikram Bhatia, Sungwoo Yang, Arny Leroy, Lenan Zhang and Evelyn N. Wang
4.	Combined heat transfer of radiation and natural convection in a square cavity containing participating gases	Iran Institute of Fluid Science, Tohoku University, Katahira, Aoba-ku, Sendai, Japan	K. Lari, M. Baneshi, S.A. Gandjalikhan, A. Komiya, S. Maruyama
5.	Numerical Investigation of Natural Convection inside a cube at sub-atmospheric pressure	Veermata Jijabai Technological Institute, Mumbai, India	Sumit Bhore, Arvind Deshpande, Mandar Tendolkar, Vivek Singh

6.	Numerical analysis of laminar natural convection in isosceles triangular enclosures for cold base and hot inclined walls	Istanbul Technical University, Istanbul, Turkey	E. Fuad Kent
7.	An experimental study on natural convection heat transfer in an inclined square enclosure containing Internal energy sources	College of Engineering, Hanyang University Korea, University of Minnesota, Minneapolis	Jae-Heon Lee, R.J. Goldstein
8.	Bejan's heatline analysis of natural convection in right-angled triangular enclosures: Effects of aspect-ratio and thermal boundary conditions	Indian Institute of Technology Madras, Chennai	Ram Satish Kaluri, R. Anandalalakshmi, Tanmay Basak
9.	Investigation of natural circulation in cavities with uniform heat generation for different Prandtl number fluids	Indian Institute of Technology Bombay, Mumbai	Parameshwar Deshmukh, Sushanta K. Mitra, U.N. Gaitonde
10.	Natural Convection of Liquid Metals in Vertical Cavities	Heat Transfer Laboratory, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana	F. Wolff, C. Beckermann, R. Viskanta

Berquist et al. [1] have done an experimental and numerical study to analyze the effect of the change in the structure of the working material on its performance and also on the temperature of intended or receiver surface. These plasmonic aerogels were made by mixing Indium Tin Oxide Nanoparticles with a silica aerogel after that a sol-gel catalyst is added so that aerogel backbone forms over particles then after that a critical point drying and annealing is done for 24 hours to remove the surfactant and now the plasmonic aerogel is ready. Upon doing study it was seen that upon addition of small amount of Transparent Conducting Oxide Nanoparticles reduces the heat losses i.e the heat losses nearly halves at 700℃ upon inclusion of the Transparent Conducting Oxide Nanoparticles. Because of addition of transparent conducting oxide nanoparticles in the required aerogel the extinction coefficient in the solar region becomes smaller and the extinction coefficient in the infrared region becomes larger due to this reason the heat losses get reduced.

Zhao et al. [2] investigated a solar thermal system with low scattering aerogel in the non evacuated closed container. A very small copper sheet of diameter of 120 mm covered by the high temperature black paint is made as blackbody absorber. The aerogel was made in the form of disk having diameter equal to the diameter of the thin copper sheet and having a thickness of 10 mm. An unconcentrated solar flux of 1000 W/m^2 was incident on the model in the beam down configuration. As incident light falls on the model the temperature of intended or required reciever plate increased reaching a value of over 200℃ in 25 minutes and then attaining a steady state value of 200℃. A low scattering aerogel medium having a thickness like 40 mm was also tested and it was found that in case of 40 mm thick aerogel layer intended plate or receiver plate will attain steady state value of 265℃. This temperature is about 100℃ greater than those temperatures achieved in case of solar receiver having non optimal silica aerogel and is in the comparable range with the value of temperature achieved in case of solar receivers with sophisticated vacuum enclosures.

Zhao et al. [3] have done analysis for analyzing dependence of haze and total transmittance with aerogel physical properties. The effect of intrinsic properties of the aerogel like mean particle radius and density on the haze and the total transmittance has been studied and investigated. A thickness of 5 mm aerogel layer has been taken to analyze the variation of haze and total transmittance with respect to both mean particle radius and density. The haze increases to a value higher than 50 percent when the mean particle radius reaches10nm. Effect of aerogel thickness on haze and the total transmittance has also been studied and considered and for this case the density of aerogel being taken as 200 kg/m^3 and it was seen that there is a strong dependence between thickness and haze, total transmittance at a larger value of mean particle radius. At high value of mean particle radius the relationship between aerogel thickness on the haze and the total transmittance was significant. This refers to conclusion that for a given value of thickness variability smaller particle size should be used to obtain good quality of aerogels.

Lari et al. [4] have conducted numerical analysis of effect of radiative heat transfer on free convection heat interaction within a square container operating in standard room condition. This model considered for analysis is a square container of whom both above and below surfaces are insulated with having an emissivity of 1, left side wall of a square cavity is having a temperature of 310K and emissivity as 1 and right surface inside a square container having a temperature of 290K and emissivity of 1. A gas having a Prandtl number of 0.717 is filled inside this square cavity and the thermophysical properties of the gas is taken at an average temperature of 300K. It was seen that for case of optical depth having no value or in a transparent medium, radiation method of heat interaction being most effective method of heat interaction but when the optical thickness keeps on increasing the radiation method of heat interaction starts reducing and the convection mode of heat transfer will be more significant or effective and it continues until the condition of pure convection is achieved.

Bhore et al. [5] have done a numerical investigation on natural convection inside a cube having sub-atmospheric pressure. For this analysis a square cavity of 50*50mm was taken whose above and below walls being completely isolated from exchanging heat, left surface having temperature of 313K and right surface having temperature of 293K. A 2-dimensional square model is considered as temperature change along third dimension is not expected. In this analysis Boussinesq approximation is considered to show the density dependence on the temperature which causes buoyancy effects and thus causes the flow to occur. 5 different points in the model has been created and temperature at these 5 points are recorded at the completion of each case. It was found that when the air pressure inside the square container is reduced the interaction of heat transfer by bulk motion decreases and at a very low pressure of air inside square container heat interaction is mainly due to conduction.

E. Fuad Kent [6] has conducted analysis numerically on streamline natural heat interaction for model having cross section of triangle which is having a base at lower temperature and the remaining two surfaces at higher temperature. Effect of changing the angle of the bottom surface from the horizontal has been taken and analyzed when Rayleigh number is changed from 1000 to 100000. It was found that in all the cases of Rayleigh number considered for analysis major mode of heat transfer is conduction only or only conduction is found is to be dominant mode of interaction of heat. As angle of bottom plate decreases then bottom surface and the other two walls come close to each other and results in more turbulence and therefore more transfer of heat occurs.

Lee et al. [7] have done analysis through experimentation to analyze free convection in laminar flow inside a model which is in the form of a square having some source of energy embedded into it and this square model is at some angle from the horizontal which are varied as 0, 15, 30 and 45 degrees when the Rayleigh number is considered as 10000 to 150000. When the angle of the square model from the horizontal are 0 and 15 degrees then two values of temperature achieved inside medium one being maximum and other is minimum and two values of temperature gradient achieved within the fluid one is maximum and other is minimum. When the angle of the square enclosure with the horizontal are 30 and 45 degrees there is one value of maximum temperature and one value of temperature difference which being maximum that is obtained inside medium. As angle of the square enclosure from the horizontal increases the value of heat transfer coefficient increases along rightside wall and at bottomside surface and value of heat transfer coefficient falls along leftside wall and value of heat transfer coefficient do not change at the topside surface.

Kaluri et al. [8] have done analysis on the free convection inside a triangular model which is a triangle having one of its angle as 90 degree. The angle at the topmost vertex is taken as 15, 30 and 45 degrees and different types of heating has been done and considered for analysis. When the angle at the abovemost vertex is increased the turbulence in the triangular model increases which results in high value of heat transfer coefficient and also heat interaction at topmost point reduces if the angle at the above most vertex is increased. The fluid is easily or more tending to gain heat if the heating is done along right surface wall of triangular model as comparision to the situation when the heating is done at the left side of the triangular model.

Deshmukh et al. [9] have conducted an analysis on the free convection in the 2-D rectangular model having some source of energy generation which is a uniform source and all the bounding four surfaces are at a given value of temperature. Angle of inclination of rectangular model with the bottom surface is considered and its effect is also studied , variation of fluid properties effect has also been taken into consideration and effect of ratio of length to thickness of the rectangular model has also been taken into account for Rayleigh number value upto 1000000. Longer models which are having the ratio of length to thickness greater than unity the state of solution becomes independent of all the Rayleigh number considered i.e steady for all conditions. For broad models which are having the value of ratio of length to thickness of the model less than 1 fluctuating and periodic pattern is achieved. By increasing the inclination angle the fluctuating and periodic pattern starts reducing and when the angle of the rectangular model with the horizontal reaches 15 degrees steady state condition being achieved for complete values of the Rayleigh numbers.

Wolff et al. [10] have conducted an analysis on free convection mode of heat transfer and movement of fluid in vertical models which are filled with liquid metals. The test was done in two different tubes which are having its two opposite sides at some values of temperature but both temperatures being different and the other surfaces as insulated. The movement of the fluid in the model was seen such that there was a high value of convection at the centre or the movement of the fluid was very high at the center whereas there was very less movement or very less flow of the fluid at the corners.

Ratzel et al. [11] have done analysis both analytically and experimentally to know about conductive and convection heat losses in circular geometries. It was found out that for decreasing the heat losses by conduction the reduction in the pressure of the gas considered in the circular geometry has to be done so reducing the pressure of the gas inside the circular geometry considered will reduce the heat losses by conduction. For any particular geometry taken the total losses of heat has been reduced to ten to fifty percent by using this technique. The temperature differences or non uniformity of the temperatures can be used to effect free mode of energy interaction and misalignment in circular geometries with respect to one another can also be used to enhance the bulk motion of the gas resulting in more natural convection heat transfer.

Flack et al. [12] have analyzed a triangle container whose sides are heated up and cooled up on the opposite sides and the base of the triangle is insulated or net heat flux through the bottom or base of the triangle is zero. When the base or bottom surface of the triangular enclosure is cool or less in temperature and the other two walls of the triangular enclosure are heated up or low in temperature the different fluid layers in the flow are not intermixing with each other or the flow is very streamlined and moves in a particular way or pattern or in other words the turbulence in the flow is very low or less resulting in lower natural convection heat transfer rates thus indicates low or less losses of heat transfer due to convection.

Holtzman et al. [13] have done a study numerically for an triangular enclosure which is an isosceles triangle whose bottom surface is high in temperature and the other two surfaces are lower in temperatures. With the increment in Grashof number above a certain range separation occurs in which non mirror images are obtained. Convection mode of heat interaction coefficient along bottom wall will vary upto 550 percent because of the change in the location of the grids of convection but overall on below wall variation in convective mode of heat interaction coefficient does not change above 5 percent.

Akinsete et al. [14] have studied free convection heat interaction in right angled triangle type of container. It has been found out that the most portion of the total energy interaction happens at bottom surface of triangular geometry as it takes place at a common point of intersection of the bottom wall of a triangular geometry and at a longest side of the triangular geometry. This implies that there is more turbulence or convection heat transfer coefficient is high or large in a meeting point of a below wall and a longest side in a triangular geometry which results in more amount of heat transfer or more heat losses in the region of meeting point of the bottom surface and the longest side of the triangular geometry.

Kim et al. [15] have analyzed the mode of heat transfer by radiation by using the S-N Discrete Ordinates method in a non gray gases. In this model of analyzing the radiation heat transfer a band of wavelength ranges were considered which will define the radiative source term in different wavelength bands. It was found out that the time required for finding out the solution for the non gray gases is more as compared to the gray gases. So it was prescribed to use the gray gases model for finding out the solution but the accuracy in the gray gases model is lost as compared to the accuracy in the non gray gases model.

Michael F. Modest [16] have analyzed the different models to model the heat transfer by radiation since radiation is a very complicated phenomenon so different types of models were developed in the past and the study of the newest models were discussed. In the fully spectral k-distribution model in radiation way of energy interaction the wavelength bands were considered to be very close to each other or in other words the range of the wavelength bands considered in this analysis were very small or very close. The absorption coefficient of the medium in all of these wavelength bands is considered to increase with the increase in the wavelength or in other words the absorption coefficient is considered to be an increasing function with the increase in the wavelength.

Zhou et al. [17] have studied an impact of distribution of a absorption coefficients in a different wavelength bands by using new techniques like taking an impact of temperature and a mole fractional of these gases are considered. It was found out that this technique of distribution of the absorption coefficients in the different wavelength bands and also considering an impact of the temperature and a mole fractional in these gases helps at reducing these errors in the model considered of using only single value of the absorption coefficient in the wavelength band or in other words only one value of the wavelength band region is considered.

Wang et al. [18] have made this model for analyzing and for studying a radiation heat transfer within the non laminar flow or the flow whose bulk motion is not so streamlined in which the flow particles are intermixing with each other or in that flow in which different fluid layers are mixing with each other or the flow is turbulent. In this study a spacial geometry was considered for analysis and the fully spectral k distribution model was taken in a study related to non gray gases. It was concluded that the non gray model of soot taken is significantly of more use than the non gray modelling of gas in the flames of soot. The modelling of soot using non gray model have higher accuracy as compared to the modelling of the gases using the non gray model.

W.C Wang [19] has developed a formula for finding out the total absorptance of the lower temperature gases which are exchanging heat due to the radiation i.e for the gases in the infrared region how much is the value of the absorptance in a given band and the formula of total absorptance in the given band is found out by using the Malkmus model of narrow band and also the large band estimation given by Edwards and Menard was also taken. The analysis of the new model considered or taken for study as mentioned in the previous few lines was also compared with other formulas or expressions which were already developed.

Bharadwaj et al. [20] have analyzed and given readings regarding a low range of wavelength bands considered for the 2.0, 2.7 and 4.3 µm bands taken for carbon dioxide at 1550K. The readings at 15 µm band for carbon dioxide was also considered or taken for analysis. The readings obtained in this updated model has low errors or have more stability at very high temperatures with respect to early readings taken for consideration. It is due to a reason that there was some problem in the previous readings which was due to the attenuation of the signal of emission which was happening in the previous readings taken which is not the case in this new setup .

CHAPTER 3

THEORETICAL MODELLING

3.1 OVERVIEW

In this study ANSYS FLUENT 24 version has been used to conduct the analysis on the Optical Transparent Insulating Materials. In this analysis different types of boundary conditions are imposed to see their effects on the Optical Transparent Insulating Materials.

Effects of parameters such as optical depth, thermal conductivity, emissivity, cut off wavelength and effect of heating the system from both top and bottom was seen and analyzed. Non Gray Radiation Model was considered for this analysis. In this analysis 2 types of Optical Transparent Insulating Materials were studied and analyzed these two being Carbon dioxide and Aerogel. But before that Fundamental Limits of Optical Transparent Insulating Materials were also studied and analyzed. In Fundamental Limits of Optical Transparent Insulating Materials, optimum conditions were studied and analyzed that in what situations the losses are minimum and efficiency is highest. In Fundamental Limits of Optical Transparent Insulating Materials also , Non Gray Radiation Model was considered for analysis, different bands of different wavelength ranges were considered for this analysis.

In Fundamental Limits of Optical Transparent Insulating Materials 2 different Bands of wavelength range was considered and in Carbon dioxide as OTIM 12 different bands of wavelength range was considered for analysis. Aerogel as OTIM is also taken and considered for analysis. Schematic diagram showing the model considered for Fundamental limits of TIM, Carbon dioxide as OTIM and Aerogel as OTIM are shown in the following section.

3.2 MODELS STUDY

3.2.1 Fundamental Limits of TIM:

i Top Heating:

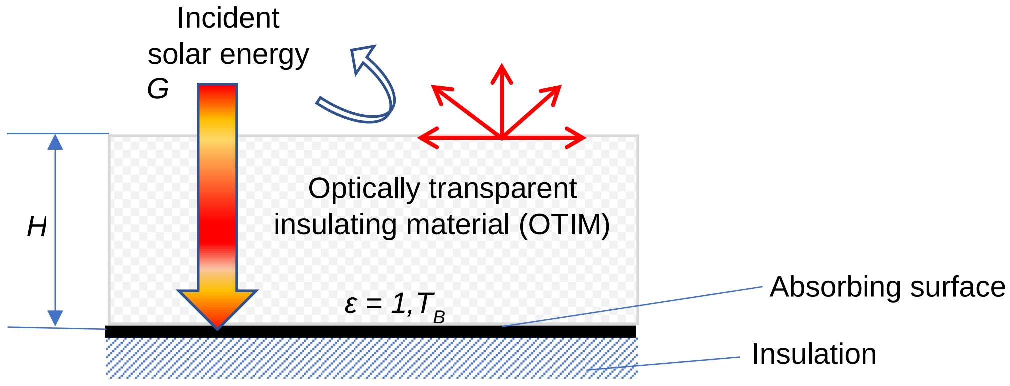


Fig. 1 Schematic of the model studied for top heating

Table 2. Details of the Model studied for top heating in Fundamental limits of TIM

DIMENSIONS	Thickness variable 5,10,20,30 mm	Length fixed 100mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BANDS (3 sets of bands are considered)	I) 0-1.5 µm II) 1.5-100 µm	I) 0-2 µm II) 2-100 µm	I) 0-2.5 µm II) 2.5-100 µm	
THERMOPHYSICAL PROPERTIES	Density: Boussinesq approx	Thermal Conductivity: k = 0.01, 0.1, 1 W/mK	Specific Heat: 1007 J/ kg K	
Optical Depth in Solar Region	0			
Optical Depth in Infrared Region	0, 1, 10, 100, 1000			
BOUNDARY CONDITIONS	Top Wall 1) Mixed BC: i) h = 10 ii) T_{amb} = 300K iii) T_{sky} = 300K 2) Semitransparent: Incident beam direction normal to top wall	Bottom Wall 1. Insulated 2. ε_{IR} : i) ε_{IR} = 1(in band 0) ii) ε_{IR} = 0.1,0.5,1 (in band 1) (variable)	Left Wall 1. Insulated 2. ε_{IR} : ε_{IR} = 0 (in both bands)	Right Wall 1. Insulated 2. ε_{IR} : ε_{IR} = 0 (in both bands)
BASE VALUES	For thickness (H) vary: i) k = 0.01 W/mK ii) λ_{cutoff}= 2.5 µm iii) ε_{IR} (in band 1) = 1	For Bottom Wall emiss ε_{IR} vary in band 1: i) k = 0.01 W/mK ii) λ_{cutoff} = 2.5 µm iii) thickness = 10 mm	For λ_{cutoff} vary: i) k = 0.01 ii) H = 10 mm ii ε_{IR} (in band 1) = 1	For k vary: i) λ_{cutoff} = 2.5µm ii) H = 10mm iii) ε_{IR} (in band 1) = 1
GEOMETRY	Rectangular			

ii Bottom Heating:

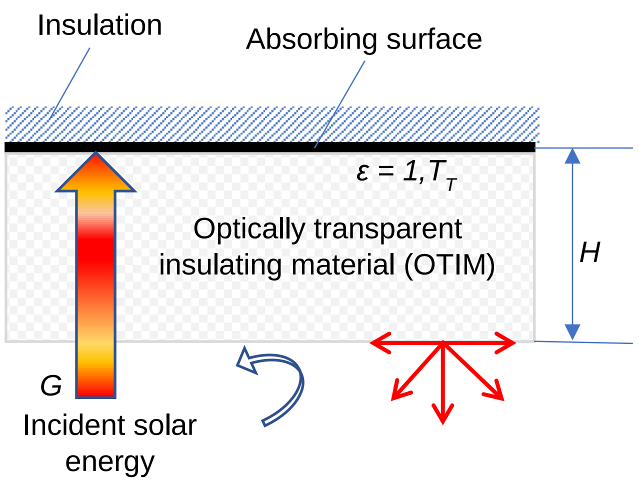


Fig. 2 Schematic of the model studied for Bottom Heating

In case of bottom heating a solar radiation is being striked on to bottom surface and because of this the energy will then travel through that medium and after travelling through the medium the energy will then be absorbed by the absorber or receiver plate which is now on the topmost location and due to this the top plate will be heated up in consideration of above heating a below plate will be heated up and in consideration of below heating an above plate will be heated up. In the above figure the top plate which is getting heated up in case of bottom heating is assumed to be having an emissivity of 1 or it is assumed to be black. Bottom heating case is analyzed with respect to the different parameters like the thickness, emissivity of the receiver surface, thermal conductivity of the medium and the cut off wavelength. In this model limits of an optically transparent insulating material has been checked and analyzed with respect to the different parameters of the medium and also with respect to the geometrical parameters of the model taken for analysis. Bottom heating is also an essential type of heating since in case of bottom heating the air at the top surface will get stuck and due to this the air cannot flow upward so there will be no bulk motion of the fluid and due to the absence of the bulk motion of the fluid there will be no convection currents in the fluid and there will be negligible convection or no convection inside the medium which results in only conduction and radiation happening through the top surface of the model taken for analysis.

Table 3. Details of the Model studied for bottom heating in Fundamental Limits of TIM

GEOMETRY	Rectangular			
DIMENSIONS	Thickness variable 5, 10, 20, 30 mm	Length fixed 100 mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BANDS (3 sets of wavelength bands are considered)	I) 0-1.5 µm II) 1.5-100 µm	I) 0-2 µm II) 2-100 µm	I) 0-2.5 µm II) 2.5-100 µm	
THERMOPHYSICAL PROPERTIES	Density: Bousinessq approx	Thermal Conductivity: k = 0.01,0.1,1 W/mK	Specific Heat: 1007 J/kg K	
OPTICAL DEPTH IN SOLAR REGION	0			
OPTICAL DEPTH IN INFRARED REGION	0, 1, 10, 100, 1000			
BOUNDARY CONDITIONS	Top Wall 1) Insulated 2) ε_{IR} : i ε_{IR} = 1(in band 0) ii ε_{IR} = 0.1,0.5,1 (in band 1) (variable)	Bottom Wall 1) Mixed BC: i) h = 10 ii) T_{amb} = 300K iii) T_{sky} = 300K 2) Semitransparent: Incident beam direction normal to the wall	Left Wall 1) Insulated 2) ε_{IR} : ε_{IR} = 0 (in both bands)	Right Wall 1) Insulated 2) ε_{IR} : ε_{IR} = 0 (in both bands
BASE VALUES	For thickness vary: i k = 0.01 W/m K ii λ_{cutoff} = 2.5 µm iii ε_{IR} in band 1 = 1	For Bottom Wall Emissivity ε_{IR} vary in band 1: i. k = 0.01 W/mK ii λ_{cutoff} = 2.5 µm iii thickness=10 mm	For λ_{cutoff} vary: i k=0.01 W/m K ii thickness=10mm iii ε_{IR} in band1 =1	For k vary: i λ_{cutoff} =2.5µm ii thickness=10 mm iii ε_{IR} in band 1= 1

3.2.2 Carbon dioxide Model:

For Carbon dioxide Model both the top heating and bottom heating were considered and analyzed and 11 bands of wavelength were taken for analysis. In this model effect of both type of heating i.e bottom and top as well as an impact of varying a thickness in a model were also considered and analyzed. The schematic indicating the Carbon dioxide Model has been shown below.

I Top Heating:

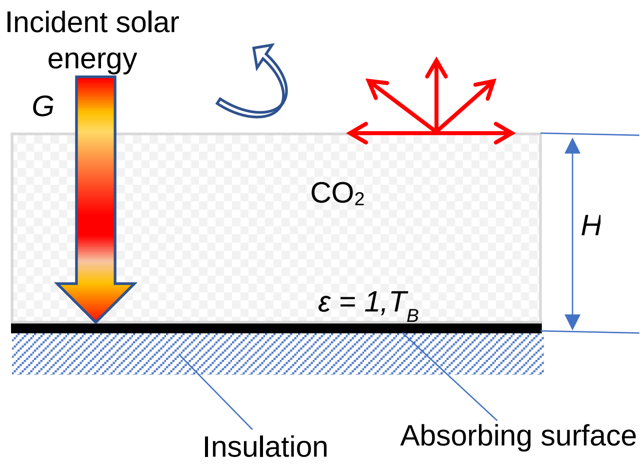


Fig. 3 Schematic of the model considered for top heating in Carbon dioxide type Aerogel

In this model carbon dioxide is taken as a medium and analysis on the carbon dioxide is done for the case of the top heating and and the temperature of the receiver surface is analyzed with respect to the thickness of the medium considered for analysis. Carbon dioxide is tested as a medium for finding its efficiency by calculating the temperature of the receiver surface. In this receiver surface is considered to be black and insulated having an emissivity of 1 left and right side walls are considered to be insulated and having an emissivity of zero top surface is taken to be semi transparent but in the carbon dioxide model 15 bands of wavelength are considered for analysis.

Table 4. Details of the Model considered for top heating in the Carbon dioxide Model

GEOMETRY	Rectangular			
DIMENSIONS	Thickness variable 5, 10, 20, 30, 40, 50, 100 mm	Length fixed 100 mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BANDS	11 bands of wavelength are taken			
THERMOPHYSICAL PROPERTIES	Density: Bousinessq approx	Thermal Conductivity:	Specific Heat:	
BOUNDARY CONDITIONS	Top Wall: 1) Mixed BC: i) h = 10 ii) T_{amb} = 300K iii) T_{sky} = 300K 2) Semitransparent: Incident beam direction normal to the wall	Bottom Wall: 1) Insulated 2) ε = 1 (in all bands)	Left Wall: 1) Insulated 2) ε = 0 (in all bands)	Right Wall: 1) Insulated 2) ε = 0 (in all bands)

ii Bottom Heating:

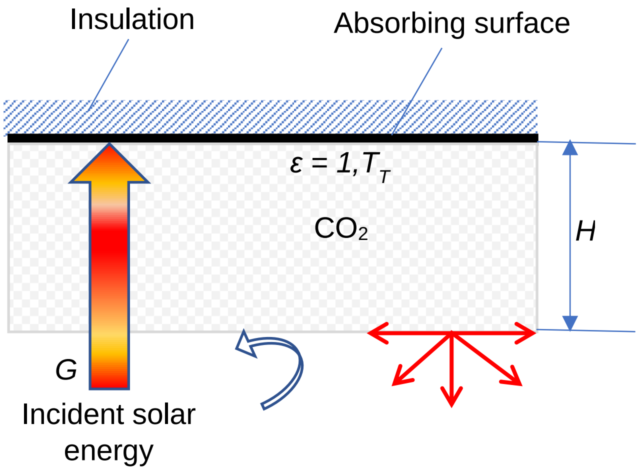


Fig. 4 Schematic of the model considered for the case of bottom heating in Carbon dioxide Aerogel

In this model of taking carbon dioxide as medium the model is heated from the bottom and its effect on receiver surface temperature is taken or considered for analysis since in this case it is heated from the bottom so the same effect of convection will be negligible or absent in this case also so only conduction and radiation will be predominant in this case and its effect of both conduction and radiation will be taken or considered on the temperature of the receiver surface attained and the effect of the thickness of the medium of the carbon dioxide is also considered on the receiver surface temperature for the case of bottom heating. In case of bottom heating the energy or solar radiation will be falling on to the bottom surface in the normal direction and the bottom surface is taken to be semi transparent, left and right side walls are well insulated both having an emissivity of zero and the top surface is taken to be well insulated and having an emissivity of 1 or top surface is also taken as black surface and in this case of bottom heating also 15 bands of wavelength are considered or taken for analysis.

Table 5. Details of the Model considered for bottom heating in the Carbon dioxide Model

GEOMETRY	Rectangular			
DIMENSIONS	Thickness variable 5, 10, 20, 30, 40, 50, 100 mm	Length fixed 100 mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BANDS	11 bands of wavelength are taken			
THERMOPHYSICAL PROPERTIES	Density: Bousinessq approx	Thermal Conductivity:	Specific Heat:	
BOUNDARY CONDITIONS	Top Wall: 1 Insulated 2 ε = 1 in all bands	Bottom Wall: 1 Mixed BC: i h = 10 ii T_{amb} = 300K iii T_{sky} = 300K 2 Semitransparent: Incident beam direction normal to the wall	Left Wall: 1 Insulated 2 ε = 0 in all bands	Right Wall: 1 Insulated 2 ε = 0 in all bands

3.2.3 Aerogel Model:

In the aerogel model two type of analysis have been done one is calculating the transmittance of the aerogel medium in a case when we consider only 2 bands of wavelength and in a same case we also calculate a temperature of an intended or receiver surface taking or considering these same 2 bands of wavelength.

I) Model studied for calculating Transmittance of the Aerogel Medium (By taking 2 bands of wavelength):

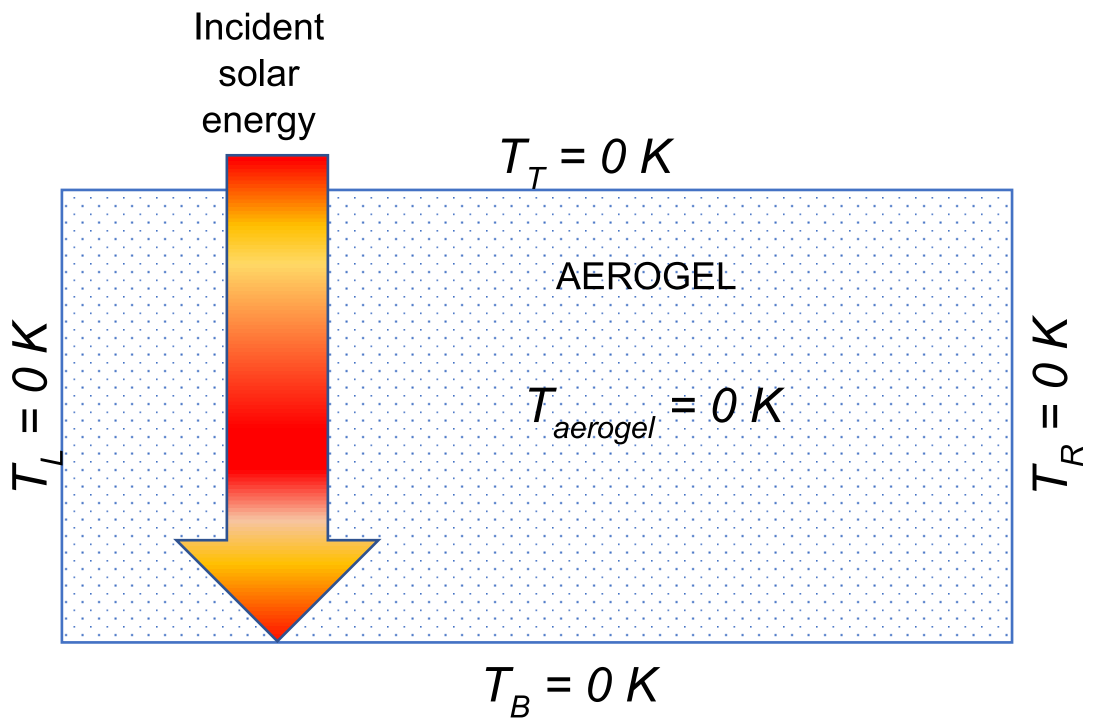


Fig. 5 Schematic of the model studied for calculating the total transmittance of the Aerogel medium

The above model is so chosen that the geometry surfaces does not emit any energy or radiation so that the solar radiation neither gets amplified nor get reduced in its value and the medium which is taken as an aerogel also does not absorb any sun radiation which leads to the fact that the aerogel medium itself does not participate in reduction or amplification of the solar energy so that the sun radiation remains undisturbed when passing by both the surfaces of the model or geometry and also by the aerogel medium itself.

Table 6. Details of the Model studied for calculating the Transmittance of the Aerogel

GEOMETRY	Rectangular			
DIMENSIONS	Thickness fixed 5 mm	Length fixed 100 mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BAND TAKEN	0- 2.5 μm 2.51-100 μm			
THERMOPHYSICAL PROPERTIES	Density 220 kg/m^3	Specific Heat 850 J/kg K	Thermal Conductivity 0.020 W/m K	
OPTICAL DEPTH IN INFRARED REGION	0 (fixed)			
OPTICAL DEPTH IN SOLAR REGION	0, 0.1, 0.2, 0.4, 0.6, 0.8, 1 (variable)			
C	0, 1, -1 (variable)			
ω	0, 0.5, 1 (variable)			
BOUNDARY CONDITIONS	Top Wall i) Temperature=0K ii) Semitransparent: 1000 W/m^2 incident beam direction normal to the top wall	Bottom Wall i) Temperature= 0K ii) Semitransparent	Left Wall i) Temperature = 0K ii)ε =0 (in all bands)	Right Wall i) Temperature=0K ii)ε =0 (in all bands)

II) Model studied for calculating Temperature of the absorber plate (By taking 2 bands of wavelength):

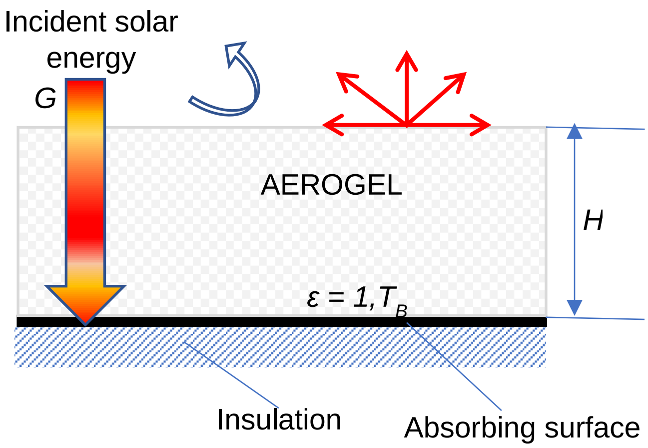


Fig. 6 Schematic of the model studied for calculating the temperature of the absorber plate

In this model the bottom surface is considered to be insulated or absorbing surface which is having an emissivity of 1 and it is considered to be black surface when it is top heated. Different values of the optical depth in the solar region have been taken and seen its effect on the absorber plate temperature, effect of thickness has also been taken and considered for analysis. When the incident radiation is falling from the top surface then bottom surface will get heated up and will attain a rise in its temperature. This rise in the temperature of the bottom surface will be seen as the effectiveness of the medium considered as an aerogel because if the aerogel transmits more solar energy to the receiver surface then the efficiency of an aerogel is considered to be good or the solar system is also considered to be of good efficiency. The left and right side of the geometry are insulated and having an emissivity of zero and the top surface of this geometry is taken as semitransparent on which the incident radiation direction is normal to the top surface and mixed boundary condition of convection and radiation also exists at the top surface of the model taken for analysis because the solar energy after passing through an aerogel medium will reach to the receiver surface and then the energy will get transmitted through the top surface by both the means of convection and radiation to the sorroundings.

Table 7. Details of the Model studied for calculating the temperature of the absorber plate

GEOMETRY	Rectangular			
DIMENSIONS	Thickness (variable) 10, 20, 30, 50	Length (fixed) 100 mm		
MESHING METHOD	Refinement- 3			
RADIATION MODEL	DO Radiation Model			
WAVELENGTH BAND TAKEN	0 -2.5 μm 2.51- 100 μm			
THERMOPHYSICAL PROPERTIES	Density 220 kg/m^3	Specific Heat 850 J/kg K	Thermal Conductivity 0.020 W/m K	
OPTICAL DEPTH IN INFRARED REGION	0, 1, 10, 100 (variable)			
OPTICAL DEPTH IN SOLAR REGION	0, 0.1, 0.2, 0.4, 0.6, 0.8, 1 (variable)			
C	0, 1, -1 (variable)			
ω	0, 1 (variable)			
BOUNDARY CONDITIONS	Top Wall: 1) Mixed BC i) h = 10 W/m^2 K ii) $T_{sky} = T_{amb}$ = 300 K 2) Semitransparent i) 1000 W/m^2 incident normal to the top wall	Bottom Wall: 1) Insulated 2) ε =1 (in all bands)	Left Wall: 1) Insulated 2) ε = 0 (in all bands)	Right Wall: 1) Insulated 2) ε = 0 (in all bands)

CHAPTER 4

NUMERICAL MODELLING

4.1 EQUATIONS USED FOR FINDING THE SOLUTION

The fundamental equations used in solving a problem are written below:

1. $\frac{\partial(\rho\upsilon)}{\partial t} + \nabla.(\rho\upsilon\upsilon) = -\nabla\mathrm{p} + \nabla.(\tau) + \rho g + F$ (1)

2. $\frac{\partial(\rho E)}{\partial t} + \nabla.(\upsilon\rho E + \upsilon\rho) = \nabla.\left(k_{eff}\nabla T - \sum_j h_j J_j + \tau_{eff.}\upsilon\right) + S_h$ (2)

3. $\frac{\partial I(r,s)}{\partial s} + (\alpha + \sigma_s)I(r,s) = \frac{\alpha n^2 \sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(r,s')\,\varphi(s,s')\,d\Omega'$ (3)

Equations (1), (2) and (3) represents the general form of Momentum, Energy and DO Radiation Model equation respectively. These 3 equations above are used by the CFD Ansys Fluent Software for finding out the planar temperature distribution and also for finding out the planar velocity distribution. An additional equation is also solved by the CFD Ansys Fluent Software which is DO Radiation Model equation which specifically is related to the problem of Radiation since in our analysis we have chosen DO Radiation Model for radiation analysis so equation (3) is used for that purpose which itself is the most general form of the Radiative Transfer Equation (RTE). These above three equations when solved simultaneously will provide the temperature distribution, velocity distribution and also the distribution of the radiative energy flux on the different surfaces present in the geometry of the model taken for analysis. DO Radiation model uses equation 3 for calculating radiative heat fluxes since it is the most general form of equation this can be used for any type of problem. To solve this equation different directions are considered and taken in the azimuthal plane and in the vertical plane or in other words angle of the spherical geometry are taken and considered for analysis and different number of discretization of these angles are taken in the azimuthal and the vertical plane. More will be the number of angles taken in the azimuthal plane and in the vertical plane more computational time will be required for processing.

4.2 METHOD USED FOR DISCRETIZATION OF EQUATIONS

In the previous section a fundamental expressions used in the CFD Ansys Fluent Software were introduced. Since these governing equations which are used by the CFD Ansys Fluent Software are non linear partial differential equations so a particular method is used to discretize these governing equations. A particular method or scheme is used to solve these fundamental non linear partial differential equations i.e a particular method of discretizing these governing equations is used. For finding out the solution of momentum and energy equation second order upwind scheme of discretization has been taken whereas for solving a Discrete Ordinates (DO) Radiation Model equation first order upwind scheme of discretization has been implemented. Second order upwind scheme is more accurate than the first order upwind scheme since the second order upwind scheme is have second degree of accuracy while the first order upwind scheme is having degree of accuracy as one. In upwind scheme in whichever direction the fluid is moving or flowing the properties of the upstream point in the cell is taken as the property of the required point since in this software the required properties are always calculated at the center of the cell taken or considered for analysis so to calculate the required property at any point in the cell we will take the value of the property at the required point to be same value of the property which is present in the upstream direction or in the upstream cell. Upstream cell in the software refers to that cell in the domain at which the flow will go when it moves in its own direction and the value of the required properties will be same value as the value of the property which is at the upstream cell so in case of first order upwind scheme only order of accuracy is present whereas in the case of second order upwind scheme second order of accuracy will be present which leads to better convergence. So in this section I have discussed the various methods or schemes used in the discretization of the fundamental or governing equations used for solving the problem or for doing the analysis.

CHAPTER 5

THEORETICAL RESULTS

5.1 INTRODUCTION

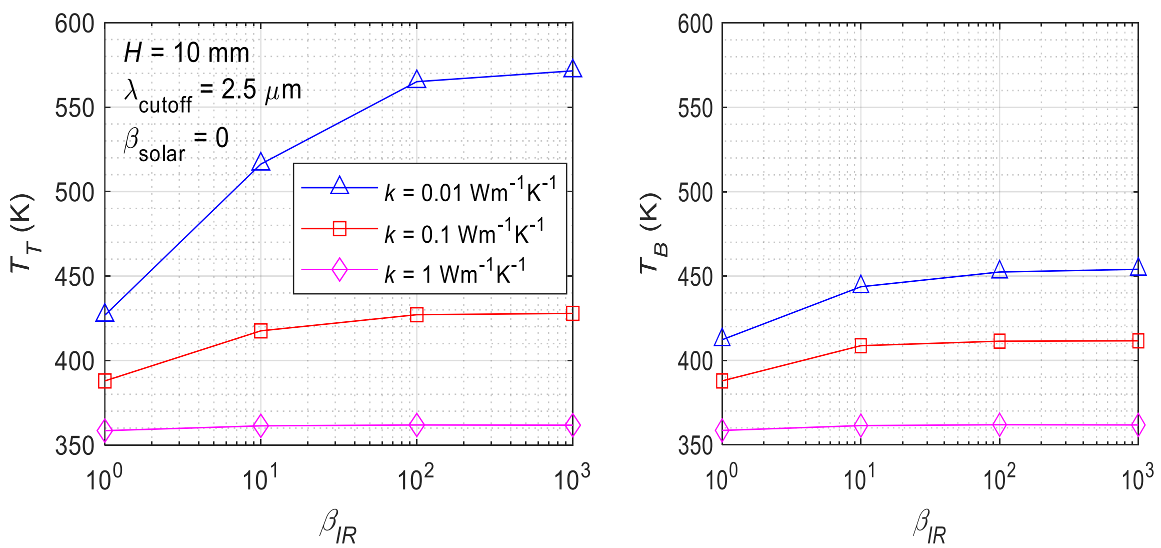
In present section the results of a Fundamental limits of TIM, CO_2 and the Aerogel model has been shown and discussed. The major objective of this analysis is to reduce these losses in the solar thermal system and to do this study various parameters or properties of the working medium has been altered to see the impact on its performance. In all the 3 models a certain amount of heat flux will be incident on the model and due to this heat flux incident on the model the absorber plate will get heated up and a certain steady state value of temperature will be attained and in this section variation of properties like Optical Depth, thermal conductivity, emissivity of the absorber plate, cut off wavelength (cow), thickness of the medium are considered and the effect of variation of all these parameters on the steady state value of temperature attained by the absorber plate has been considered or analyzed. By varying the Optical Depth how the Diffuse Transmittance is varying or effect of Optical Depth on the Diffuse Transmittance has also been considered. Both Optical and Thermal analysis has been done in this section. In this section basic idea has been given of what will be discussed in the result section of following models studied for analysis so effect of using carbon dioxide and using an aerogel as an Optically Transparent Insulating materials has been studied for analysis and its effect on the temperature of the receiver surface and on the optical properties of the medium like transmittance and haze has also been studied.

5.2 FUNDAMENTAL LIMITS OF TIM RESULTS DISCUSSION:

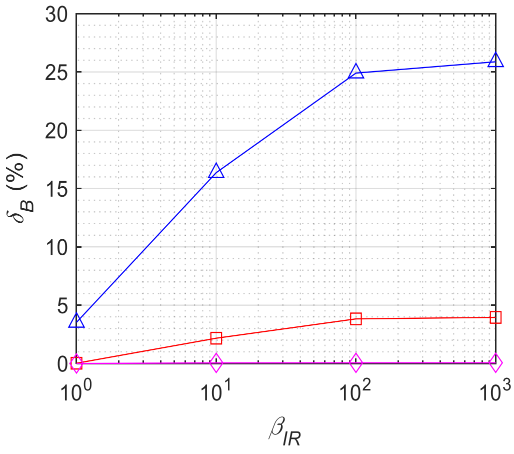
Table 8. Overview of the model studied in the Fundamental Limits of TIM

Length of the model	100 mm
Thickness or depth of the model	5, 10, 20, 30 mm (variable)
Type of Heating	i) Top Heating ii) Bottom Heating
Top Wall	Can be semitransparent or insulated depending upon top or bottom heating
Left and Right Wall	Insulated
Bottom Wall	Can be semitransparent or insulated depending upon top or bottom heating
Magnitude of Heat Flux incident	1000 W/m^2

5.2.1 EFFECT OF THERMAL CONDUCTIVITY OF MEDIUM:



(a) (b)

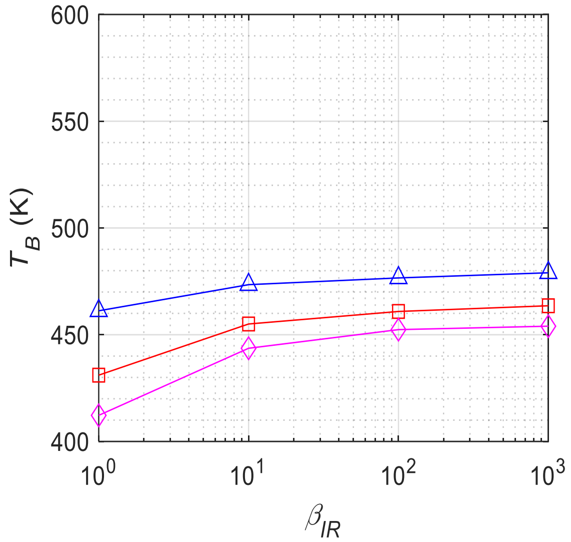


(c)

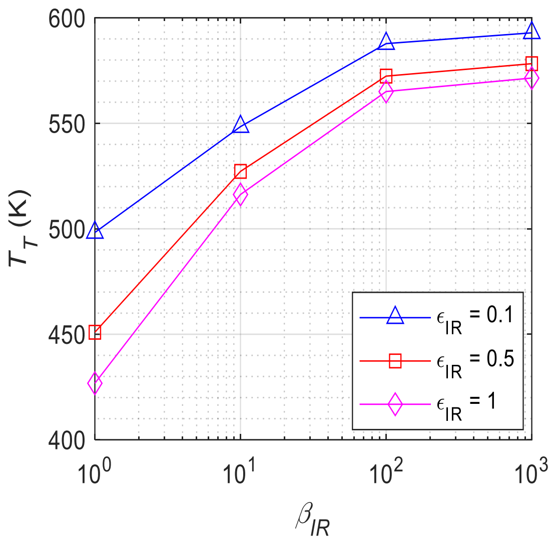
Fig. 7(a) Variation of absorber plate temperature with Optical depth in bottom heating case, (b) Variation of absorber plate temperature with Optical Depth in top heating case and (c) Percentage increase in absorber plate temperature for both top and bottom heating

In figure 7 (a) the variation of temperature for different thermal conductivities with respect to Optical Depth has been considered or analyzed in case of bottom heating. For any particular value of Optical Depth considered or taken if we increase a magnitude of thermal conductivity then these value of temperature of absorber or receiver plate tend to keep on reducing in both the cases of top and bottom heating, this is happening because if this magnitude of thermal conductivity is high or if we increase this magnitude of thermal conductivity then due to that heat loss by conduction will also increase and since the conduction losses are increasing if we increase this magnitude of thermal conductivity so a value of temperature of the absorber or receiver plate will also decrease by increasing thermal conductivity. Figure. 7(b) shows the case of top heating i.e how the temperature of absorber or receiver plate is varying for different thermal conductivities with respect to Optical Depth in case of top heating. From fig. 7(a) and fig. 7(b) we can say that the temperatures of the absorber or receiver plate achieved in case of bottom heating in most cases are higher than the temperatures achieved in case of top heating. The reason of achieving more temperatures in case of bottom heating as compared to top heating is that in top heating the effect convection also comes into play but in case of bottom heating the convection effect is not there, there are no convection currents in the bottom heating and due to this reason the temperatures achieved in case of bottom heating are more. For lesser values of an Optical thickness the temperatures achieved for case of top heating and bottom heating will nearly be equal there will not be very much difference between them, this is because at very low values of Optical Depth convection will almost be negligible in case of top heating case and in bottom heating case there is no convection at all values of the Optical thickness so in lower magnitude of Optical thickness top heating case and bottom heating cases are almost identical but during large values of an Optical thickness this convection becomes very dominant in case of top heating so at a higher magnitude of Optical thickness these top heating and bottom heating cases becomes different. If we keep on increasing this value of an Optical thickness of working medium in Infrared region for any particular value of thermal conductivity then the energy emitted by an intended or receiver surface would be absorbed more by this working medium and due to more absorption of energy by the working medium this temperature of an intended or receiver surface will keep as increasing if this value of optical depth in infrared region is increased.

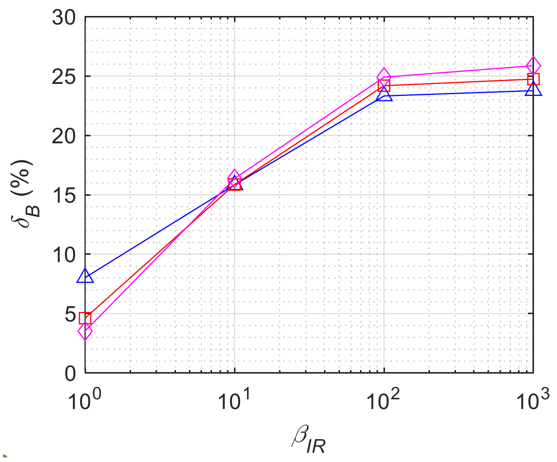
5.2.2 EFFECT OF EMISSIVITY OF THE ABSORBER PLATE:



(a)



(b)

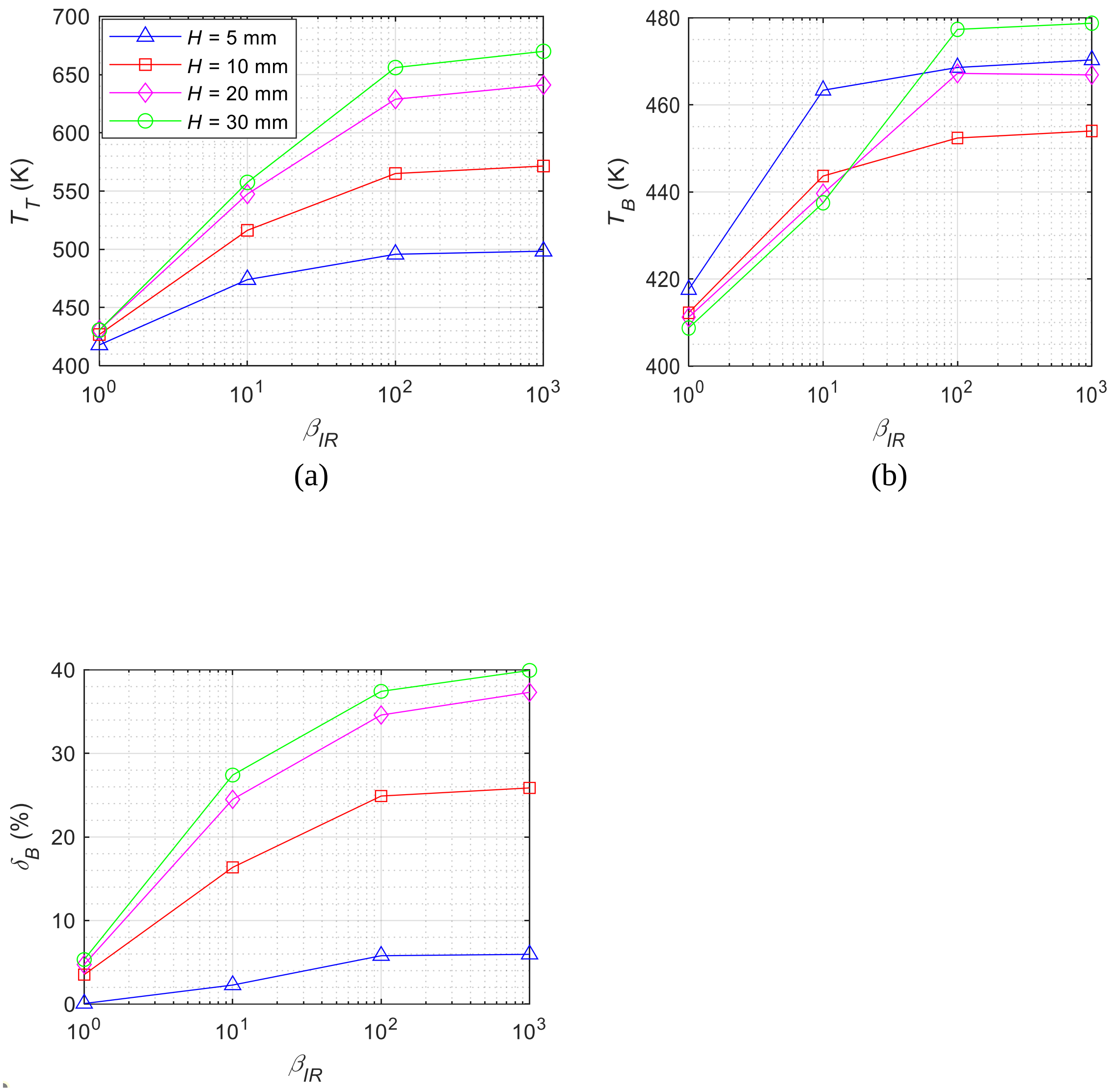


(c)

Fig. 8 (a) Variation of the absorber plate temperature with Optical Depth for different values of emissivity of absorber plate in the infrared region for top heating, (b) Variation of the absorber plate temperature for different values of emissivities for bottom heating and (c) Percentage increase in absorber plate temperature for both top and bottom heating

In fig. 8(a) the top heating case has been considered and shown and it is clear from the fig. 8(a) that if the Optical Depth in Infrared region is increased then the value of temperature of the absorber which is at the top in bottom heating case is also increased, the reason of rise in a temperature of an intended surface with rise with its optical depth is due to the fact that if this magnitude of an optical thickness under this infrared region is increased for any particular value of emissivity then the energy emission from the absorber plate which emits in the infrared region will not be easily escaping through that medium which results in trapping of that energy which is emitted by the absorber plate and by increasing the optical depth in the infrared region it means that an ability of a working substance to absorb this energy which is in an infrared region is increased and due to this increased tendacy of working substance to absorb more energy in an infrared region similar trend or pattern can be seen under the fig. 8(b) which indicates the case of the bottom heating. At any particular magnitude of an optical thickness in an infrared region if the value of the emissivity of the absorber in the infrared region is increased then the value of the energy emitted by the absorber will also be more and since more energy is being emitted by the absorber so due to this more energy will be lost from the absorber if the value of emissivity of the absorber in the infrared region is increased so due to this reason if the value of emissivity of the absorber in the infrared region is increased then the value of the losses from the absorber will also increase so due to increase of losses by increasing the value of emissivity the temperature of the absorber will be less or low in cases of higher value of emissivity and the temperature of the absorber will be high in cases of lower values of emissivity so due to this reason if the value of emissivity of the absorber plate in the infrared region is increased for any particular value of optical depth in infrared region then the value of the absorber plate will decrease in both the cases of top heating and bottom heating. The values of an intended plate temperatures attained under the case of bottom heating is higher than the value of the temperatures achieved in case of top heating, the reason of higher values of temperature of absorber plate in bottom heating as compared to top heating is that in case of bottom heating the convection are not there or negligible but in case of top heating the convection losses are also present and due to this additional convection losses in case of top heating the overall losses in case of top heating are more in comparision to the losses in the case of bottom heating so due to more overall losses in case of top heating the temperature of an intended surface attained under the case of top heating will be lower or lesser than the value of the temperature of an intended surface attained under case of bottom heating.

5.2.3 EFFECT OF THICKNESS OF THE MEDIUM:

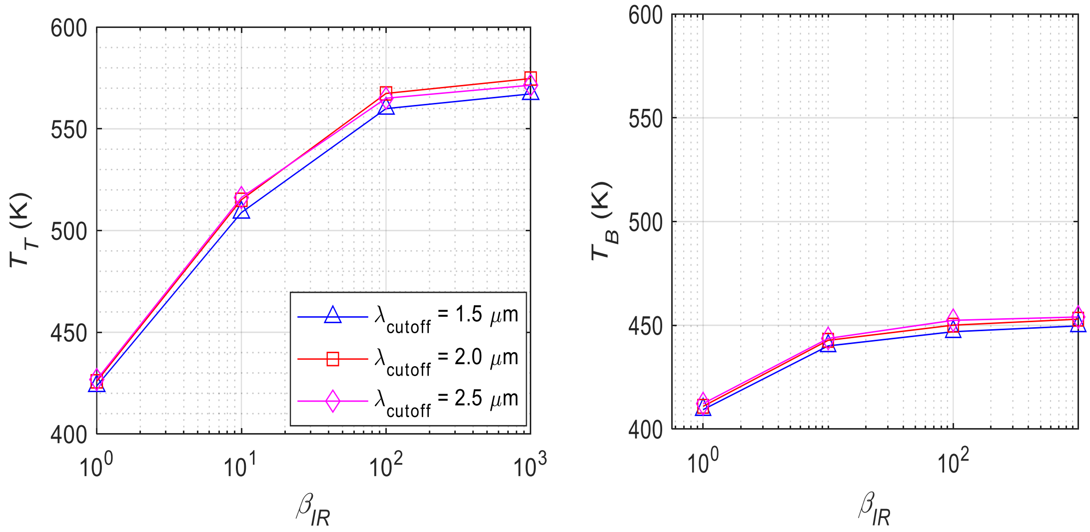


(c)

Fig. 9 (a) Variation of the temperature of the absorber plate with the optical depth for different values of thickness of the medium considered in bottom heating, (b) Variation of the absorber plate temperature for different values of thickness of the medium considered in top heating and (c) Percentage increase in absorber plate temperature for different values of thickness for both top and bottom heating

In fig. 9(a) the variation of a temperature of an intended or receiver surface has been shown w.r.t Optical Depth in an infrared region for various values of thickness of the medium considered in case of bottom heating. If the value of the optical depth increases for any particular value of the thickness of the medium considered then the temperature of the absorber plate will increase because of enhanced ability of the medium to absorb the radiation in the infrared region so due to this fact energy will get trapped inside the working medium resulting in lesser losses and hence more value of the temperatures achieved of the absorber plate so with increase of value of optical depth in infrared region the temperature of the absorber or receiver plate will also increase for any particular value of thickness of the medium considered. If the value of thickness of the medium considered is increased for any particular value of Optical Depth in the Infrared region then the temperature of the absorber plate also increases with increase in the thickness of the medium, the reason of this trend is that with increase in the thickness of the medium for both top heating and bottom heating cases is that the conduction losses reduce with increase in the thickness of the medium and since the conduction losses are inversely proportional to the thickness of the medium so when the thickness of the medium is increased the temperature gradient reduces so due to reduction in the temperature gradient the conduction heat loss also reduces so due to decrement of conduction losses with increase in thickness the temperature of the absorber plate also increases with increase in the thickness of the medium for both the cases of top heating and bottom heating. The value of temperature of absorber plate reached or attained in case of bottom heating is more than the temperature reached or attained in case of top heating the reason of more temperatures in case of bottom heating as compared to the case of top heating is that in case of bottom heating the top surface gets heated up due to the top surface being heated the air in contact with the top surface will then try to move up but it cannot move up because the top surface is just at the top of this air which will not allow the air to flow or move and due to this restriction in the movement of the air the convection currents will be absent or convection will be absent so in case of bottom heating the convection will be absent or convection losses will be absent but in case of top heating convection currents will be there and convection heat losses will be present and due to the presence of convection heat losses in case of top heating the overall losses in the case of top heating will be more as compared to bottom heating so due to more losses in top heating case less value of absorber plate temperature will be reached or attained as compared to bottom heating.

5.2.4 EFFECT OF CUT- OFF WAVELENGTH:



(a) (b)

Fig. 10 (a) Variation of the absorber plate temperature with optical depth for different values of cut off wavelength in top heating and (b) Variation of temperature of absorber plate temperature with optical depth for different values of cut off wavelength in bottom heating

As we can see from the fig. 10(a) in the case of top heating the value of the temperature of the bottom wall increases with increase in the value of the optical depth in the infrared region the reason for increase in the temperature of the bottom wall or absorber plate temperature is that with increase in the value of the optical depth in the infrared region the medium capacity to absorb the radiation or energy emitted by the bottom surface also increases which results in the trapping of the energy which is emitted by the bottom surface so due to this trapement of the energy emitted by the bottom surface the temperature of the absorber plate or temperature of the bottom surface also increases with increase in the value of the optical depth in the infrared region. The value of the absorber plate temperature or the bottom surface temperature increases with increase in the value of cut off wavelength. As the cut off wavelength is increased for any particular value of the optical depth in the infrared region considered or taken the amount of solar energy or solar radiation which will be getting incident on the bottom surface or the absorber plate will be high or more as compared to the amount of solar radiation or energy which will be getting incident on the absorber plate when the value of the cut off wavelength is low or less so due to this reason the temperature of the absorber plate increases with increase in the value of the cut off wavelength for both the cases of top heating and bottom heating taken or considered for analysis. The value of the temperatures attained of the absorber plate in case of bottom heating are significantly higher or more than the value of the temperatures of the absorber plate attained in case of top heating the reason for more value of temperatures of the absorber plate in case of bottom heating is due to the fact that in case of bottom heating there is no heat loss or there is no heat transfer due to convection or convection currents are negligible or absent in case of bottom heating so due to this reason the overall heat losses are low or less in bottom heating but in case of top heating the convection currents are also present or there is heat loss by convection so due to this reason the overall heat losses in case of top heating are more so therefore in case of bottom heating the value of the temperatures of the absorber plate attained or reached will be more or high as compared to the value of the temperatures of the absorber plate attained or reached in case of top heating.

Table 9. Incident Radiation in Solar region and in IR region for different values of cut off wavelength

Cut off Wavelength	1.5 µm	2 µm	2.5 µm
Incident Radiation in Solar Region	880.78 W/m^2	940.9868 W/m^2	966.34 W/m^2
Incident Radiation in IR Region	119.22 W/m^2	59.0132 W/m^2	33.56 W/m^2

5.3 CO_2 MODEL RESULTS DISCUSSION:

Length of Model	100 mm
Thickness of Model	5, 10, 20, 30, 40, 50, 100 mm (variable)
Type of Heating	i) Top Heating ii) Bottom Heating
Top Wall	Can be semitransparent or insulated depending upon top or bottom heating
Bottom Wall	Can be semitransparent or insulated depending upon top or bottom heating
Left and Right Wall	Insulated
Magnitude of Heat Flux	1000 W/m^2

Table 10. Details of the model considered for Carbon dioxide as an aerogel medium

5.3.1 EFFECT OF THICKNESS OF MEDIUM:

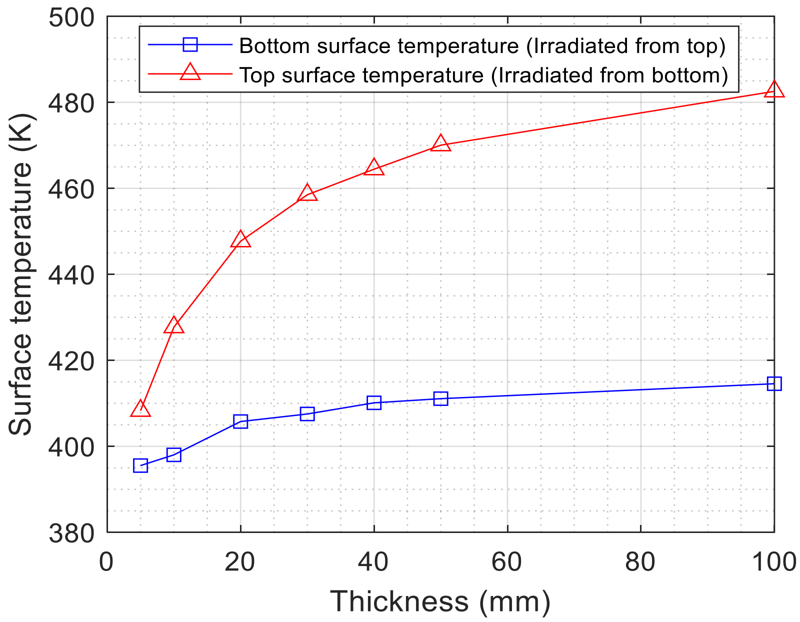


Fig. 11 Effect of thickness of the medium on the absorber plate temperature for both top and bottom heating cases

In the fig. 11 the variation of temperature of the absorber or receiver plate has been shown with the thickness of the medium for both the cases of bottom heating and top heating. We can see from the graph that if the thickness of the medium is increased then the value of temperature of the absorber or receiver plate is also increased for both top heating as well as for bottom heating. The reason of increase in temperature of absorber or receiver plate with increase in thickness is due to the fact that the Optical Depth in the solar region is kept zero and the value of absorption coefficient in the Infrared Region is kept constant having some finite value and if the absorption coefficient in the Infrared Region is kept constant and now if we increase the value of the thickness then the Optical Depth in the Infrared region will also increase since Optical Depth is the product of physical thickness and absorption coefficient so if the value absorption coefficient is same so on increasing the value of physical thickness the value of Optical Depth will also increase which results in increase of temperature of absorber or receiver plate with increase of thickness since Optical Depth is directly proportional to the physical thickness of the medium for constant absorption coefficient. Since in this model carbon dioxide is taken as an Optically Transparent Insulating material so we can see from the above graph that the thickness has a major impact on the receiver surface temperature in both the cases of top and bottom heating for carbon dioxide.

5.4 AEROGEL MODEL RESULTS DISCUSSION:

5.4.1 RESULTS FOR DIFFUSE INCIDENT RADIATION/ DIFFUSE INCIDENT SURFACE:

5.4.1.1 EFFECT OF DIFFERENT PARAMETERS ON ABSORBER TEMPERATURE:

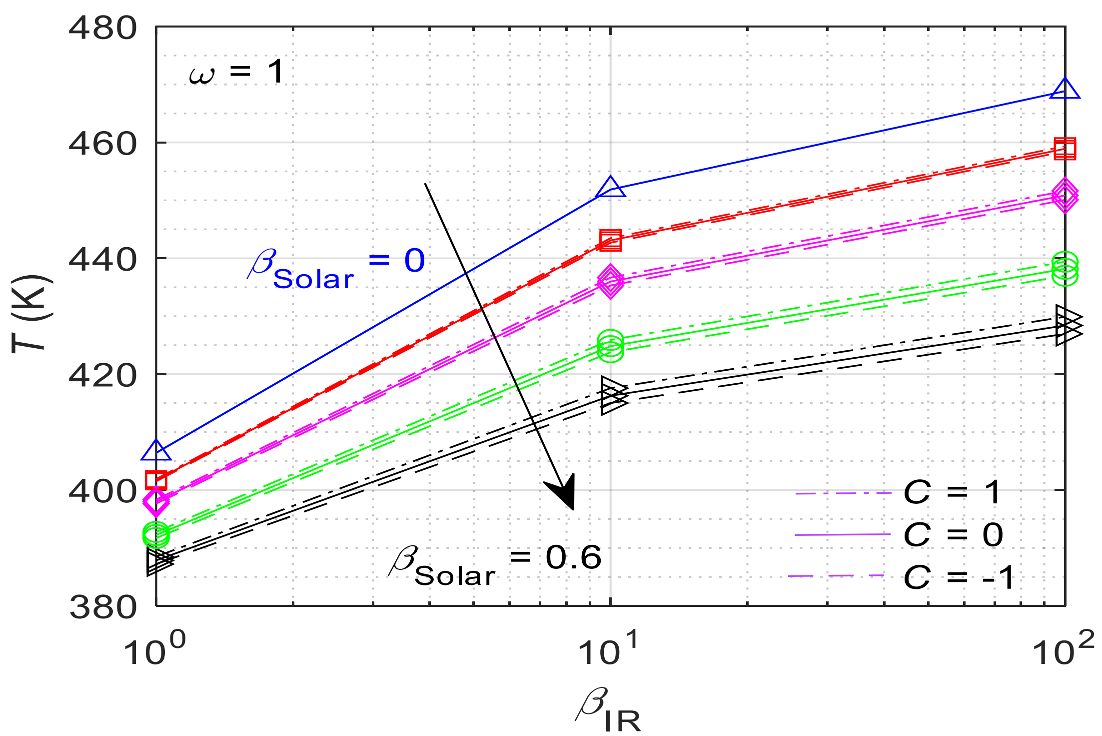


Fig. 12 Effect of different parameters on the absorber temperature

As we can see from the fig. 12 that the absorber temperature varies with respect to different parameters like Optical depth in the Infrared Region, Optical depth in the Solar region and Scattering Phase function (C) at a particular value of Scattering albedo which is taken as 1. It can be seen from the above graph that by increasing the value of the Optical Depth in the Infrared region at any particular value of Optical Depth in the Solar region and for any particular value of the Scattering phase function the value of the absorber temperature increases and the reason for this is that by increasing the value of the optical depth in the infrared region the tendacy of the medium to absorb the energy or radiation emitted by the bottom or absorber surface will increase which results in less energy being passed through the medium and more energy being absorbed in the medium which results in less losses from the absorber plate and therefore the temperature of the absorber plate increases as the value of the Optical Depth in the Infrared region increases. The value of the absorber plate temperature decreases if the value of the Optical Depth in the Solar region increases this happens because when the value of the optical depth in the solar region increases then the tendacy of the medium to absorb radiation coming from the sun or solar radiation increases which results in more absorption of the radiation coming from the sun and therefore less amount of radiation will then be reaching or less amount of radiation will then be incident on to the absorber plate so when less amount of radiation will be reaching or incidenting on the absorber plate so absorber plate will be exposed to lesser solar radiation and hence the value of the absorber plate will decrease or reduce if the value of the optical depth in the solar region is increased so therefore by increasing the value of the optical depth in the solar radiation the temperature of the absorber plate reduces or decreases. By taking constant values of the Optical depth in the solar region and Optical depth in the infrared region if we change the value of the scattering phase function then the effect of change of scattering phase function on the absorber temperature can be seen and it is found that in the case of forward scattering the temperature of the absorber plate achieved or reached is maximum or highest i.e for C=1 , in the case of the backward scattering the temperature of the absorber or receiver plate achieved or reached is lowest i.e for C=-1 and in the case of isotropic scattering i.e for C=0 the temperature of the absorber or receiver plate achieved or reached is in between the temperatures achieved in case of the forward scattering and backward scattering. The reason for high temperature in forward scattering is due to the fact that when the energy or radiation is scattered more in the forward direction as compared to the energy or radiation in the backward direction so therefore due to this reason more amount of solar energy or radiation will be getting incident on to the absorber plate or in other words the absorber plate will be exposed to more solar radiation and therefore due to more exposure of absorber plate to the solar radiation the temperature of the absorber plate will be highest in case of the forward scattering case and for backward scattering case more amount of energy or radiation will be getting scattered in the backward direction as compared to the energy or radiation scattered in the forward direction so less amount of the energy will be incident on to the absorber plate which results in less value of temperature of the absorber plate as comparision to the absorber plate temperature in case of forward scattering and in isotropic scattering the radiation or energy will get scattered in all the directions in an equal amount so temperature of the absorber plate reached in isotropic scattering case will be in between the temperature values reached in forward scattering and backward scattering.

5.4.1.2 EFFECT OF THICKNESS OF MEDIUM ON ABSORBER TEMPERATURE:

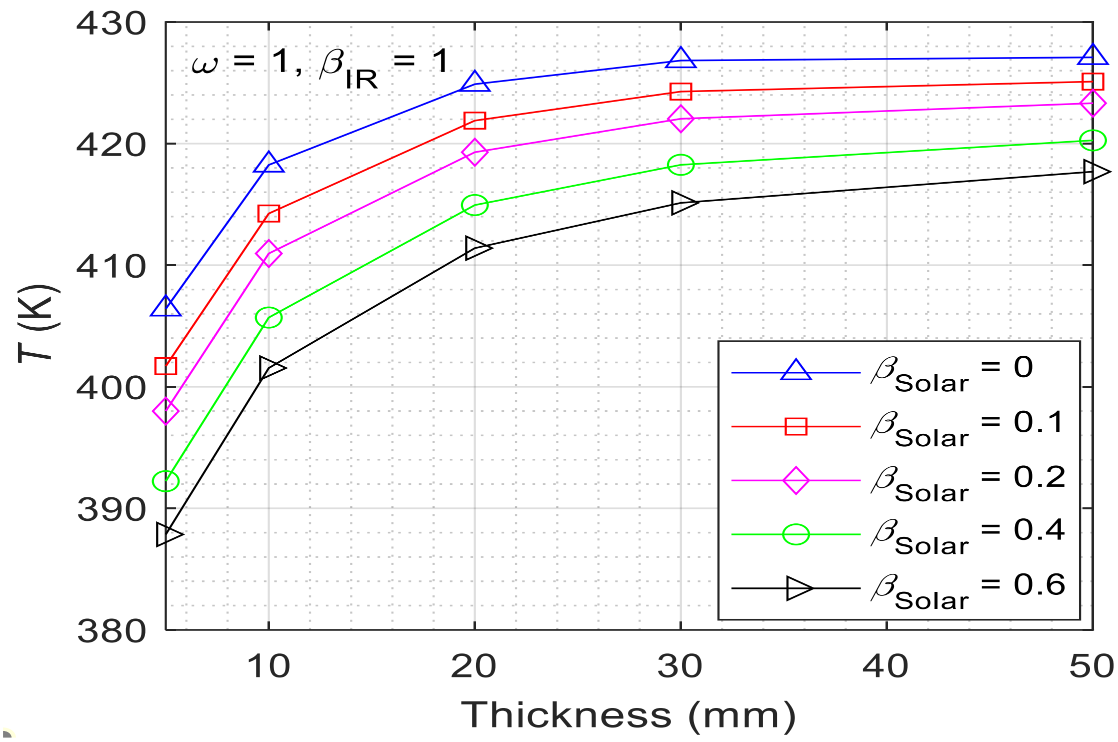


Fig. 13 Effect of thickness of the medium on the absorber plate temperature for different values of optical depth in the solar region

In the fig. 13 the effect of the thickness of the medium on the absorber plate temperature has been shown and from the above figure it can be seen that for a paricular value of scattering albedo (w) which is taken as 1, optical depth in infrared region which is also taken as 1 and optical depth in the solar region the value of the temperature of the absorber plate reached or attained increases as the thickness of the medium increases. As the thickness of the medium increases the value of the absorber plate temperature also increases because when the thickness of the medium increases the conduction losses through that medium reduces or decreases which results in the lesser losses and amounts to increase in temperature of the absorber plate. The conduction losses through that medium reduces or decreases as the thickness of the medium increases the reason of decrement of the conduction losses through that medium with increase in the thickness of the medium is due to the fact that conduction losses or heat loss due to the conduction is inversly proportional to the thickness of that medium so when the thickness of the medium increases and heat losses due to conduction heat transfer or conduction heat losses being inversly proportional to the thickness of the medium less losses will be occuring in case of higher thickness of the medium so due to this reason as the losses reduces or decreases when the thickness of the medium increases the value of the temperature attained or reached will be high or will increase with increase in the thickness of the medium. For any paricular value of the optical depth in the solar region, thickness of the medium and scattering phase function the value of the temperature of the absorber plate increases with increase in the value of the optical depth in the infrared region the reason of this increase of temperature of absorber plate with optical depth in infrared region is same as when medium tendacy to absorb infrared radiation increases the energy or radiation gets trapped inside the medium and energy or radiation emitted by the absorber plate cannot escape from the medium and due to this entanglement of energy or radiation in the medium the temperature of the absorber plate rises with rise in optical depth in the infrared region. Thickness plays an important role in knowing the temperature of the absorber plate or how the absorber plate temperature varies as the thickness of the medium also varies, since conduction losses are inversly proprtional to the thickness of the medium so by increasing the thickness of the medium the losses gets reduced and hence the value of the temperature of the absorber plate also increases with increase in the value of the thickness of the medium.

5.4.1.3 EFFECT OF OPTICAL DEPTH ON TOTAL TRANSMITTANCE:

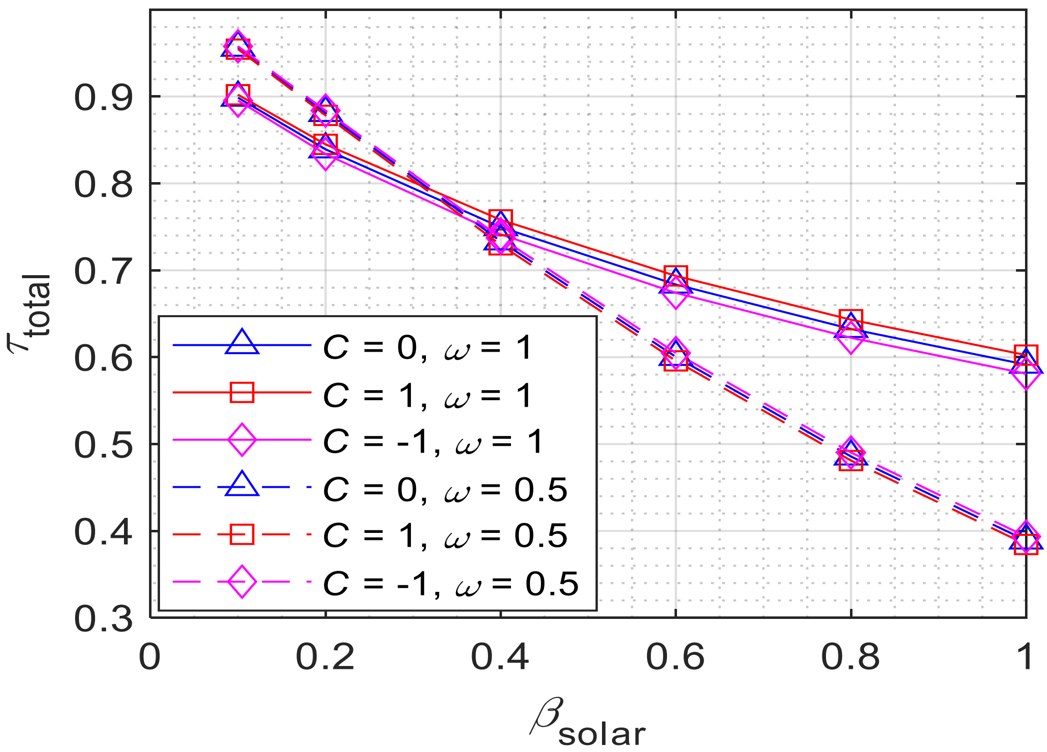


Fig. 14 Effect of the Optical Depth in Solar Region on the total transmittance of the aerogel medium for different types of scattering considered

In the fig. 14 the effect of the optical depth in the solar region is considered and analyzed on the total transmittance of the aerogel medium for different values of the scattering albedo and for different values of the scattering phase function considered. For any particular value of the Optical depth in solar region considered or taken the total transmittance is maximum in the forward scattering case because in forward scattering more amount of energy gets scattered in the forward direction which results in more amount of energy reaching the bottom surface or absorber plate for any particular value of scattering albedo taken or considered and the total transmittance is least or minimum in case of the backward scattering case because of less value of energy reaching the bottom surface or the absorber plate as energy gets scattered in the backward direction more as compared to the energy scattered in the forward direction and the total transmittance in case of isotropic scattering is in between or intermediate of the values attained in case of forward and backward scattering. For most of the optical depth in the solar region the value of the total transmittance reached or attained is higher for higher value of the scattering albedo and low for lower value of scattering albedo considered or taken. At high value of scattering albedo taken or considered for analysis the scattering is more as compared to the amount of scattering in case of lower value of scattering albedo taken so due to more scattering at higher value of scattering albedo as compared to lower value of scattering albedo more amount of energy radiation is getting incident on the bottom surface or absorber plate surface and therefore due to this reason the total transmittance of the aerogel medium is high for high value of scattering albedo as compared to total transmittance for lower value of scattering albedo taken or considered. The effect of total transmittance of the aerogel medium is also taken or considered with respect to the optical depth in the solar region as we can see from the graph that with increase in the value of the optical depth in the solar region the total transmittance of the aerogel medium also reduces or decreases the reason for this type of trend is that if the optical depth in the solar region is increased then the capability of the aerogel medium to absorb the solar radiation also increases and due to increase in the capability of the aerogel medium to absorb the solar radiation the value of the solar radiation which will be reaching the bottom surface or the absorber plate will be reduced so due to this reason the total transmittance of the aerogel medium will decrease with increase in the optical depth in the solar region.

5.4.1.4 EFFECT OF OPTICAL DEPTH ON HAZE:

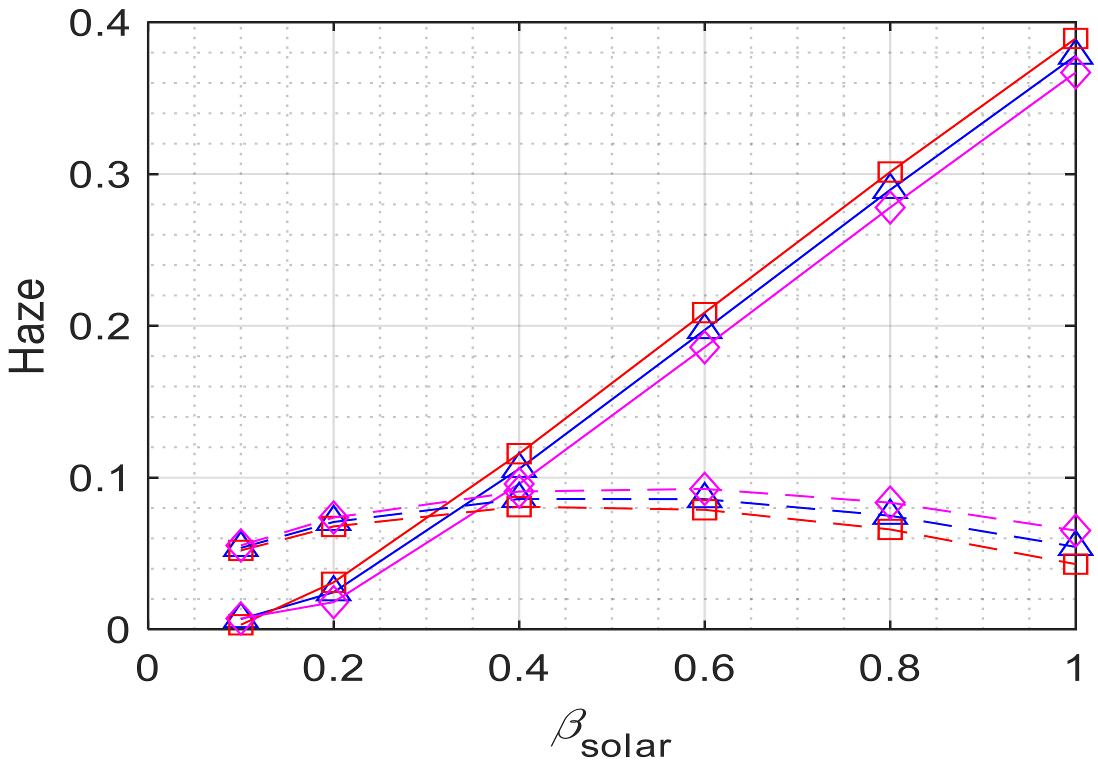


Fig. 15 Effect of Optical depth in solar region on the haze of the medium for different values of scattering albedo and for different types of scattering

In Fig. 15 the effect of the optical depth on the haze of the medium is considered or taken for analysis as we can see from the above figure that if the value of the optical depth in the solar region is increased the value of the haze also increases for most of the times or for most of the cases the reason of increase in the value of haze with increase in the value of the optical depth in the solar region is because for any particular value of the scattering albedo considered if we increase the value of optical depth in the solar region the extinction coefficient also increases and due to increase in the value of the extinction coefficient the scattering coefficient also increases and because of increase in the value of the scattering coefficient the aerogel medium tendacy to scatter the incident radiation also increases and due to more scattering by the aerogel medium the energy or radiation gets deviated from its original path due to this reason the haziness of the aerogel medium increases as the optical depth in the solar region also increases.

The value of haze is also dependent on the value of scattering albedo and the value of scattering phase function considered because if the value of scattering phase function is changed by considering other parameters to be constant then for forward scattering case since more amount of energy will be scattered in the forward direction so haziness or haze will be high for forward scattering case and in backward scattering case since more amount of energy will be scattered in the backward direction so due to more amount of energy getting scattered in the backward direction so haziness or haze will be least in case of backward scattering.

5.4.2 RESULTS FOR SPECULAR INCIDENT RADIATION/ SPECULAR INCIDENT SURFACE:

5.4.2.1 EFFECT OF DIFFERENT PARAMETERS ON ABSORBER TEMPERATURE:

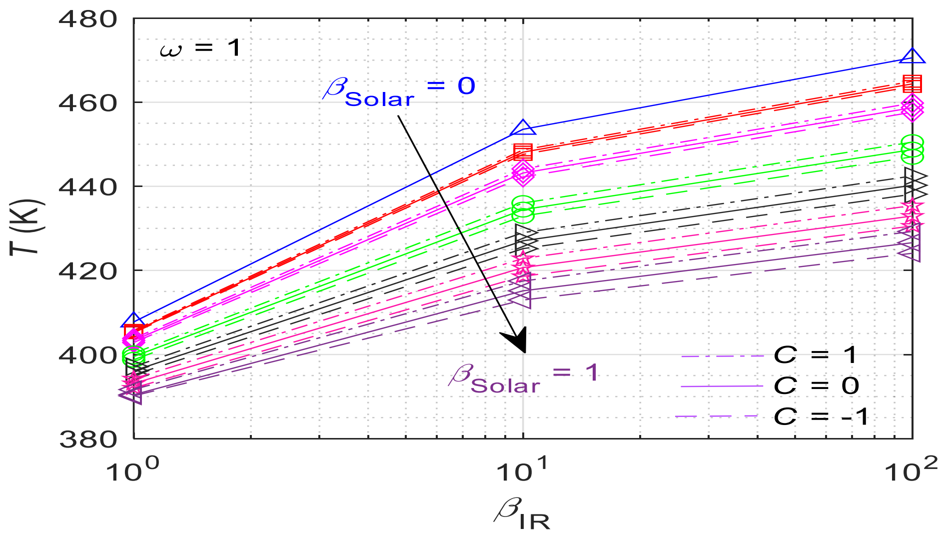


Fig. 16 Effect of different parameters on the absorber plate temperature

In the Fig. 16 as we can see that if the Optical Depth in the infrared region is increased then the value of the absorber plate temperature is also increasing for any particular value of the Optical depth in the solar region and for any particular value of the Scattering phase function considered. The reason of increase in the value of the absorber plate temperature with increase in the value of the optical depth in the infrared region is that if the optical depth in the infrared region is increased then the aerogel medium capability of storing or absorbing the energy or radiation emitted from the absorber plate surface also increases which results in increase in the value of temperature of the absorber plate since energy emitted from the absorber plate which is in the infrared region cannot escape from the medium it gets trapped inside the aerogel medium which results in increase in the temperature of the absorber plate. From the fig we can also see that if the value of the optical depth in the solar region is increased then the temperature of the absorber plate decreases because with increase in the value of the optical depth in the solar region the incident radiation falling on to the aerogel medium gets more absorbed in the aerogel medium itself which results in low or less amount of energy or radiation reaching the bottom surface or absorber plate and due to less amount of energy or radiation getting transmitted to the absorber plate so due to this reason the temperature of the absorber plate reduces or decreases if the value of the optical depth in the solar region is increased. For considering the effect of type of scattering on the absorber plate temperature it was found that for forward scattering case the temperature of the absorber plate achieved is maximum and for backward scattering case the temperature of the absorber plate attained or reached is minimum and for isotropic scattering case the temperature of the absorber plate is in between the forward scattering and backward scattering case.

5.4.2.2 EFFECT OF THICKNESS OF AEROGEL MEDIUM ON ABSORBER TEMPERATURE:

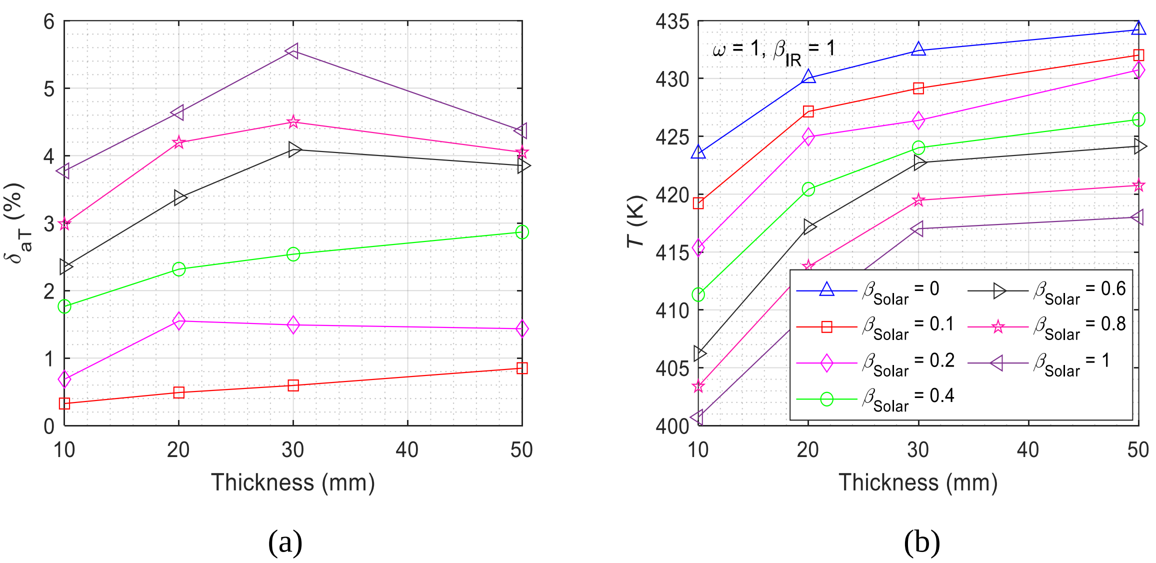
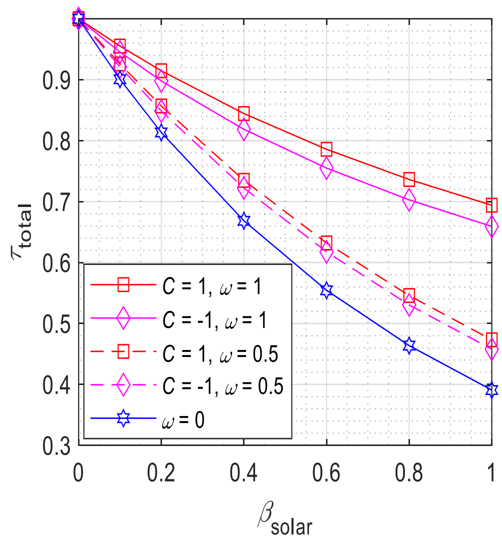


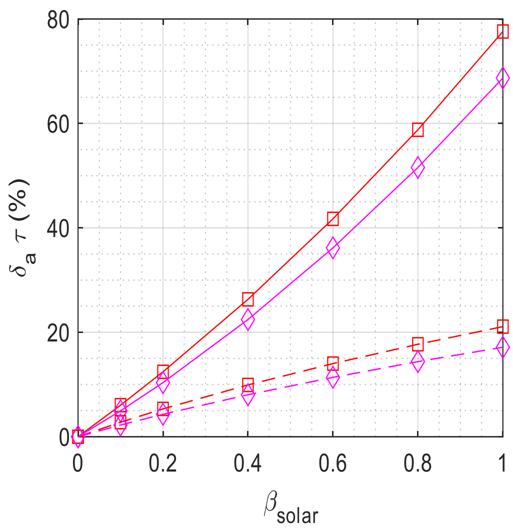
Fig. 17 (a) Percentage increase in absorber plate temperature for pure scattering medium as compared to pure absorbing medium for different values of thickness of the medium considered and (b) Effect of thickness of the medium on the absorber plate temperature for different values of the Optical Depth in the solar region

From the fig. 17(b) we can see that with increase in the thickness of the aerogel medium the temperature of the absorber plate also increases for any particular value of Optical Depth in the solar region and in this case the value of scattering albedo is taken as 1 and the value of the optical depth in the infrared region is also taken as unity the reason of increase in the value of the absorber plate temperature with increase in thickness is due to the fact that if the thickness of the aerogel medium is increased then the conduction heat losses or heat losses due to conduction heat transfer also reduces because the conduction heat transfer or rate of heat transfer due to conduction is inversely proportional to the thickness of the aerogel medium so when the thickness of the aerogel medium is increased then the rate of heat transfer due to conduction also decreases or reduces or in other words overall loss of heat is reduced with increase in the thickness of the medium so due to less amount of losses with increase in the thickness of the aerogel medium the temperature of the absorber plate increases with increase in the thickness of the medium. The value of the absorber plate temperature also increases with the decrease in the value of the optical depth in the solar region so if the value of the optical depth in the solar region decreases then due to decrease in the value of the optical depth in the solar region most of the solar energy will get transmitted through that aerogel medium and will fall or incident on the absorber plate which results in increase in the value of the absorber plate temperature with decrease in the value of the optical depth in the solar region.

5.4.2.3 EFFECT OF OPTICAL DEPTH ON TOTAL TRANSMITTANCE:



(a)



(b)

Fig. 18 (a) Effect of optical depth in solar region on the total transmittance of the aerogel medium (b) Percentage increase in the total transmittance of the aerogel medium in pure scattering medium as compared to pure absorbing medium

From the fig. 18 (a) the effect of the optical depth in the solar region has been taken or considered on the total transmittance of the aerogel medium. From the graph it can be seen that with increase in the value of the optical depth in the solar region the value of the total transmittance of the aerogel medium is decreasing for any particular value of scattering albedo and scattering phase function considered or taken for analysis. With increase in the value of the optical depth in the solar region the aerogel medium will absorb the solar radiation more and due to more absorption of the solar energy by the aerogel medium less solar energy will be available or less energy will be falling on to the absorber plate due to which the transmitting capability or the transmitting behaviour of the aerogel medium will decrease with increase in the optical depth in the solar region. The value of the total transmittance is high for the case of forward scattering because in case of forward scattering the energy gets scattered in the forward direction more as compared to the energy which is getting scattered in the backward direction and due to more energy getting scattered in the forward direction more energy or radiation will be reaching the absorber plate and due to this reason the transmittance of the aerogel medium will be highest for forward scattering, least for backward scattering and in between forward and backward scattering for the case of isotropic scattering.

5.4.2.4 EFFECT OF OPTICAL DEPTH ON HAZE:

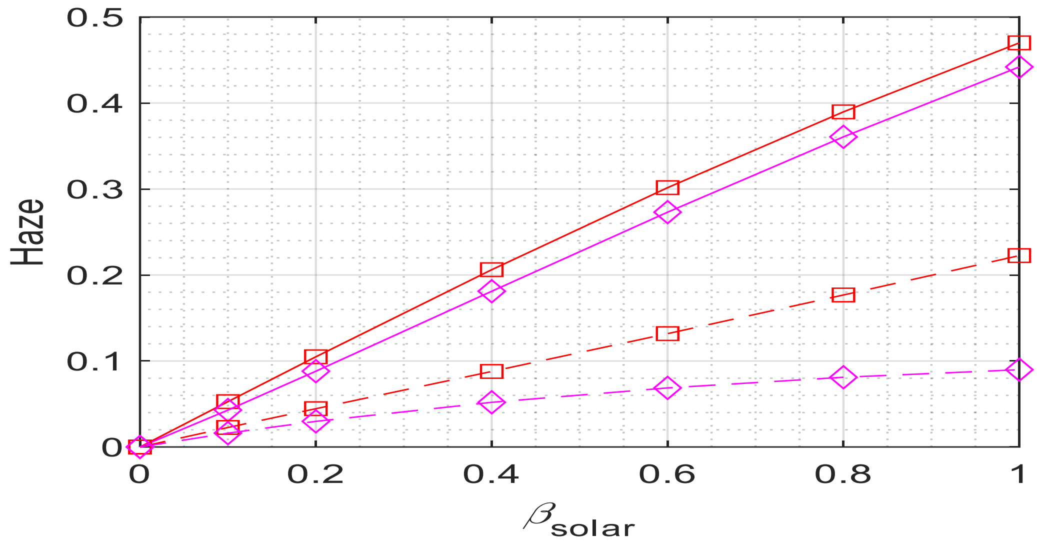


Fig. 19 Effect of the optical depth in the solar region on the haze of the aerogel medium

From the fig. 19 we can see that with increase in the value of the optical depth in the solar region the value of the haze of the medium decreases or reduces the reason for this type of trend is due to the fact that if the optical depth in the solar region is increased then the amount of solar radiation or solar energy will be absorbed more by the aerogel medium. For any particular value of the optical depth in the infrared region and scattering albedo if the value of the optical depth in the solar region increases the value of the extinction coefficient also increases which results in the increase in the value of the scattering coefficient and if the value of the scattering coefficient increases then the amount of scattering in the aerogel medium also increases and due to more amount of scattering in the aerogel medium more energy or radiation will be getting scattered in different directions leading to more haziness in the medium so due to this reason the value of the haze of the aerogel medium will increase with increase in the value of the optical depth in the solar region.

CHAPTER 6

VALIDATION OF THE THEORETICAL MODEL

6.1 VALIDATION OF THE THEORETICAL MODEL WITH LARI ET AL.

In our analysis we have validated the results of the theoretical model considered with the results of the paper given by Lari et al [4].

Table 11 Comparison of the different parameters taken in the theoretical model with the parameters given in the paper by Lari et al.

	Lari et. al., 2011	**Present model**
Type of study	Theoretical	Theoretical
Length, Height, Width	2,2,4 m	2,2,4 m
Internal Volumetric Heat Generation	5 kW/m^3	5 kW/m^3
Absorption Coefficient of Medium	0.5 m^{-1}	0.5 m^{-1}
Density of Medium	1.225 kg/m^3	1.225 kg/m^3
Specific heat of Medium	1006 J/kg K	1006 J/kg K
Thermal Conductivity of Medium	0.0242 W/m K	0.0242 W/m K

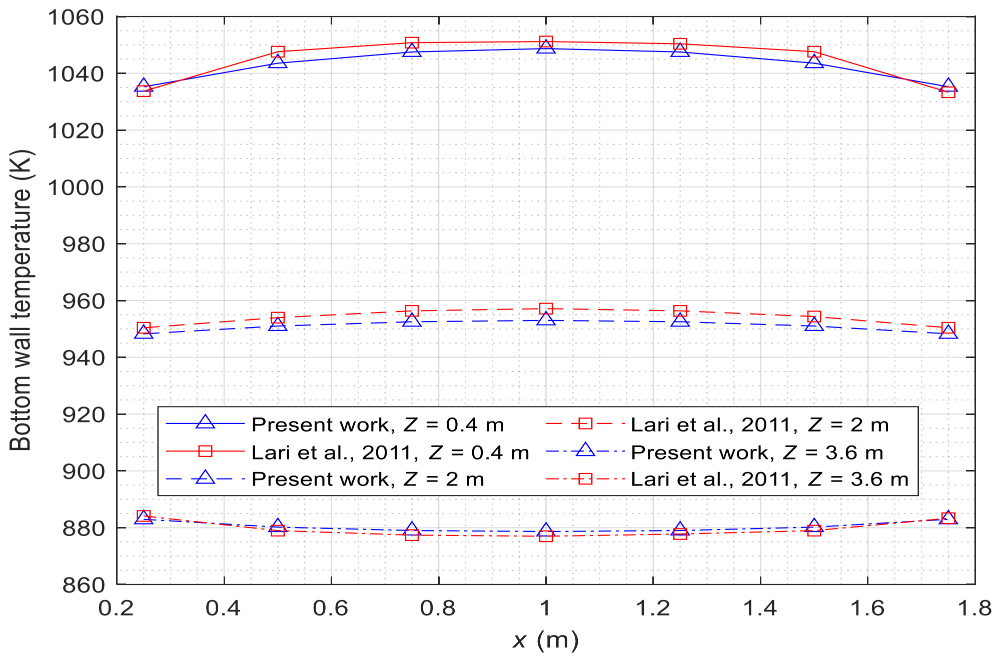


Fig 20. Comparision of results of the present model with the results of Lari et al paper

6.2 VALIDATION OF THEORETICAL MODEL WITH ZHAO ET AL.

In this we have validated the results of the present work with the results of the paper given by Zhao et al [3].

Table 12 Comparision of the different parameters taken in the present work with the parameters given in the paper by Zhao et al.

	Zhao et. al., 2019	**Present Model**
Type of study	Theoretical	Theoretical
Density of Medium	220 kg/m^3	220 kg/m^3
Specific Heat of Medium	850 J/kg K	850 J/kg K
Thermal Conductivity of Medium	0.02 W/m K	0.02 W/m K
Optical Depth in Solar region	0	0
Optical Depth in Infrared region	Variable	Variable

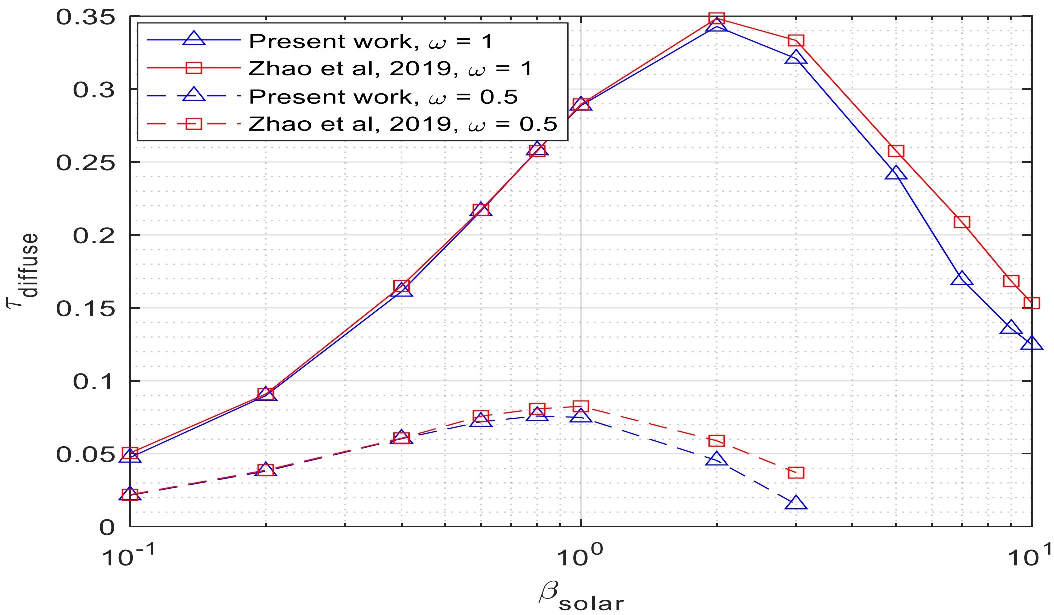


Fig 21. Comparision of the results of the present model with the results of Zhao et al paper

CHAPTER 7

CONCLUSIONS AND FUTURE SCOPE

A theoretical model was developed for analyzing and studying the effect of different parameters on the aerogel medium. From the results of the aerogel considered it was found out that by introducing scattering in the aerogel medium in replacement of only absorption in the medium the temperature of the absorber plate rises by maximum of 5.5 percent in case of 30 mm thickness of the aerogel medium for the case of optical depth in the solar region as 1. In other words if we consider the aerogel medium having a thickness of 30 mm and optical depth in the solar region as 1 then in that case or in that situation the value of the temperature of the absorber plate rises by maximum percentage in case of pure scattering medium in comparision to the case of pure absorption medium. For the case of pure scattering aerogel medium the value of the temperature of the absorber plate rises by maximum percentage of 5.5 percent in comparision to the case of the pure absorbing aerogel medium for the thickness of the aerogel medium taken as 30 mm and the optical depth in the solar region taken as unity or 1.

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