CFD Analysis of PCM Heat Exchanger Used In Free Cooling Applications

Mr. Mohammed Ajmal Shakeeb[1], Dr. V.M. Kulkarni[2]
1 Department of Thermal Power Engineering , PG Student VTU RC Kalaburagi
2 Department of Thermal Power Engineering , professor and HOD VTU RC Kalaburagi

Abstract:
Free cooling is the technique of accumulating the cold energy present in the night time atmospheric air in its natural state in the storage equipment. In the day, the cold energy is extracted from the storage equipment for cooling of the building by the use of mechanical ventilation system. In this, the heat exchanger built is of a shell and tube heat exchanger with the phase change material (PCM) which is present in the shell portion of the module and the way for flow of air is through the holes. The exchanger modules are placed one above the other with the air spacers in between every module. This heat exchanger arrangement is appropriate for application of free cooling where the variation of temperature is less. In this study, steady state heat transfer analysis is carried out for heat exchanger with one module and two air spacers. The CFD results are compared with the experimental results. To calculate the pressure drop over module and spacer, steady state flow analysis is used and flow and temperature variation in the module can also be calculated with steady state flow analysis. . The project is carried out for different configurations of the PCM module by changing the hole diameter and the thickness of the module.

Keywords **— : CFD, Free Cooling, Phase Change Material (PCM), Air Spacers, Steady State.**

I. INTRODUCTION

Now days, most of the people are using the air conditioners for their comfort life. It has become one of the essential commodities in household items. But the air conditioners consume lots of electrical energy whose bill is increasing every year and thus it has become expensive to afford by a common man. The air conditioners release the maximum amount of emissions to the atmosphere and this increases emission levels in the atmosphere. The temperature in the atmosphere goes on increasing due to industrialization and also due to urbanization like the construction of malls and new buildings by cutting the trees in the ecosystem. Thus its emissions also cause damage to the environment and also to the ecosystem. In the malls, a large number of air conditioners are installed for cooling purposes which gives maximum heat to the atmosphere. In order to reduce the heat load on air conditioner, one can go building, in order to have improved thermal comfort with almost low or no energy consumption for alternate methods of building cooling technologies which will give the similar comfort level. The cooling methods are classified as active cooling methods and passive cooling methods.
(i)Active **Cooling Methods**: In these methods, there are various cooling devices like air conditioner, fans, pumps etc. which use some external power source for input energy like solar power and photovoltaic power etc.
(ii)Passive cooling methods, cooling takes place without any external power. Passive cooling is a technique where a building is designed by focusing on heat gain and heat dissipation rate in a building in order to have improved thermal comfort with almost low or no energy consumption.

II. LITERATURE REVIEW

Level plate encapsulation was utilized by **Zalba et al**. [1] studied about the possibility of free cooling system with the liquefying temperature of PCM is about 20-25C.In this influential factors like energy ratio or volume in the encapsulates, the various load or unload storage rate and installation cost were determined. The study of statistical shows the effects with the influence in solidification process which would be due to encapsulation thickness, air flow inlet temperature. In this the charging and discharging times where explained in brief.

Nagano et al. [2] discussed PCM straightly on the section of flooring as granules of a few mm in diameter across. In this floor supply was used using PCM to show building granules of several mm in diameter with phase change temperature of 20 C. He showed that 89% of cool energy daily can be saved every night in a system using closed bed of 30mm thickness of granular PCM.

Arkar et al. [3] in this free cooling application in low energy structure of building with LHTES device which had been integrated into mechanical. They give an only hollow cylindrical LHTES having the diameter of circle embodied with PCM.

Arkar et al. [4] in this it has been studied about the efficiency in a heavy weight and light weight less energy building, it uses the system as automated ventilation method with 2 LHTES, one for supplying cooled air and the next for cooling recirculated inside air.

Arkar et al. [5] in this solar energy and coldness of ambient air is provided for decreasing energy requirement for cooling and heating. In this the differential scanning calorimeter is used to determine the apparent capacity of heat. In this the temperature response functions on the basis of storage of heat ,various, sizes the various flow rates of air and thermal properties of PCM's are determined in Fourier series form and empirical equation form.

Turnpenny et al. [6] prepare an apparatus on free cooling with the various heat tube installed in PCM for improving the transfer of heat. It consists of various heat tubes surrounded in PCM. In this heat transfer rates and melting times are shown.

Turnpenny et al. [7] In this there is an improvement with the development of working of prototype of LHTES. In this heat transfer rates of 200W have been noted which is suitable for high summer temperatures. In this energy saving benefits are there in this paper.

Boards and pockets was utilized as embody for free cooling which has been considered by.

Lazaro et al. [8] and it was discovered that PCM board was more higher than pockets. In this for the solidification of PCM low air temperature is used. In this the system can be cooled by transferring the heat with the PCM. In this charging and discharging takes place in very short times.

Meyer [9] used the model that is based on enthalpy for the PCM that transforms the phase with a little temperature ranges. In this implicit finite difference method is used. An implicit time appropriately reduces formulation of sequence of monotone elliptical problems. In this discontinuous enthalpy is replaced by Stefan problems. In this the resulting algebraic non-linear equations can be solved by using the gauss-seidel method.

Voller and Cross [10] demonstrated that on selection of temperature range of PCM accuracy depends and also on time step and elemental control volume. In this it is also numerical implementation of Stefan problems using enthalpy formulation .This technique is extended to 2 dimensional problems and is shown by explicit method.

Shamsunder and Sparrow [11] had built a relationship for the integral model of enthalpy and estimation of T is obtained from the H-T relationship while following the node to find 1 phase node and 2 phase node. In this also implicit finite difference is used to solve for solidification process in a cooled square container. In this the results are represented with Stefan-Fourier number.

Date [12] made more widespread the relationship of H-T such that as to there is no need to follow or track. In this a new finite difference formulation of multi-dimensional phase changes problems having different phase change temperatures. In this solution is obtained by finite difference equations. It allows solution for equations by tri-diagonal matrix.

Velraj[13] The velraj does the modification to fit it for the various materials which has a variety of phase changing temperature. In this V-shape enclosure for PCM gives higher margin to the fins.

A theoretical model is used for heat flowing circumferentially in between the tube wall is found by formulation of enthalpy model.

Beasley [14] In this experiment measurements of temperature distributions of transient in randomly bed of PCM having spheres for step change in inlet air is shown.

Lamberg [15],Hed [16] They all have built a calculated model for the level plate PCM heat exchanger for the purpose of free cooling by taking into account the forms of cp(T) curve. Numerical investigations relating to the technique of free cooling had been examined very deeply by Arkar and Medved [5]. They have taken into account DSC analysis result curve to display apparent heat capacity for the solution of continuous model of solid phase by the use of method of finite difference.

III. METHODOLOGY

Statement of problem

The model which has been utilized for examination has one PCM module which contains the tubes for air entry and furthermore it comprises of two air spacers, one is placed at the top side and the other is set at the end of the module of PCM. The pictographic shape and the PCM module measurements are shown in fig 3.1. The PCM module is of the state of the round and hollow container having 36 to 56 air section tubes each of measurement 65mm, 55mm, 45mm and of length 125mm, and 100mm.The passages for air have been arranged in 3 circles of tubes. In the inner circle there are 6 tube passages and in the middle circle there are 12 tube passages and in the outside circle there are 18 tube sections. The measurements of the air spacers are 750mm diameter and 150mm length. The most noteworthy or highest PCM temperature is 299K and fusion heat of latent is 82720kj/g. In one module, total volume is 0.04179m^3 and a mass of 36.35 kg, and the density is 870 kg/m^3 are used for the modelling. The pictographic view and the PCM module measurements are appeared in figure3.1. The PCM module is of the shape of the cylindrical and hollow container having 36 to 56 air passage tubes each of diameter 65mm, 55mm, 45mm and of length 125mm, and 100mm.The modules are placed one over the other and in between of every module air spacers are placed. Firstly the fluid is at liquid state at 305 K. In the module its phase changes in the process of charging. In our project phase change material is used in between module and spacer. Phase change material is utilized to store the cold energy. In this module, phase change material used is paraffin.

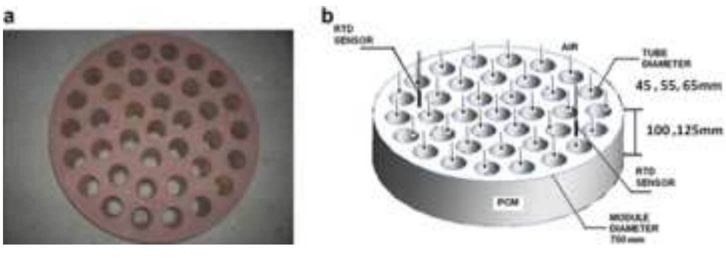


Figure 3.1

CFD modeling and analysis

The model of liquid area transferring heat comprises of two air spacers and the passage for the air flow in the module. One of the air spacers is placed at the top of the module and the other is placed at the bottom of the module and in between them the phase change material is placed. All areas are analyzed, meshed and modeled inside the ANSYS programming. Various velocities of inlet conditions and outlet conditions of boundaries are made in the pre-processor and the model is transferred to the ANSYS programming for the process of analyzing. In the ANSYS programming mass, force and energy conditions have been solved by using Finite volume technique.

The options for solving the fully implicit function used are SIMPLE algorithm as the option for solving the analysis. The area of PCM is assumed to be static. For the approximation k-e model and convective term is used, a II upwind order difference scheme is used for turbulence modeling for heat transfer. The parameters of velocity, pressure, temperature are solved by conservation equations in the ANSYS software. For the simulations, the boundary conditions of inlet are given as inlet temperature and inlet velocity. The weighing outflow function which is selected as the boundary conditions of exit is one. The convergence criterion of mass is taken as 1*10^-3 and for momentum as 1*10^-5 is used as energy residuals. In this the various velocity, temperature and pressure are analyzed. In the steady state analysis the pressure drop and heat transferring fluid flowing in module and the air spacers are found in this steady state analysis assuming wall temperature as constant. The first temperature of PCM is taken as 305 K for various velocities of frontal.

IV. RESULTS

Velocity vector plots

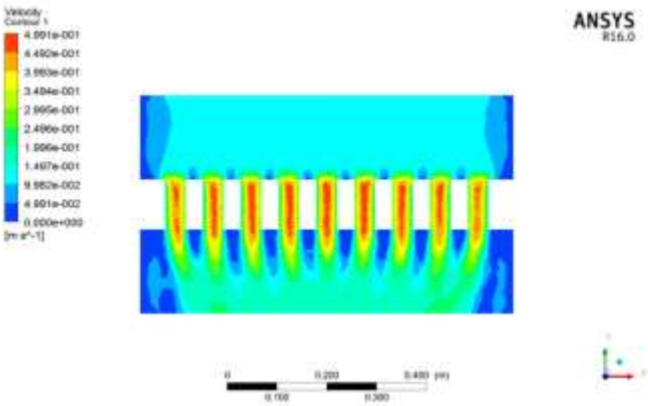


Figure 4.3.1 : Velocity Vector plots of module 45 mm hole diameter and 100 mm thickness

The above figure represents the Velocity Contour of the PCM module with 45mm hole diameter and 100 mm module thickness We can observe the minimum Velocity is at the top end of the module because of the initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area, the maximum velocity recorded is 0.499 m/s.

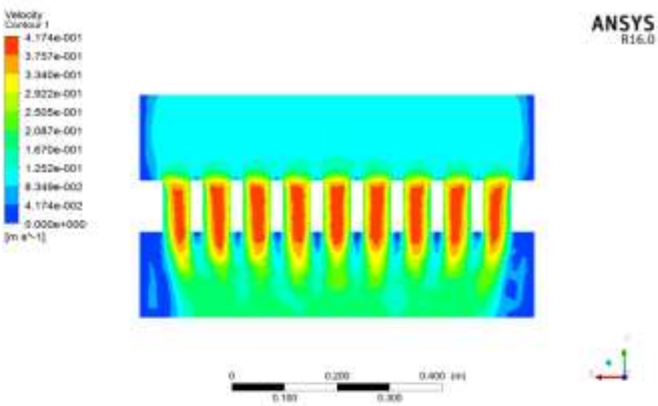


Figure 4.3.2: Velocity vector plots of module 55 mm hole diameter with 100 mm thickness

In figure 4.3.2, in this case it is observed that as the hole diameter increases the velocity is distributed all over the holes. The above figure represents the velocity contour of the PCM module with 55mm diameter holes and 100 mm module thickness We can observe the minimum Velocity at the top end of the module because of the initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area the maximum velocity recorded is 0.417 m/s at this area. We can say than the previous value at 45mm hole diameter the velocity is recorded as 0.499m/s. From this we can say that as the diameter of hole increases, the velocity decreases

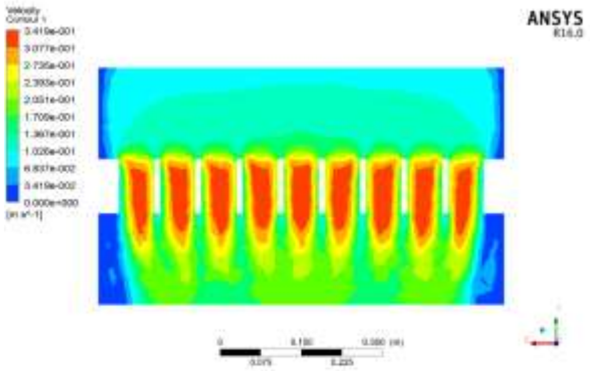


Figure 4.3.3 : Velocity vector plots of module 65 mm holes diameter with 100 mm thickness

In the above figure the distributions of fluid increases as the hole diameter increases The above figure represents the Velocity Contour of the PCM module with 65mm diameter holes and 100 mm module thickness. We can observe the minimum Velocity is at the top end of the module because of the initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area because of the reduced volume area the maximum velocity recorded is 0.349 m/s at this area.

We can say that the previous value at 45mm and 55mm hole diameter the velocity is recorded as 0.499m/s and 0.417 m/s. From this we can say that as the diameter of hole increases, the velocity decreases

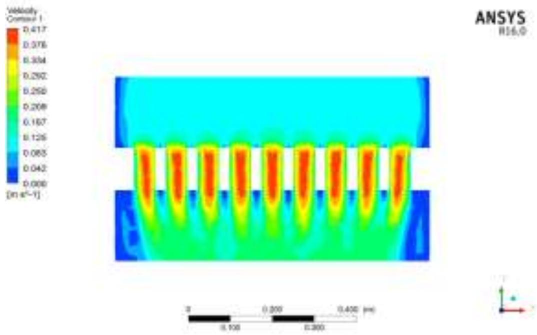


Figure 4.3.4: velocity vector plots of module 45 mm holes diameter with 125 mm thickness

In figure 4.3.4 it is observed that the velocity is more at the Centre of the holes that is in the module region. The above figure represents the Velocity Contour of the PCM module with 45mm hole diameter and 125 mm module thickness We can observe the minimum Velocity is at the top end of the module because of the initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area because of the reduced volume area the maximum velocity recorded is 0.565 m/s at this area. The analysis done on the previous module thickness 100 mm the total velocity recorded is 0.499 m/s where as in this case increase in velocity suggests that when the thickness is increased by 25%, the Velocity increases from 0.499m/s to 0.565 m/s. Hence as the thickness increases Velocity increases.

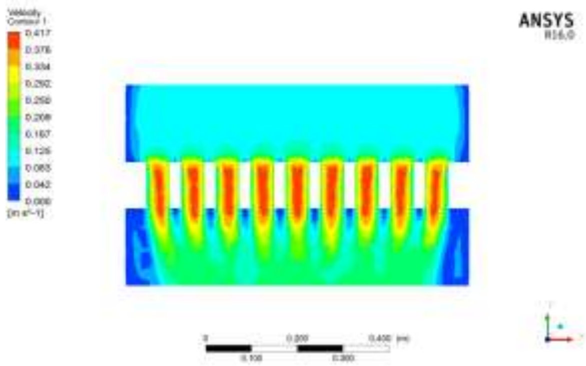


Figure 4.3.5 : Velocity vector plots of module 55 mm hole diameter with 125 mm thickness

In figure 4.3.5, in this case it is observed that as the hole diameter increases the velocity is distributed all over the holes. The above figure represents the Velocity Contour of the PCM module with 55mm diameter holes and 125 mm module thickness We can observe the minimum Velocity at the top end of the module because of the initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area because of the Reduced volume area the maximum velocity recorded is 0.417 m/s.

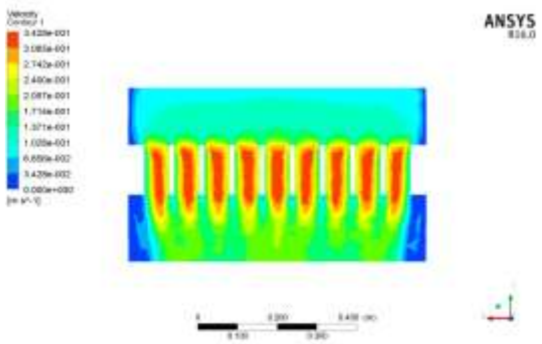


Figure 4.3.6 : Velocity vector plots of module 65 mm holes diameter with 125 mm thickness

In the above figure the Distributions of fluid increases as the hole diameter increases .The above figure represents the Velocity Contour of the PCM module with 65mm diameter holes and 125 mm module thickness We can observe the minimum Velocity at the top end of the module because of the
initial conditions and the inlet boundary condition given where the velocity is increasing at the tube area because of the Reduced volume area the maximum velocity recorded is 0.342 m/s.

Pressure contour plots

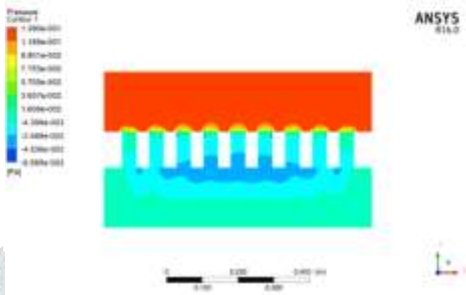


Figure 4.3.7: Pressure contour plots of module 45 mm hole diameter with 100 mm thickness

The above figure represents the pressure contour of the PCM module we can observe the maximum pressure recorded in the PCM module that is at inlet region for 45mm hole diameter and 100 mm module thickness. We have to understand that the pressure shown by the FLUENT represents the static pressure 0.139 Pascal the minimum pressure is recorded at the hole region because of low volume, the pressure decreases.

Figure displays the distribution of air pressure in the module and also in the spacer for 0.1 m/s inlet frontal velocity, with an inlet temperature of 295K. As the air from the spacer end strikes the portion of the non-flow at the down module there will be rise in local pressure due to which the kinetic energy is converted to pressure energy.

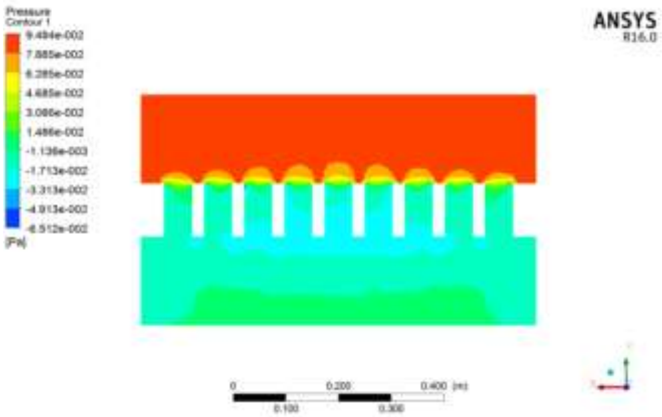


Figure 4.3.8 : Pressure contours of module 55 mm holes diameter with 100 mm thickness

As the diameter of holes increases from 45mm to 55mm the total pressure decreases from 0.139 Pascal to 0.0948 Pascal. The above figure represents the temperature contour of the PCM module we can observe the maximum pressure recorded in the PCM module is at inlet region for 55mm hole diameter and 100 mm module thickness We have to understand that the pressure shown by the FLUENT represents the static pressure of 0.0948 Pascal, the minimum pressure is recorded at the hole region because of low volume the pressure decreases. As the diameter of holes increases from 45mm to 55mm the total pressure decreases from 0.139 Pascal to 0.0948 Pascal

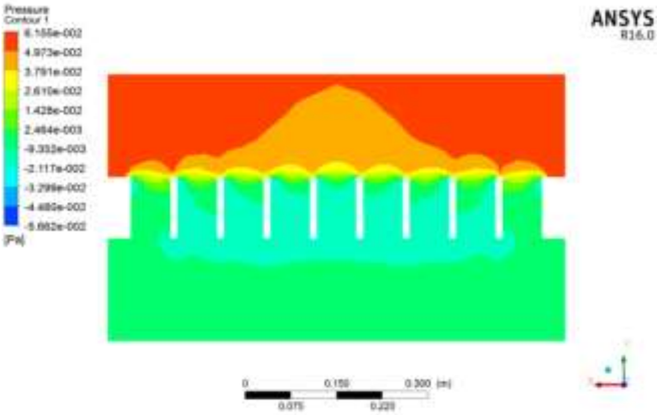


Figure 4.3.9 : Pressure contours of module 65 mm holes diameter with 100 mm thickness

As the diameter of holes increases from 55mm to 65mm the pressure decreases from 0.0948 Pascal to 0.0615 Pascal. The above figure represents the temperature contour of the PCM module we can observe the maximum pressure recorded in the PCM module is at inlet region for 65mm hole diameter and 100 mm module thickness We have to understand that the pressure shown by the FLUENT represent the static pressure 0.0615 Pascal, the minimum pressure is recorded at the hole region because of low volume the pressure decreases. As the diameter of holes increases from 55mm to 65mm the pressure decreases from 0.0948 Pascal to 0.0615 Pascal.

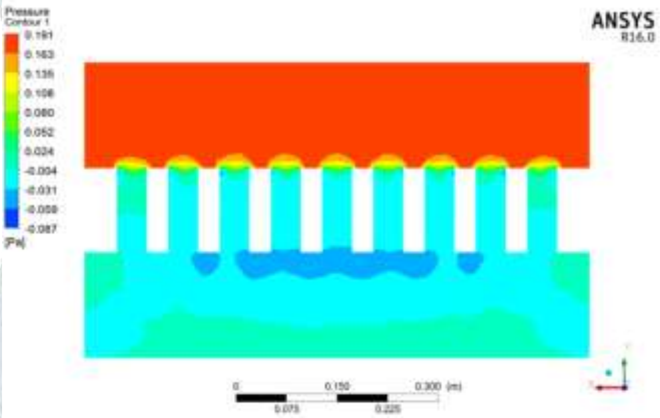


Figure 4.3.10 : Pressure contour plots of module 45mm holes with 125mm thickness

The above figure represents the temperature contour of the PCM module it can be observed that maximum pressure recorded in the PCM module is at inlet region for 45mm hole diameter and 125 mm module thickness. We have to understand that the pressure shown by the FLUENT represents the static pressure 0.191 Pascal, the minimum pressure is recorded at the hole region because of low volume the pressure decreases.

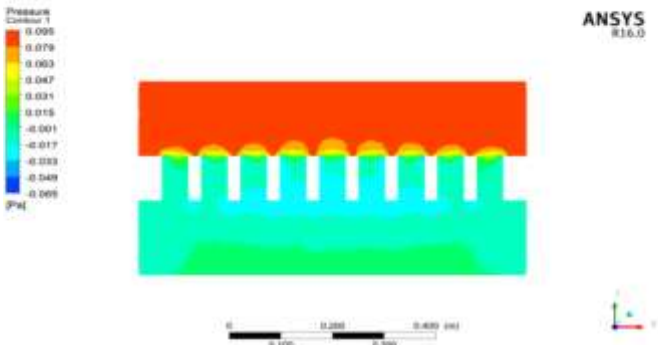


Figure 4.3.11: Pressure contour of module 55mm holes diameter with 125mm thickness

The above figure represents the temperature contour of the PCM module we can observe the maximum pressure recorded in the PCM module is at inlet region for 55mm hole diameter and 125 mm module thickness .The static pressure recorded is 0.095 Pascal.

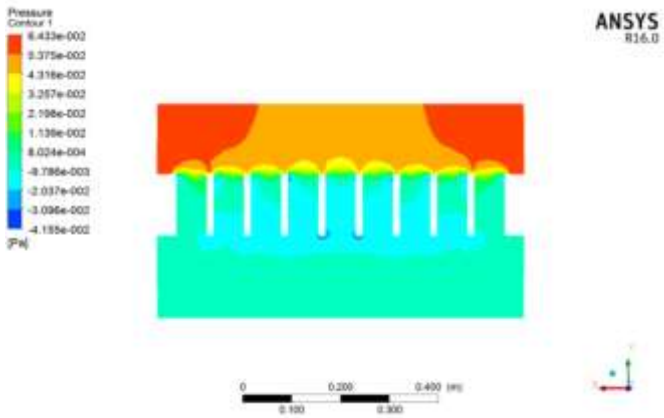


Figure 4.3.12: Pressure contours of module 65mm holes diameter with 125mm thickness

The above figure represents the temperature contour of the PCM module we can observe the maximum pressure recorded in the PCM module is at inlet region for 65mm hole diameter and 125 mm module thickness. The static pressure obtained for this is 0.0643 Pascal. As the diameter of holes increases from 55mm to 65mm the static pressure decreases from 0.095 Pascal to 0.0643 Pascal.

Temperature contour plots

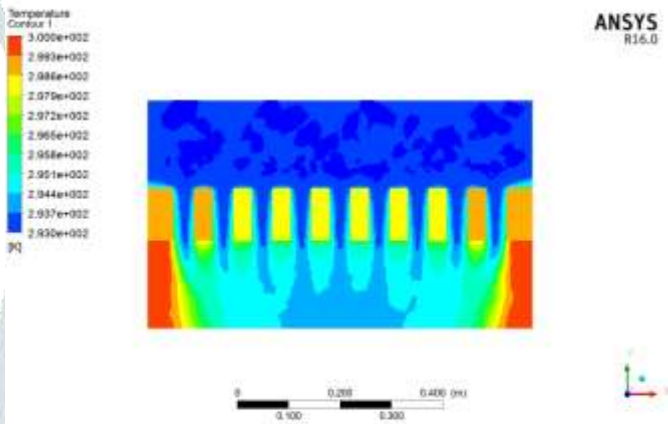


Figure 4.3.13: Temperature contour plots of 45 mm hole diameter with 100 mm thickness

The above figure represents the temperature contour of the PCM module with 45 mm hole and 100 mm thickness where the temperature is higher in the PCM wall because we are assuming it to be pre-heated surface at 300K, where the air at the inlet is entering at the temperature of 293K. Highest temperature is observed on the wall ends and minimum temperature is seen at the module end.

It can be seen from figure that the temperature at the inlet of the down spacer is very much constant of 295 K till it reaches module tube surface because in the spacer region there is no heating . For the steady state analysis the surface temperature of tube wall is kept at a constant temperature of 299 K.

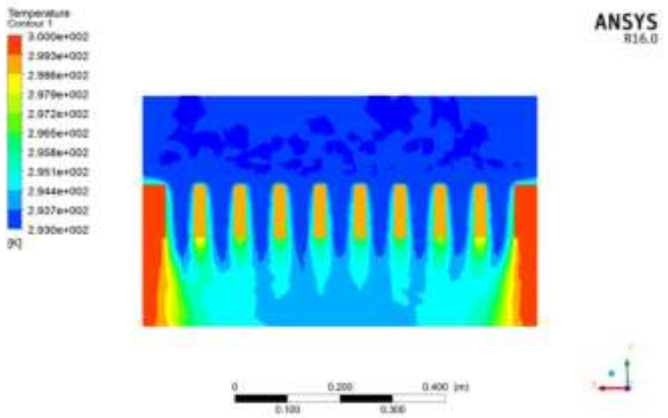


Figure 4.3.16 : Temperature contour of module 55 mm holes diameter with 100 mm thickness

The above figure represents the temperature contour of the PCM module with 55mm hole and100mm thickness where the temperature is higher in the PCM wall because we are assuming it to be pre-heated surface at 300K. Where The air at the inlet is entering at the temperature of 293K .

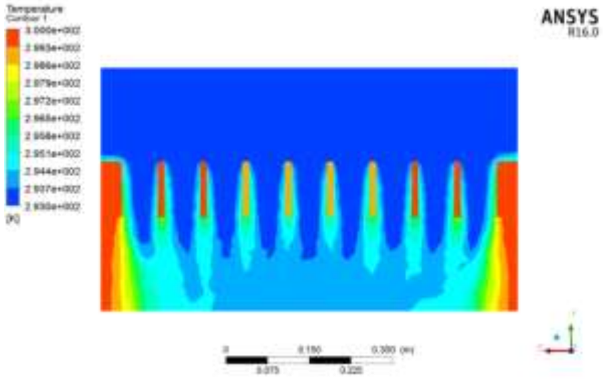


Figure 4.3.17 : Temperature contours of module 65 mm holes diameter with 100 mm thickness

As the hole diameter increases the temperature is maximum in the top spacer and module. The above figure represents the temperature contour of the PCM module with 65mm hole and 100mm thickness where the temperature is higher in the PCM wall because we are assuming it to be pre-heated surface at 300K. Where The air at the inlet is entering at the temperature of 293K .

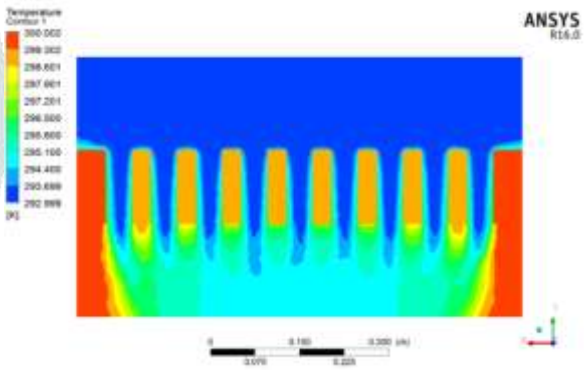


Figure 4.3.18: Temperature contour of module 45mm holes with 125mm thickness

The above figure represents the temperature contour of the PCM module with 45mm hole and 125mm thickness where the temperature is higher in the PCM wall because we are assuming it to be pre-heated surface at 300K Where The air at the inlet is entering at the temperature of 293K. In this there is a minimum temperature of the heat transfer between the hot surface and the flow of air.

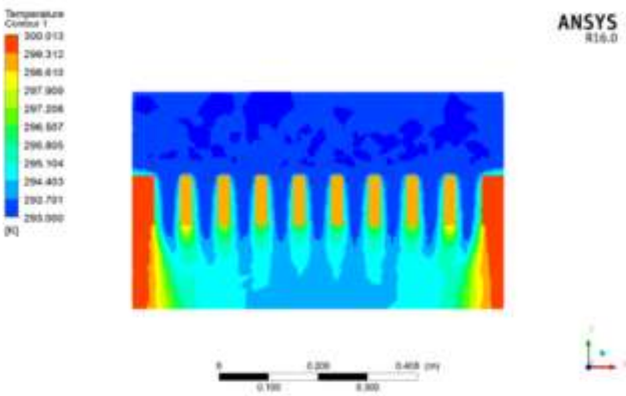


Figure 4.3.15: Temperature contour of module 55mm holes diameter with 125mm thickness

The above figure represents the temperature contour of the PCM module with 55mm hole and 125mm thickness where the temperature is higher in the PCM all because we are assuming it to be pre-heated surface at 300k Where The air at the inlet is entering at the temperature of 293K .

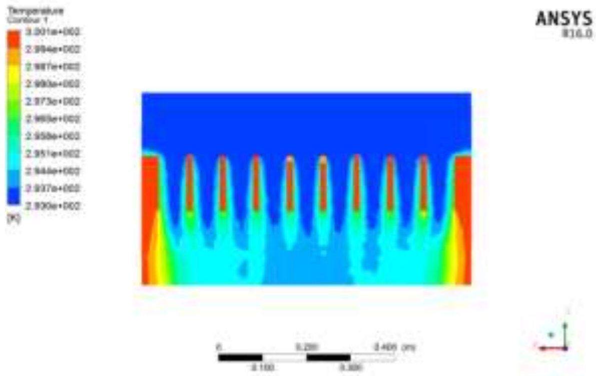
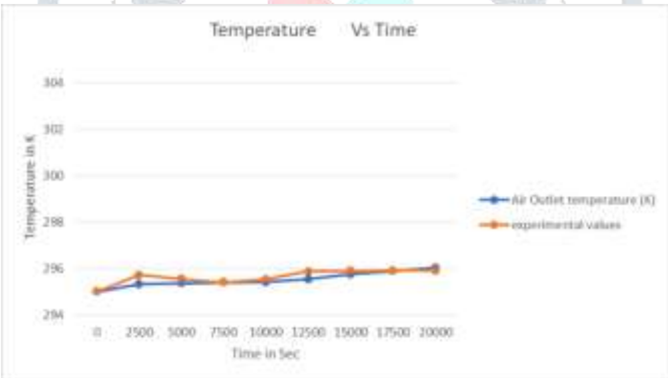


Figure 4.3.18: Temperature contours of module 65mm holes diameter with 125mm thickness

The above figure represents the temperature contour of the PCM module with 65mm hole and 125mm thickness where the temperature is higher in the PCM wall because we are assuming it to be pre-heated surface at 300k Where The air at the inlet is entering at the temperature of 293K .

VALIDATION OF CFD MODEL

Validation of the CFD model helps to determine the agreement of computational simulation results with that of the actual physical phenomena of free cooling occurring in the cooling of buildings. For this the results obtained from FLUENT software are compared with the values determined experimentally for transient cooling process for one case , though the present work namely deals with steady state analysis .The same geometry is considered for both computational and experimental work. Results are obtained from ANSYS software and the correctness of results obtained by software can be validated against experimental values available in any open literature paper. The temperature values obtained for transient analysis are compared with the experimental values by taking the time from the beginning of the experiment, not the computational time . The plot of temperature verses time is shown in the figure



The above graph represents the variation of temperature the air flowing through the PCM module with respect to time. Hence, it is plotted as temperature VS time. We can observe from the graph that there is a slight variation in the Temperature of air outlet as there is a slight decrease in the level. Also the apparent heat capacity model will provide accurate results if experimental phase change range of temperature is available for given application. The results of simulations in the form of graphs like temperature vs time plots show good agreement of temperature values obtained from the experimental work. The CFD simulation work under predicts results compared to experimental results but within 10% variation, and thus CFD model is validated.

V. CONCLUSIONS

In this project work , heat transfer and flow phenomena has been analyzed for a modular heat exchanger used in free cooling of buildings during night time . Typically time period for analysis is taken from 2AM to 6AM in morning hours during which cold air breezes into the buildings and thus free cooling occurs. Numerical simulation of free cooling process is carried out taking into account the phase change material (PCM) which changes its solid phase to liquid while releasing the heat energy by way of melting and changes its liquid state to solid state while accumulating the energy in the systems. Computational heat and flow analysis have been carried out by using commercially available CFD programming software ANSYS FLUENT which uses finite volume method for discretizing the governing equation. Experimental results are available for transient analysis; from these experimental results the validation is conferred. Parametric study has been carried out to understand the behavior of the system using free cooling.

The following conclusions can be stated from the present project work involving the analysis of PCM heat exchanger used in free cooling system for cooling the buildings.

1. Velocity vectors were obtained from ANSYS FLUENT software after solving Navier stokes equations for all simulations of single module and spacer of a PCM heat exchanger. It is observed from simulation results that the maximum velocity of 0.499 m/s is achieved for hole diameter of 45mm and 100 mm module thickness and the maximum velocity for hole

diameter of 45mm and 125 mm module thickness is 0.565 m/s. The minimum velocity is observed at the top end of the module because of the applied initial conditions and the inlet boundary condition. Velocity goes on increasing along the length of tube from top to bottom end.

2. As the hole diameter increases from 45 mm to 55mm with same module thickness, the velocity of fluid decreases from 0.499 m /s to a velocity of 0.417 m/s. From this, we can conclude that as the hole diameter increases the velocity decreases.
3. For hole diameter of 45mm, the velocity increases from 0.499 m/s to 0.565 m/s when module thickness is increased from 100 mm to 125 mm. From this, we can conclude that as the thickness increases by 25%, the velocity is increases by 12% . Hence as the thickness increases the velocity increases.
4. Static pressure contours are obtained for steady state analysis of PCM heat exchanger during CFD simulations. The maximum pressure of 0.139 Pascal is recorded.
5. PCM module at inlet region. We observed that for single module with 45mm hole diameter and 100 mm module thickness, the static pressure is 0.139 Pascal while for module with 55 mm hole diameter and 100 mm thickness, the static pressure is 0.094 Pascal. Thus, it is seen that the static pressure decreases when thickness is increased from 0.139 Pascal to 0.094 Pascal.
6. The temperature contours for PCM module are also obtained from CFD simulations for various hole diameter and different module thickness. Highest temperature is observed on the wall ends and minimum temperature is seen at the module end. The higher temperature in PCM wall is due to pre-heating of the surface at 300K. The air inlet temperature is considered 293K. It is observed that temperature remains almost constant in all cases of thickness and diameter variations.

Future Work

In the present work, steady state analysis of fluid flow and heat transfer has been carried out for single module of a PCM heat exchanger using commercially available Softwares like Solid works and ANSYS FLUENT. With this PCM heat exchanger is normally used in free cooling process used to cool the building at morning hours. The present work can be extended further and transient fluid flow analysis can be carried out .In the present work mass flow rate is considered as a constant parameter which can be varied. The future work shall include the analysis with variation in mass flow rate along with variation in both diameter and thickness of a module. The analysis can also be extended to take care of seasonal performance of PCM heat exchanger in all three seasons namely summer, winter and rainy season. There is also a scope for optimization work to optimize the heat transfer characteristics subjected to conditions of minimum pressure drop and maximum heat transfer .

REFERENCES

[1] B. Zalba, J.M. Marin, F.L. Cabeza, H. Mehling, Free-cooling of structures with stage change materials, International Journal of Refrigeration 27 (2004) 839e849.

[2] S. Nagano, S. Takeda, T. Mochida, Study of the floor supply aerating and cooling framework utilizing granular stage change material to expand building mass warm stockpiling heat reaction in little scale analyses, Energy and Buildings 77 (2004) 329e338.

[3] C. Arkar, S. Medved, Free cooling of building utilizing PCM heat stockpiling incorporated into the ventilation framework, Solar Energy 81 (2007) 1078e1087.

[4] C. Arkar, B. Vidrih, S. Medved, Efficiency of free cooling utilizing inactive heat stockpiling incorporated into the ventilation arrangement of a low vitality building, International Journal of Refrigeration 30 (2007) 134e143.

[5] C. Arkar, S. Medved, Influence of exactness of warm property information of a stage change material on the consequence of a numerical model of a stuffed bed dormant heat stockpiling with circles, Thermochimica Acta 438 (2005) 192e201.

[6] J.R. Turnpenny, D.W. Etheridge, D.A. Beam, Novel ventilation cooling framework for decreasing aerating and cooling in structures. Part I: testing and hypothetical demonstrating, Applied Thermal Engineering 20 (2000) 1019e1037.

[7] J.R. Turnpenny, D.W. Etheridge, D.A. Beam, Novel ventilation cooling framework for decreasing airconditioning in structures. Part II: testing of model and hypothetical displaying, Applied Thermal Engineering 20 (2000) 1019e1037.

[8] A. Lazaro, P. Dolado, J.M. Marin, B. Zalba, PCM-air heat exchangers for freecooling applications in structures: experimental aftereffects of two genuine scale models, Energy Conversion and Management 50 (2009) 439e443.

[9] G.H. Meyer, Multidimensional Stefan issues, SIAM Journal of Numerical Analysis 10 (1973) 522e528.

[10] V. Voller, M. Cross, A precise arrangement of moving limit issue utilizing enthalpy technique, International Journal of Heat and Mass Transfer 24 (1981) 545e556.

[11] N. Shamsunder, E.M. Sparrow, Analysis of multidimensional conduction stage change by means of the enthalpy show, ASME Journal of Heat Transfer 97 (1975) 330e340.

[12] A.W. Date, Novel emphatically certain enthalpy definition for multidimensional Stefan issues, International Journal of Heat and Mass Transfer 21 (1991) 231e251.

[13] R. Velraj, R.V. Seeniraj, B. Hafner, C. Faber, K. Schwarzer, Experimental examination and numerical displaying of internal cementing on a finned vertical tube for an idle heat stockpiling unit, Solar Energy 60 (1997) 281e290.

[14] D.E. Beasley, C. Ramamarayanan, H. Torab, Thermal reaction of a stuffed bed of circles containing a stage change material, International Journal of Energy.