Analysis of Heat Transfer Mechanisms in the Solidification of PCM with Different Passive Enhancement Techniques for Free Cooling Applications

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Abstract: The continuous increase in the level of green-house gas emissions and the depletion of fossil fuels are identified as the major driving forces behind efforts to effectively utilize different sources of renewable energy. Free cooling concept is gaining importance in building cooling applications. The medium which is used to store energy is Phase Change Material. Among the phase change materials available commercial PCM is of great use. The only drawback with the PCM is its thermal conductivity is very low. Various heat-transfer enhancement techniques between the phase change material (PCM) and the heat transfer fluid (HTF) were tried by researchers. Passive enhancement techniques are very simple and give good heat transfer enhancement that decreases the solidification time and increases the solidification rate. In the present work two types of passive enhancement techniques like increasing the roughness of the heat transfer surface and dimples over the heat transfer surface were tried and it has been observed that the dimpled surface will provide better results compared to rough surface over normal surface. Overall there is decrease in solidification time of 37 min. and increase in solidification rate of 19.37% with dimpled surface over normal surface.

***Keywords*: Solidification, PCM, Rough Surface, Dimple Surface, Thermal Storage Unit**

1. Introduction

In the current scenario, Latent heat storage system employing phase change materials is one of the energy saving technology. The process of storing the cool energy after the sunset and releasing the same for cooling the buildings during daytime is referred as free cooling. Phase change materials having the above property, find potential application in the field of heating, ventilation and air conditioning (HVAC). Paraffin, one of the commonly used organic phase change material exhibits high thermal storage capacity, chemical stability and low sub cooling. The major limitation despite the above merits is its poor thermal conductivity. One of the techniques for heat transfer enhancement is passive techniques like creating rough surface and adding dimples on the surface. Chen et.al [1] in his experimental work on coaxial pipe heat exchanger used dimples as the heat transfer modification of inner tube. After conducting experiment, a correlation was proposed which accurately predicts the heat transfer coefficient and friction of dimpled tube heat exchanger. Burgess et.al [2] conducted experiment with dimpled test surfaces placed on one wall of different channels. Experiments are carried out to illustrate the effect of Reynolds number, and stream wise development for dimple depth to dimple diameter (δ / D) for 0.1, 0.2 and 0.3 ratios. It has been found variations with Reynolds number are mostly apparent on flat surfaces just downstream of individual dimples. Small et.al [3] in his study on heat sinks for cooling of mock processors, evaluated the thermal performance of heat sink experimentally and numerically with and without dimples. Result of the work shows dimples improve the heat transfer capability of heat sinks with slight drop in pressure. Wei et.al [4] numerically studied the heat transfer inside a rectangular microchannel with dimpled bottom surface. It has been found that the dimples provide an effective passive heat transfer augmentation for macroscale channels, and can also be used to enhance heat transfer inside microchannels. Solomon et.al [5] concluded that a fin height of approximately 60% of the annual gap is enhancing the solidification heat transfer by a maximum of 22.1% and suppressing the free convection prior to solidification. Arkar et.al [6] conducted experimental work on cylindrical Latent Heat Thermal Energy Storage System (LHTES) with paraffin filled in spheres. The investigation was carried with both experimental and numerical analysis and it has been concluded that phase change material's thermal properties plays very important role in the work. Solomon et.al [7] observed that higher cooling rate increases the sub cooling effect. The PCM located the farthest away from the heat transfer surfaces had a much higher temperature gradient and a longer time span. So a large portion of the PCM was cooled below the phase change temperature before the solidification process was initiated. Subsequently the temperature of the PCM increased. When the driving potential between the PCM and the fluid was increased, the subsequent increase in the inlet velocity had little or no effect during the liquid sensible cooling and therefore, the subsequent solidification process. Giram et.al [8] in his experimental work studied the heat transfer characteristics and pressure drop on six dimpled plates subjected to forced convection and of varying densities. It was found that Nusselt number increases with increase in dimple density and percentage increase is high for staggered dimple arrangement.

Chinaruk et.al [9] conducted experimental work on dimpled tube fitted with twisted tape swirl generator and founded the friction and compound heat transfer behaviour of the above with air as the working fluid. The experimental results show

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both heat transfer coefficient and friction factor in the dimpled tube fitted with the twisted tape, are higher than those in the dimple tube acting alone and plain tube. Also it has been reported that the heat transfer coefficient and friction factor in the combined devices increase as the pitch ratio and twist ratio decrease. Prasad et.al [10] in his experimental work found that Convective heat transfer coefficient between absorber plate and air in a flat-plate solar air heater can be enhanced by providing the absorber plate with artificial roughness. Li et.al [11] in his experimental work studied the mechanism of turbulent convective heat transfer enhancement by measuring the heat transfer in two dimensional roughness tubes with different roughness heights at various Reynolds numbers. It has been reported that best heat transfer enhancement for a given pumping power is observed when the height of roughness is three 6655times of viscous sublayer thickness.

Arrangement of Thermocouples

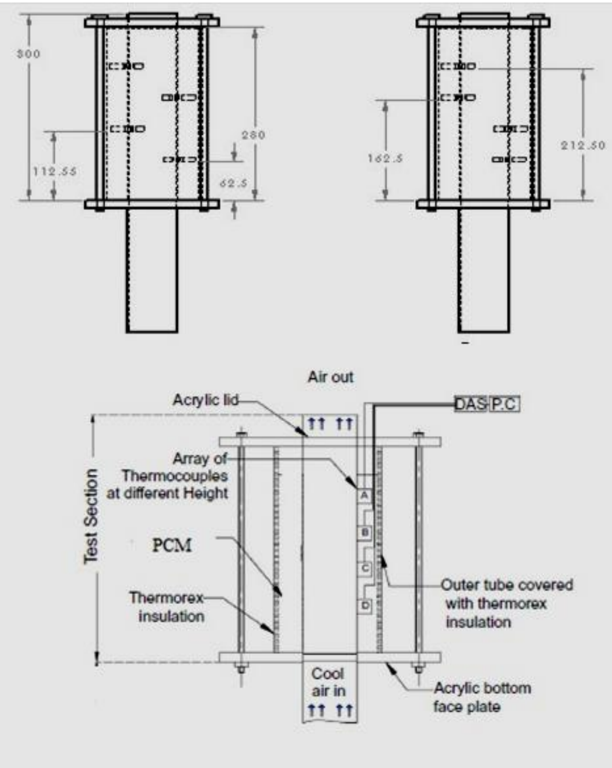

Fig.1 Schematic Diagram on the Arrangement of Thermocouples

2. Material and Methods

<u>**Experimental Setup**</u>

The experimental setup consisted of a test section, and the HTF flow control section, that regulated the flow through the inner tube of the test section. The test section was a double pipe annular heat exchanger, comprising an inner copper tube with an OD of 80 mm, thickness 1.5 mm and height 300mm and an outer acrylic tube of OD of 150mm, thickness 5mm and height of 280 mm. The PCM (RT21), which was in the liquid state at room temperature, was filled to height of 245 mm in annular space. The phase change material used to store the heat energy was paraffin, commercially known as RT21, obtained from Rubitherm, Germany. It is chemically inert and stable, nontoxic, and inorganic compound.

The liquid PCM did not require any clearance volume in annular space, as the volume contracts by about 14% during solidification. The bottom side of the inner tube was externally threaded, and assembled with an acrylic bottom face plate of 10 mm thickness, which was internally threaded.

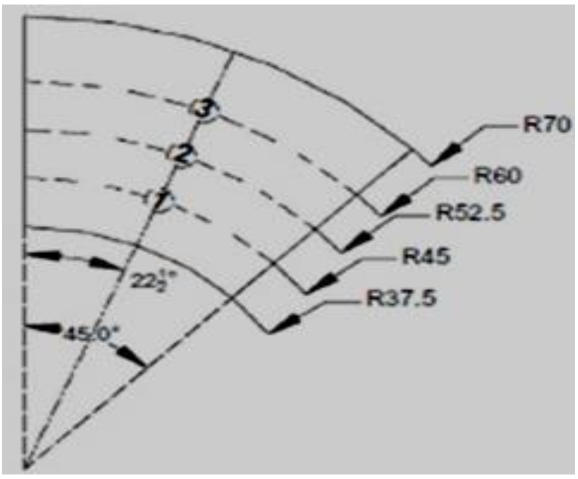

Fig.2 Angle on Arrangement of Thermocouple

The outer acrylic tube was also fixed on the bottom face plate, in a ring groove to ensure proper sealing. The PCM filled outer acrylic container was covered with an acrylic lid of 80 mm ID, 150 mm OD and 10 mm thickness. Three layer of 3mm thickness thermorex insulation were tightly wrapped on the outer acrylic tube to provide perfect insulation, the concentric cylinder was fastened using 4 bolts and nuts as shown in Fig. 2.1

Fig.2.1 Test section

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The HTF flow control section consisted of an entry length tube, a conical diffuser and a flow straightening section. The entry length tube made of copper, identical in dimensions to the inner tube, was attached at the bottom of the face plate. The conical GI diffuser having a major diameter of 300 mm and a minor diameter of 75 mm was fixed at the bottom of the entry length tube and this is fixed to the coupler. At the bottom of the conical GI diffuser, the flow straightener having 400 holes, each of 3 mm diameter, and 150 mm height was fixed. The above arrangement was supported rigidly on a 50 mm thick wooden platform as shown in Fig. 2.2.

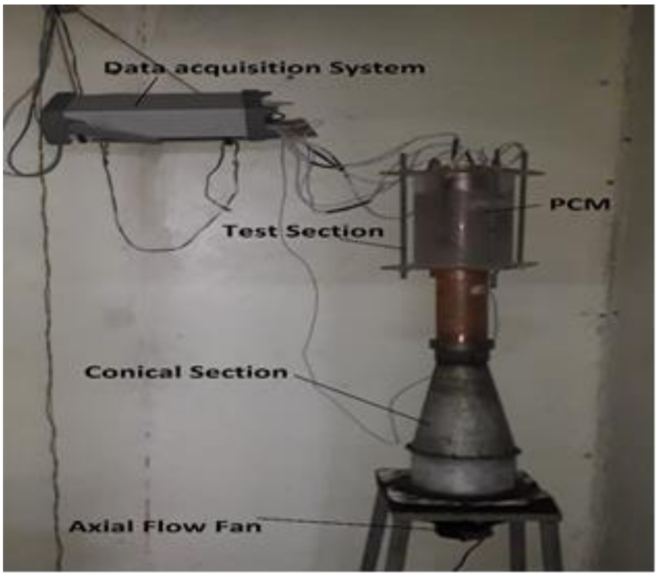

Fig.2.2 Experimental Setup

Experimental Procedure

During the start of each experimental trial, the ambient air was circulated through the test section until all the thermocouples located in the PCM regions attained the same temperature, whereby the thermal equilibrium of the PCM was ensured. The climatic simulator was switched on, to reduce the space temperature to the required level. Then the blower was switched on, and the flow rate was obtained by applying the pre-determined set voltage, which was maintained at a constant level throughout the experiment. The temperature measurements at all the thermocouple locations were continuously monitored using the Data Acquisition System (DAS). The experiments were conducted at two HTF inlet temperatures (12ºC, 11ºC) and two HTF inlet velocities (6 m/s, 5 m/s). The surface heat flux was varied with the combination of the HTF inlet temperature and its velocity. A higher inlet temperature and lower inlet velocity resulted in Low Heat Flux (LHF), while lower inlet temperature and higher inlet velocity resulted in High Heat Flux (HHF) among the tested parameters. In most of the experimental conditions, there was no deviation in the readings when the experiments were repeated. In case of variation in some trials, the experiments were continued till the repeatability of the readings was ensured.

Fig. 2.4 Rough Copper Tube with Roughness Value of 8 to 10 µm

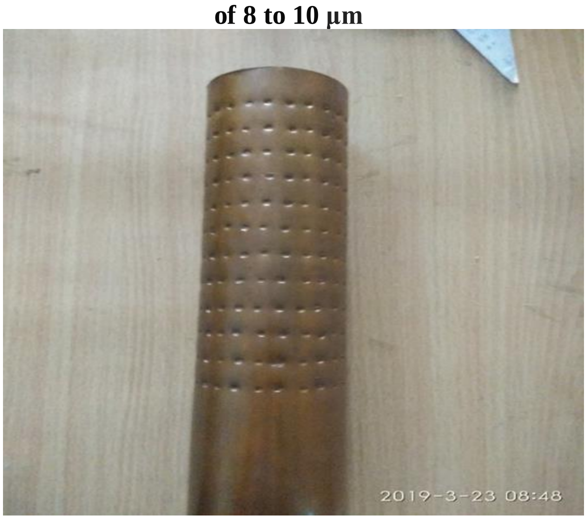

Fig.2.5 Circular Dimpled Surface

3. RESULTS AND DISCUSSION

3.1 COMPARISON OF AVERAGE SOLIDIFICATION TIME

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Type of Copper Surface	S.no	Constraints	Time taken for Solidification of PCM at Various Locations (21°C to 18°C) in Minutes												
			A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	Average
Normal Copper Tube with Surface Roughness of 2-3µm	1	11°C @ 5 m/s	125	157	168	165	193	189	147	187	203	115	178	201	169.00
	2	11°C @ 6 m/s	120	149	155	93	148	158	120	151	164	67	134	151	134.17
	3	12°C @ 5 m/s	144	179	191	200	231	226	171	215	230	135	202	216	195.00
	4	12°C @ 6 m/s	127	157	168	188	219	216	165	210	229	99	166	179	176.92
Copper Tube with Surface Roughness beyond 8µm	1	11°C @ 5 m/s	107	130	145	93	151	169	114	159	172	73	147	165	135.42
	2	11°C @ 6 m/s	101	130	150	92	147	159	106	153	159	71	160	171	133.25
	3	12°C @ 5 m/s	127	156	176	116	171	187	136	185	198	101	188	203	162.00
	4	12°C @ 6 m/s	109	150	165	70	167	179	116	179	191	54	182	197	146.58
Copper Tube with Densely Dimpled Surface	1	11°C @ 5 m/s	102	122	140	71	149	147	130	159	179	119	155	165	136.50
	2	11°C @ 6 m/s	97	115	131	68	144	144	129	172	165	106	155	165	132.58
	3	12°C @ 5 m/s	122	141	154	90	173	173	156	195	210	134	185	198	160.92
	4	12°C @ 6 m/s	108	130	145	85	164	164	145	191	208	114	177	193	152.00

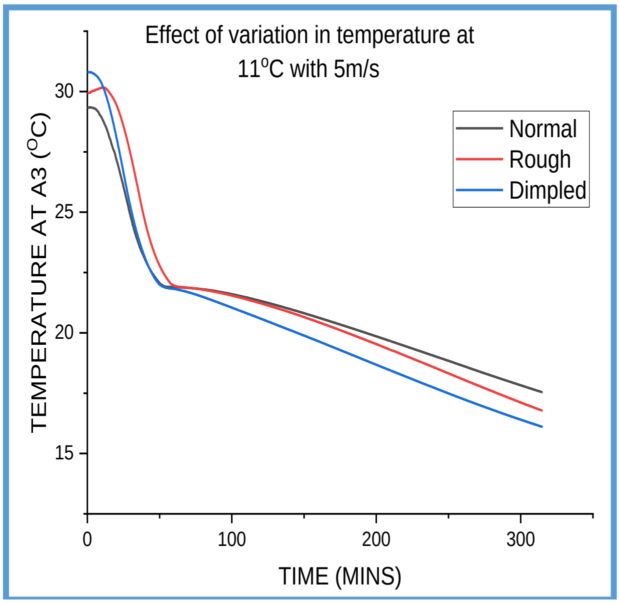
Table 3.1 Comparison of Solidification Time at all the Positions with Normal, Rough and Dimpled Surface

The solidification time at various positions and the average value of solidification time of PCM in three types of copper surfaces which are Normal, Rough, dimpled are tabulated in the table.

- At inlet temperature of 11°C and inlet air velocity of 5 m/s, the average solidification time of PCM with rough surface is compared with normal surface, the average solidification time has been decreased by 33.58 minutes and rate of solidification is increased by 19.86%. On comparing dimpled surface with normal surface, the average solidification time has been decreased by 32 minutes and rate of solidification is increased by 19.23%.
- At inlet temperature of 11°C and inlet air velocity of 6 m/s, the average solidification time of PCM with rough surface is compared with normal surface, the average solidification time has been decreased by 0.92 minutes and rate of solidification is increased by 0.7%. On comparing dimpled surface with normal surface, the average solidification time has been decreased by 1.58 minutes and rate of solidification is increased by 1.18%.
- At inlet temperature of 12°C and inlet air velocity of 5m/s, the average solidification time of PCM with rough surface is compared with normal surface, the average solidification time has been decreased by 33 minutes and rate of solidification is increased by 16.92%. On comparing dimpled surface with normal surface, the average solidification time has been decreased by 34 minutes and rate of solidification is increased by 17.48%.
- At inlet temperature of 12°C and inlet air velocity of 6m/s, the average solidification time of PCM with rough surface is compared with normal surface, the average solidification time has been decreased by 30.34 minutes and rate of solidification is increased by 17.15%. On comparing dimpled surface with normal surface, the average solidification time has been decreased by 24.92 minutes and rate of solidification is increased by 14.1%.

Therefore, with this comparison dimpled surface on copper tube leading to provide better results in all the constraints

3.2 EFFECT OF VARIATION IN TEMPERATURE AT A3 (Farthest position from Entry region)



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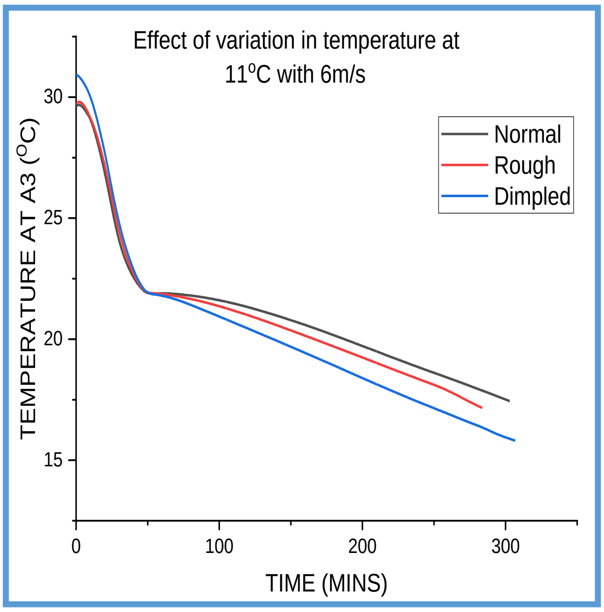

Fig. 3.1 Effect of Variation in Temperature at A3 with 11° C with 5m/s and 6m/s

- . At inlet temperature of **11℃** and the inlet velocity of air at **5m/s**, the variation of temperature with respect to time is plotted in Fig 3.1. The rate of decrease in temperature at A3 is observed to be faster in dimpled surface compared to the rough and normal surface. On comparing rough surface with normal surface, the solidification time has been decreased by 23 minutes and rate of solidification is increased by **13.7%.** On comparing dimpled surface with normal surface, the solidification time has been decreased by 28 minutes and rate of solidification is increased by **16.7%.** Therefore, dimpled surface is much better comparing with others.
- At inlet temperature of **11℃** and the inlet velocity of air at **6m/s,** the variation of temperature with respect to time is plotted and shown again in Fig.3.1. The rate of decrease in temperature at A3 is observed to be faster in dimpled surface compared to the rough and normal surface. On comparing rough surface with normal surface, the solidification time has been decreased by 5 minutes and rate of solidification is increased by **3.2%.**
- On comparing dimpled surface with normal surface, the solidification time has been decreased by 24 minutes and rate of solidification is increased by **15.4%.** Therefore, dimpled surface is much better comparing with others.

3.3 EFFECT OF VARIATION IN TEMPERATURE AT A3 (Farthest position from Entry region)

(with temperature 12° C and velocity 5 m/s and 6 m/s)

- At inlet temperature of 12℃ and the inlet velocity of air at 5m/s, the variation of temperature with respect to time is plotted in fig 3.2. The rate of decrease in temperature at A3 is observed to be faster in dimpled surface compared to the rough and normal surface. On comparing rough surface with normal surface, the solidification time has been decreased by 15 minutes and rate of solidification is increased by 7.85%. On comparing dimpled surface with normal surface, the solidification time has been decreased by 37 minutes and rate of solidification is increased by 19.37%. Therefore, dimpled surface is much better comparing with others.
- At inlet temperature of 12℃ and the inlet velocity of air at 6m/s, the variation of temperature with respect to time is plotted in fig 3.2. The rate of decrease in temperature at A3 is observed to be faster in dimpled surface compared to the rough and normal surface. On comparing rough surface with normal surface, the solidification time has been decreased by 3 minutes and rate of solidification is increased by 1.78%. On comparing dimpled surface with normal surface, the solidification time has been decreased by 23 minutes and rate of solidification is increased by 13.7%.

Compared on the overall result at A3, the dimpled surface is far superior than the normal surface with highest decrease in solidification time of 37 minutes and increase of rate of solidification by 19.37%. This is obtained at 12℃ with inlet velocity of 5 m/s.

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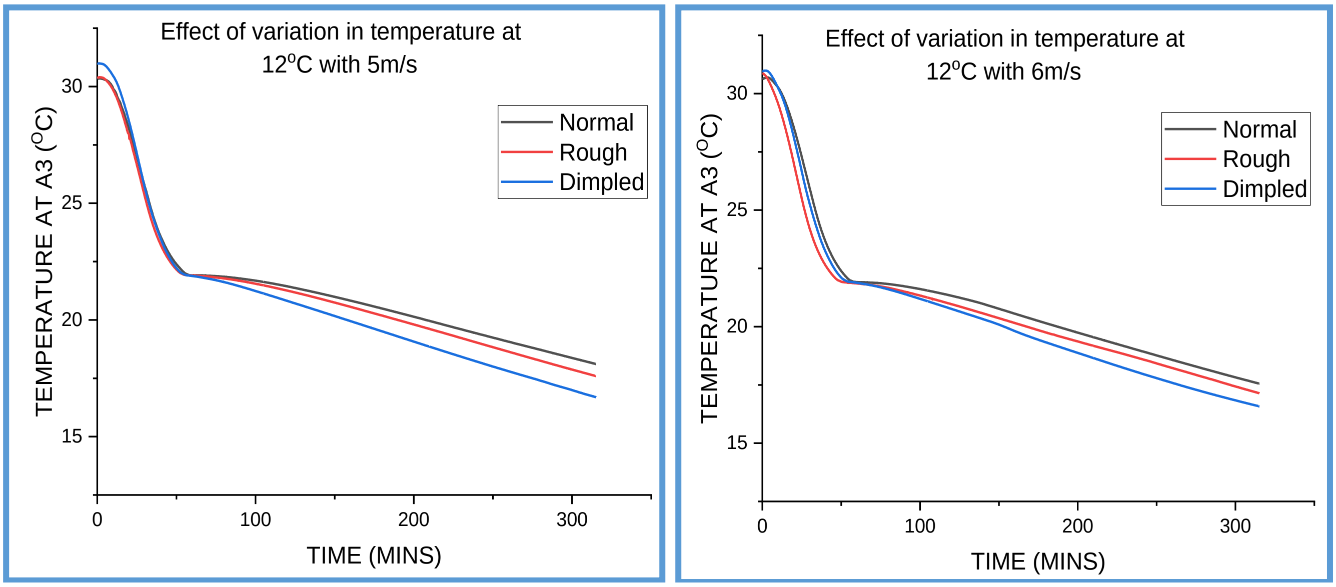
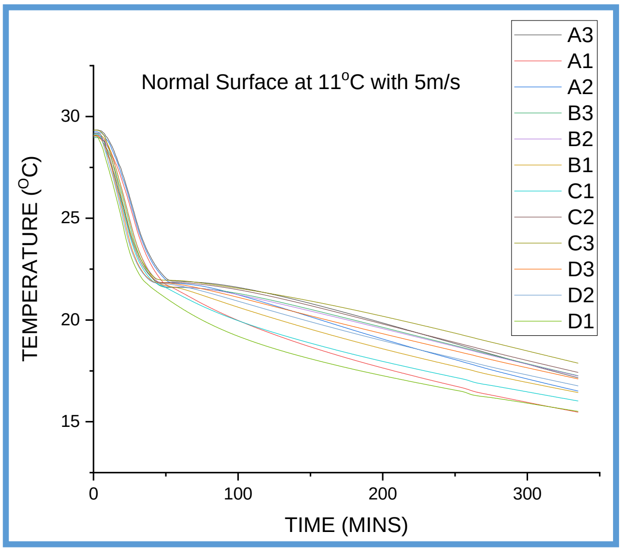


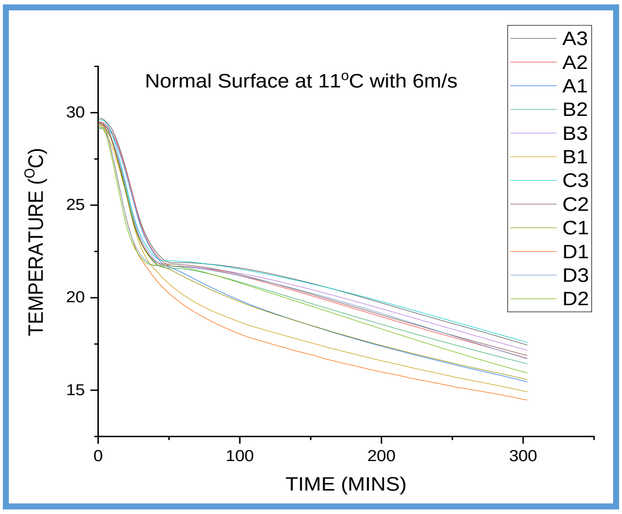
Fig. 3.2 Effect of Variation in Temperature at A3 with 12° C with 5m/s and 6m/s

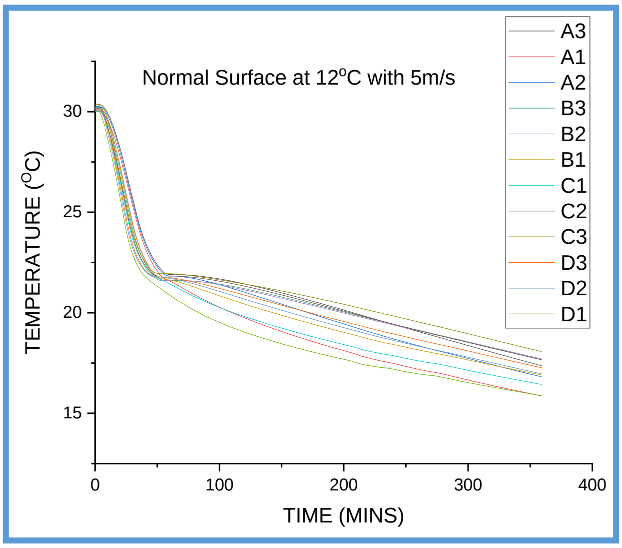
4. VARIATION OF TEMPERATURE AT VARIOUS POSITIONS WITH VARIOUS CONSTRAINTS

The following graph are plotted to show the variations of change in temperature of PCM at various axial and radial positions as mentioned in the experimental procedure. The various environmental constraints are 11℃ with 5m/s; 11℃ with 6m/s; 12℃ with 5m/s; 12℃ with 6m/s.

4.1. NORMAL SURFACE OF COPPER TUBE







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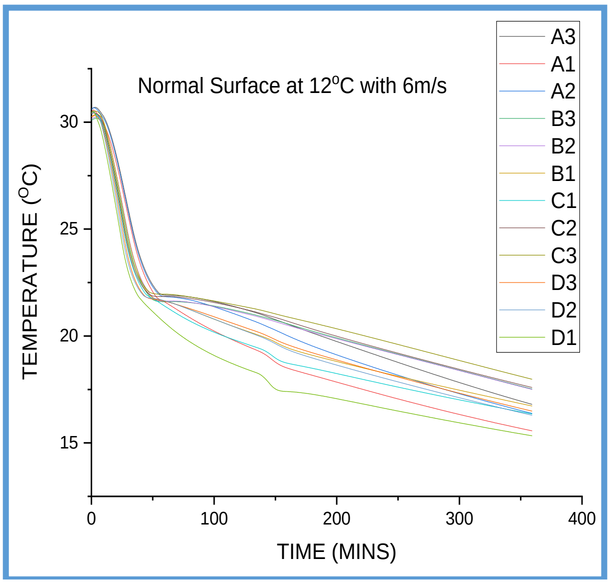
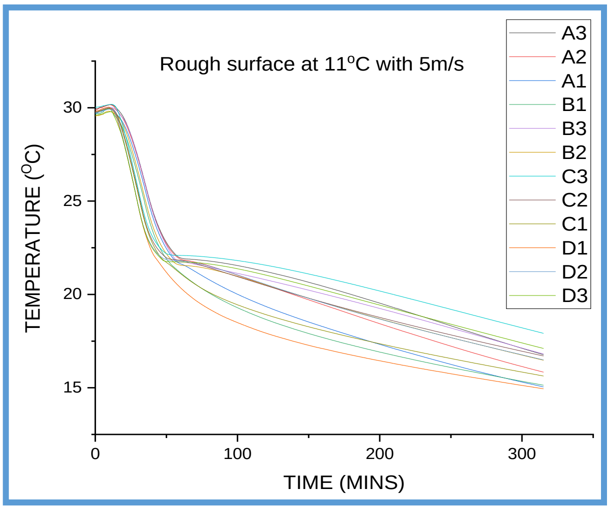
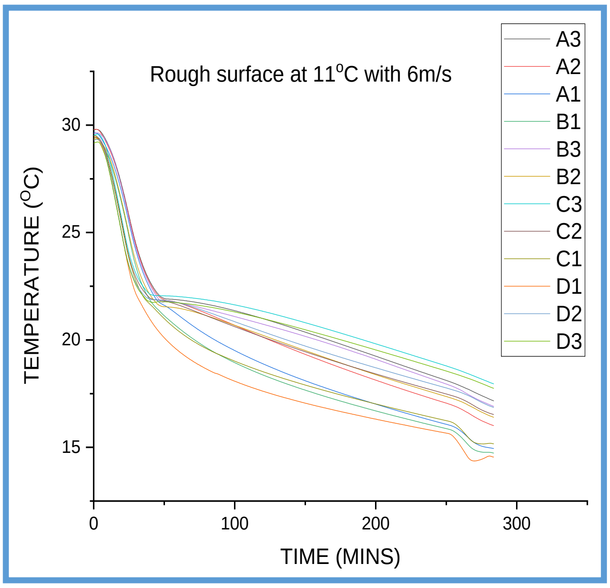
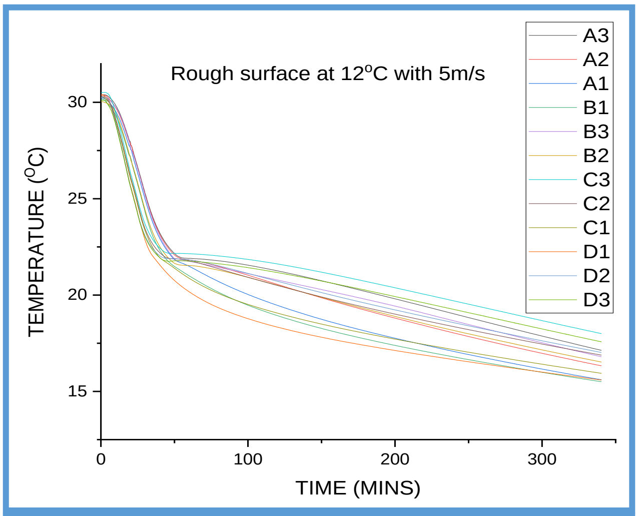


Fig.4.1 Normal Surface at 12°C with 6 m/s

4.2. ROUGH SURFACE OF COPPER TUBE







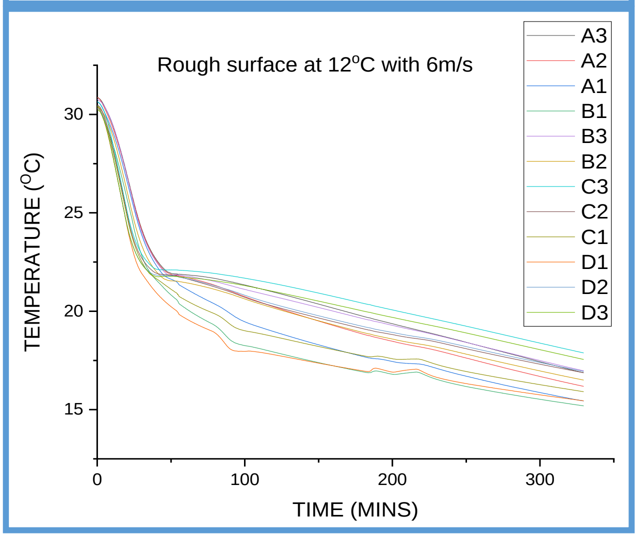
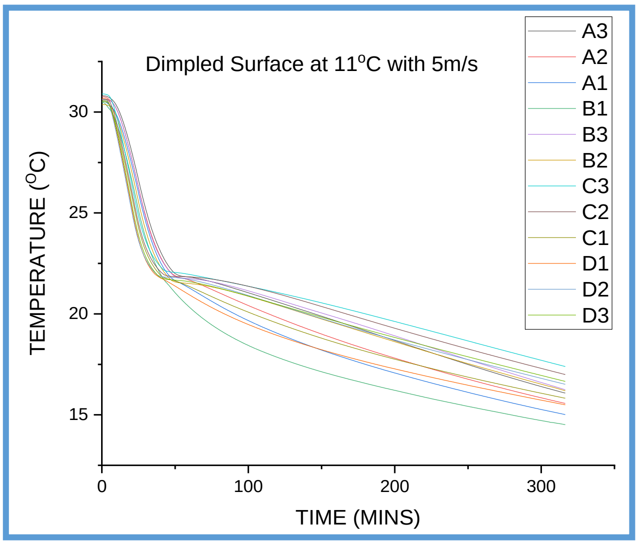


Fig. 4.2 Rough Surface at 11° C and 12°C with 5m/s and 6m/s

4.3. DIMPLED SURFACE OF COPPER TUBE



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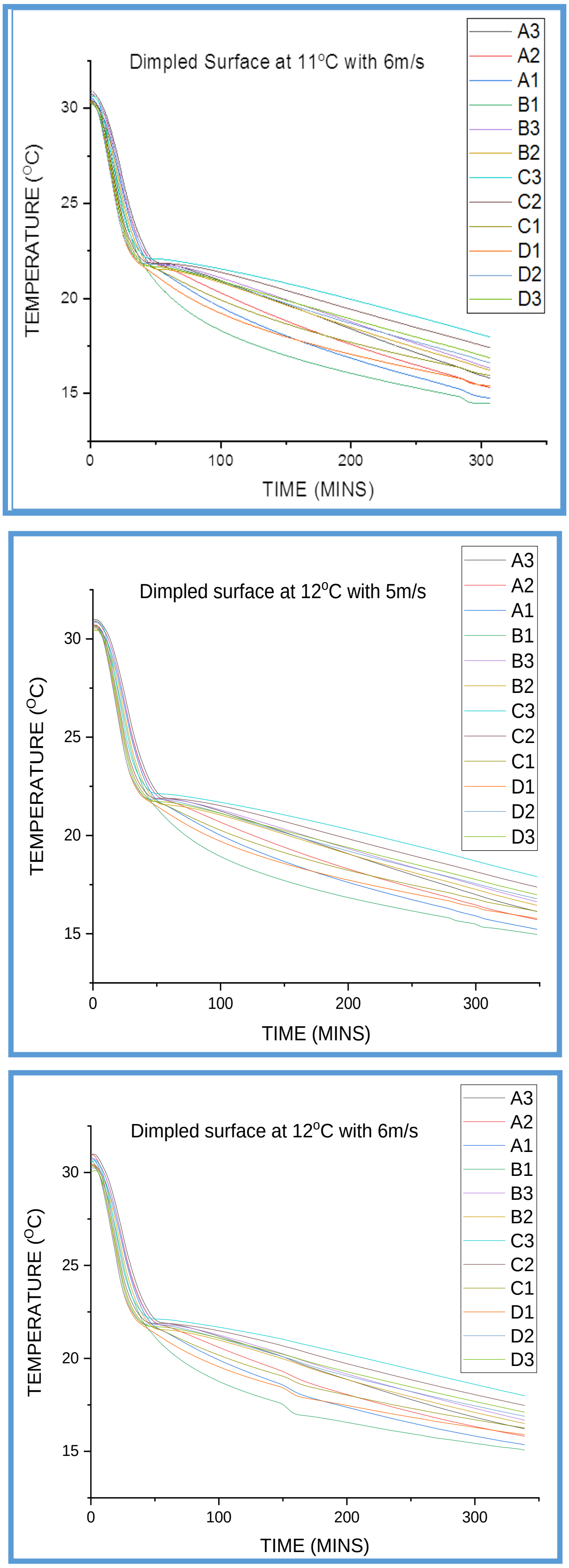

Fig. 4.3 Dimpled Surfaces at 11°C and 12°C with 5m/s and 6m/s

Therefore, among the variations plotted in Fig 4.1, Fig. 4.2 and Fig. 4.3 above for temperature change with respect to time, the sub cooling effect observed in all the cases is almost negligible. And also, the dimpled surface gives better heat transfer enhancement compared to other two cases i.e., normal surface and surface with increased roughness.

Therefore, among the variations plotted in Fig 4.1, Fig. 4.2 and Fig. 4.3 above for temperature change with respect to time, the sub cooling effect observed in all the cases is almost negligible. And also, the dimpled surface gives better heat transfer enhancement compared to other two cases i.e., normal surface and surface with increased roughness.

5. CONCLUSION

The following conclusions are made from the experimental investigation carried out, to study the heat transfer in the PCM during the outward cylindrical solidification in a double pipe heat exchanger, with the PCM filled in the annulus and air as the HTF passing through the inner tube. The results are applicable for the inlet air velocity range of 5 m/s, 6 m/s, and for the range of the driving temperature potential difference of 11℃–12 ℃. Though the results of the present study are useful for several applications, they have a direct relevance for the free cooling application of buildings, during the charging process, with air as the HTF.

- The experimental observation of solidification of temperatures at various cooling rates are achieved under different operating conditions with normal, dimpled and rough copper surfaces.
- Among normal, rough and dimpled surface the better results are obtained for dimpled surface due to high heat transfer rate by increasing the contact area and this helps in reducing the solidification time.
- Similarly comparing rough and normal surface the better results are obtained for rough surface due to increase in contact area of the surface.

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