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Effect of inlet temperature of HTF on PCM based solar thermal energy storage

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Abstract: Nowadays, research is conducted to focus on developing efficient and cost-effective energy storage systems. Sensible and latent heat thermal storage systems are the most widely used energy storage technologies. Latent thermal storage is more advantageous than sensible thermal storage as it has higher energy storage density with isothermal charging and discharging process. However, it has poor heat transfer characteristics resulting in more charging and discharging times. To address this issue, various methodologies related to heat transfer enhancement have been suggested. The main objective of this work is to enhance the heat transfer of the thermal storage system by the inclusion of longitudinal fin configuration. The thermal storage system considered is vertical shell and tube type, where paraffin wax is used as phase change material (PCM), and water is used as heat transfer fluid (HTF). The performance of a shell and tube type latent storage system with and without fins has been experimentally investigated under different operating conditions. The operating parameters are considered as inlet temperature of HTF. The results obtained under the present study revealed that additions of longitudinal fins improve the system efficiency significantly by reducing the charging and discharging times.

Keywords: solar, thermal energy storage, phase change material, PCM, heat transfer fluid, HTF

1. Introduction

Welfare, environment protection, and economic developments of any society depend on how energy-related activities are carried out efficiently. The world energy consumption from 2018 to 2050 as per International Energy Outlook 2019 (IEO2019) will rise by approximately 50%. There is an increase in more than 40% of natural gas global consumption from 2018 to 2050, and it will reach nearly 200 quadrillions Btu at the end of the year 2050. But due to the non-renewability nature of natural gas, coal, petroleum, and other liquids, future fuel is renewable energy sources like solar, hydro, wind etc. and renewable energy demand will increase up to 28% from 15 % during the tenure 2018 to 2050 as shown in Fig.1[1]. India is performing much better in the utilization of the renewable energy sector. It ranked 4th in the sector of wind power and 5th in installed renewable energy in 2018. Moreover, it also ranked second in switching from non-renewable to clean energy compared to emerging economies across the world in 2018.

India will successfully meet the objectives of the Paris Agreement. Till June 2019, it has achieved a renewable energy capacity of 80.46 GW, which incorporates solar energy (29.55 GW), wind energy (36.37 GW), biomass (9.81GW), and small hydropower (4.6 GW). It is highly expected that 40 percent demand of the power sector will be successfully meet by 2030 through renewable sources and will reach a figure of 15,820 TWh till 2040 [2]. The world's future is highly dependent on renewable energy resources. They are broadly categorized into two categories, namely renewable and non-renewable resources. Renewable resources used to produce again and again like solar energy, wind energy biomass energy, etc. and they are also referred to as alternate sources of energy [3–10]. It significantly helps in reducing environmental pollutions directly, benefiting severe human health issues [11-12]. It finds a significant role by replacing conventional fuels during space or water heating, especially power generation in rural areas and transportation.

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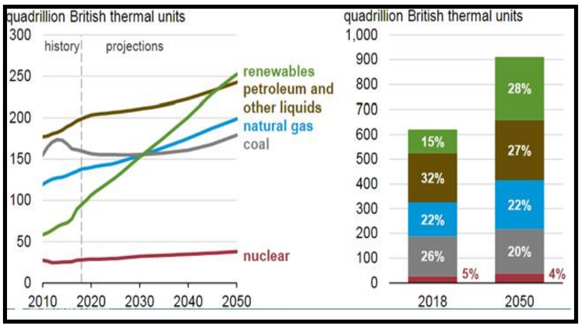


Fig. 1: Primary energy global consumption by energy source (2010-2050) [1]

The thermal energy storage (TES) is the storage of thermal energy temporarily at high or low temperatures. It helps in reducing the mismatch between energy supply and demand in the market and follows the principle of energy conservation. In this technology, thermal energy storage done by proper heating or cooling a PCM, which is further utilized based on different heating or cooling applications like buildings and industrial sectors, as shown in Fig 2.

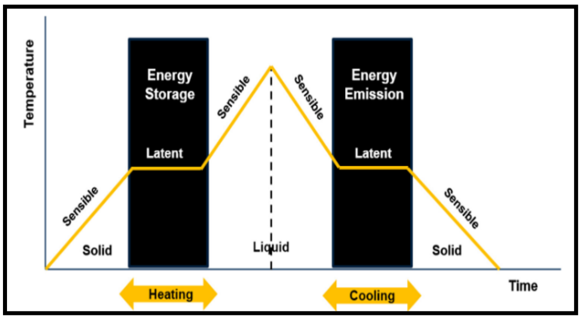


Fig. 2: Working principle of TES [4]

Recently, many researchers carried out their works based on both experimental and numerical analysis focusing on enhancement of heat transfer rate of latent heat energy storage system (LHESS) . There is various ways to increase the heat transfer rate of the system [11,13–21]. One common method is to increase outer surface area of HTF tube. An extensive literature review related to this topic has been carried out and also areas are identified which requires more attention.

Charunyakor et al. [22] carried out a numerical and experimental analysis of the effect of micro-encapsulated of a PCM where HTF flow in a circular pipe conduit. They worked on heat transfer enhancement by micro-encapsulation of a PCM on a simple shell and tube TES. They found that there was a significant enhancement of the heat transfer coefficient, which is about two to four times higher than single-phase flow.

Velraj et al. [23] presented a paper on heat transfer enhancement techniques based on numerical and experimental analysis with the incorporation of different fin configurations, i.e., longitudinal and lesser rings on a simple shell and tube type LHS systems. They observed that after the incorporation of fin and lesser rings, there was a drastic reduction in solidification time and a slight loss in total heat extraction per unit tube length. Also, heat transfer has been enhanced by perforated blocks in solar air heater [14–19, 22]. Agarwal and Sarviya [29] carried out an experimental work on a horizontal shell and tube type LHS. Air was used as HTF and paraffin as a PCM. Thermal characteristics of LHS have been determined. Cumulative energy stored was determined to evaluate the thermal performance of the system. It was observed that due to the buoyancy effect, the melting rate is higher at the uppermost part, and charging and discharging times increases by decreasing inlet temperature of HTF.

Majumdar and Gong [30] carried out a numerical work in order to determine the influence of parallel and counter flow directions on thermal performance in a shell and tube type LHESS. It was observed that the parallel flow model has a 5% higher charge/discharge rate than the counterflow model. Also, there was no effect of super-cooling for parallel flow as compared to the counter flow at the fluid entry-level. Yang et al. [31] presented an experimental study of a vertical shell and tube type heat exchanger comparing the thermal performance of the system with/without circular fins. They observed that there was a significant enhancement of heat transfer characteristics due to the increase in the surface area of the HTF tube. Avci et al. [32] performed an experimental work out on the effect of fin edge length ratio on melting and solidification times in a vertical shell and tube type heat exchanger. Abdulateef et al. [33] carried out both experimental and numerical studies on the effect of different fin configurations, namely longitudinal and triangular types on melting and solidifying times on triplex tube heat exchanger type LHESS.

In order to enhance the heat transfer of the thermal storage system by the inclusion of longitudinal fin configuration, followings are the objectives of the study as;

i. To study and identify the system and working parameters.
ii. To design and fabrication of an experimental work.

iii. To conduct experiments for performance analysis of a shell and tube type PCM storage system.
iv. To compare the system performances with and without longitudinal fin configurations.
v. To recommend the optimal parameters of PCM storage system under different operating conditions.

2. Methods

Schematic and photographic views of this experimental setup are shown in Fig. 3. The setup is used to carry out the performance analysis of phase change material storage system. The performance is analyzed based on the variation of inlet temperatures and mass flow rates of HTF during each charging and discharging cycle. Paraffin wax is used to store heat, and water is used as HTF.

The setup consists of a heat storage system, K-type thermocouples, data logger, water- heater, storage tanks for water, rotameter, control valves, and pump. Paraffin wax is filled inside the shell through a window provided. Water is permitted to flow through a central tube from the upper plenum section.

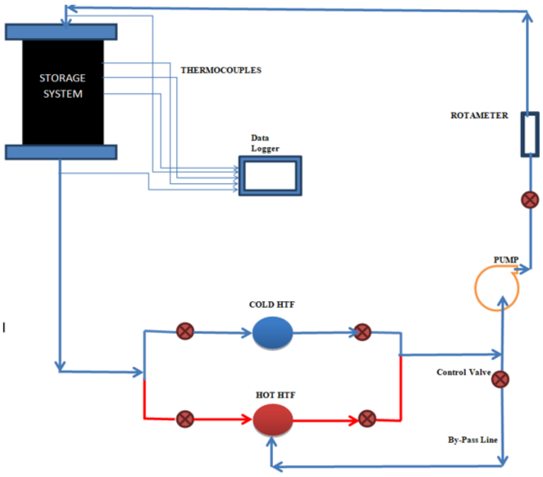


Fig. 3: Schematic diagram of an experimental setup

The temperature of PCM, inlet, and outlet temperatures of the HTF is measured with the help of thermocouples located at different radial and axial positions, as shown in Fig. 4. These thermocouples are connected to a computer through a data logger. A rotameter measures flow rate of heat transfer fluid. The outer surface of heat storage system, HTF carrying pipelines, joints, etc. are properly insulated by using polyethylene foam to prevent heat loss. An electric heater of 1 kW capacity is placed into a hot storage tank to heat the HTF at the required temperature. Control valves positioned at different locations are used to control the flow rate of HTF [27].

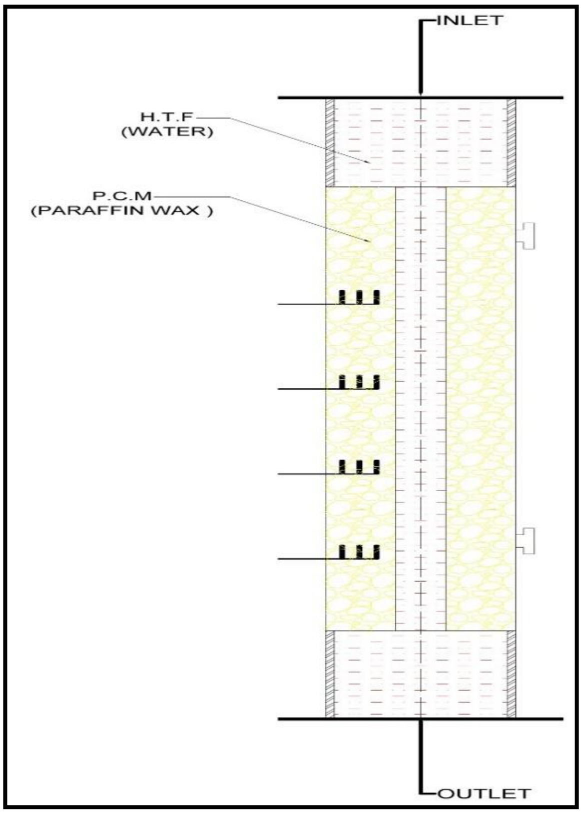


Fig. 4: Cross-sectional view of a heat storage unit

3. Modelling of longitudinal fin configuration

Longitudinal fin is adapted to enhance the heat transfer rate in the system. Design and modeling of this fin configuration have been done with the help of SOLIDWORKS and AUTOCAD software. The comparison of system performance parameters under different operation conditions is carried out for two different cases i.e., without fin and with longitudinal fin, as shown in Fig. 5 (a) and (b), respectively.

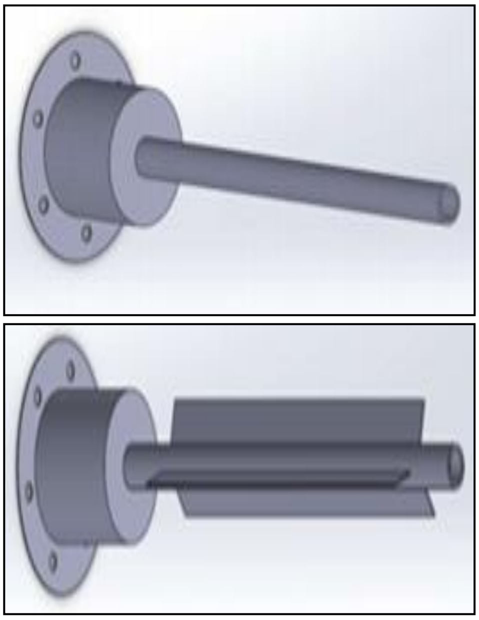


Fig. 5 (a) Without fin and (b) With longitudinal fins

The detail dimensions of a longitudinal fin configuration are shown in Fig. 6.

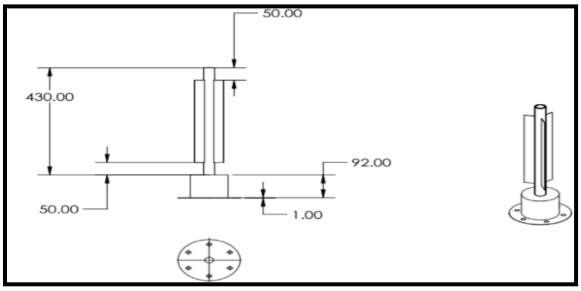


Fig. 6: Longitudinal configuration of a fin arrangement.

4. Thermo-physical properties of PCM and HTF used

Various thermo-physical properties of paraffin wax and water were studied and tested using an instrument Differential Thermal Analyzer (DTA).The properties of paraffin wax & water are obtained as tabulated in Tables 1 and 2.

Table 1: Properties of PCM (Paraffin Wax)

Property	Value
Melting Temperature Range	50.29°C to 59.17°C (54.9°C)
Latent Heat	176 kJ/kg
Specific Heat	1.92 kJ/kg K
Density	845.4 kg/m^3
Thermal Conductivity	0.18 W/mK
Viscosity	0.004416 Ns/m^2

Table 2: Properties of HTF (Water)

Property	Value
Density	997 kg/m^3
Specific Heat at 90°C	4.199 kJ./ kg K
Specific Heat at 80°C	4.197 kJ./ kg K
Specific Heat at 70°C	4.191 kJ/kg K

5. Results

A series of experiments were performed for defined operating parameters, namely inlet temperature of HTF for both charging and discharging cycles. The system operates at HTF inlet temperatures of 70°C, 80°C, and 90°C and mass flow rates of 0.066 kg/s and 0.085 kg/s. Based on various system parameters like charging and discharging times, the total energy stored by PCM, charging, and system efficiencies, the performance of a vertical shell and tube type LHESS is defined and discussed in the following sections.

The effects of varying inlet temperatures of HTF on charging and discharging times, cumulative/total energy stored in the PCM, charging, and system efficiencies have been assessed for a shell and tube type LHESS with and without the use of longitudinal fins. The experiments were carried out by varying the varying inlet temperature of HTF at 70°C, 80°C, and 90°C.

5.1 Charging/melting time

The effect of varying inlet temperatures of HTF on charging time for both the cases, i.e., with and without fins, was found to be lesser when the inlet temperature is higher. It took charging times, without fin case, nearly 255 minutes, 180 minutes, and 150 minutes to complete melt the PCM with inlet temperatures of 70°C, 80°C, and 90°C, respectively as shown in Fig. 7. Also, nearly 210 minutes, 160 minutes, and 130 minutes to complete melt the PCM with an inlet temperature of 70°C, 80°C, and 90°C, respectively, for longitudinal fins.

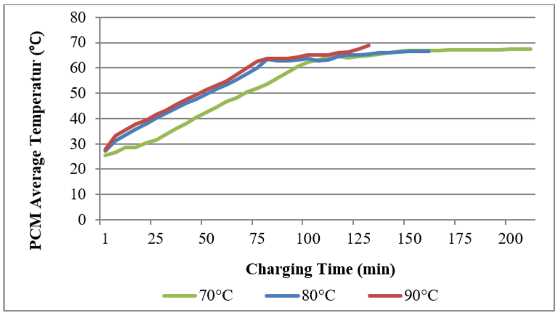
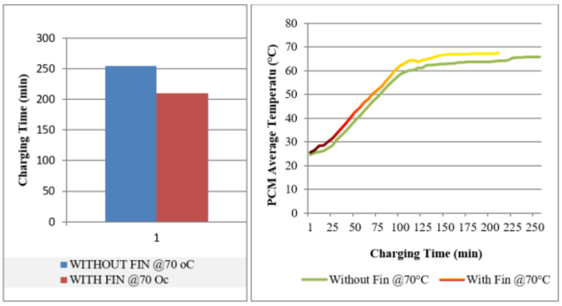


Fig. 7: Effects on charging times by varying HTF`s inlet temperatures with fins.



(a) (b)

Fig. 8: Effect of fins on charging times at an HTF`s inlet temperature of 70°C

Various technologies are there to reduce the charging time; application of fin is one of them. The minimum value of charging time represents a significant heat transfer rate, and optimal value of system performance as shown in Fig. 8.

5.2 Discharging/solidification time

It is the time to complete the solidification of a liquid PCM while releasing heat to the HTF. Lesser the discharging time, the faster the heat transfer rate and discharge rate has to match with the energy demand rate for effective thermal energy storage. It took discharging times for without fin case, nearly 175 minutes, 135 minutes, and 105 minutes to complete solidification with an inlet temperature of 70°C, 80°C, and 90°C, respectively as shown Fig. 9. Also, nearly 140 minutes, 115 minutes, and 95 minutes took to complete solidification with inlet temperatures of 70°C, 80°C, and 90°C, respectively, for longitudinal fins.

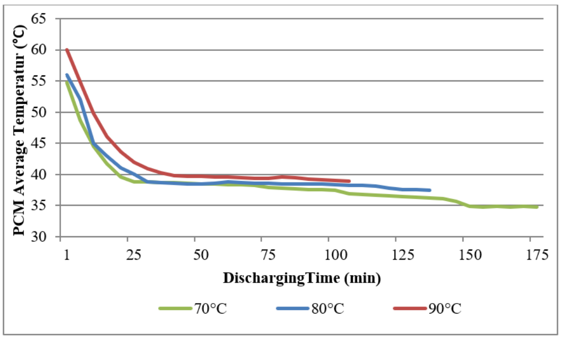
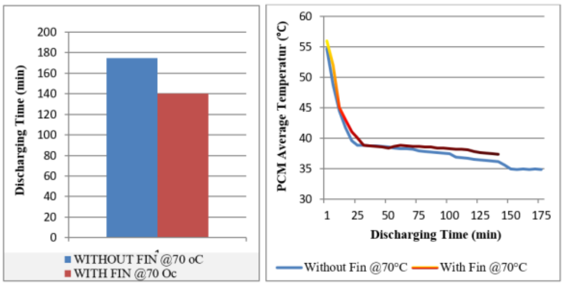


Fig. 9: Effects on discharging times by varying HTF`s inlet temperatures without fins

The effect of with and without application of fins on discharging time is shown in Fig. 10.



(a) (b)

Fig. 10: Effect of fins on discharging times at an HTF`s inlet temperature of 70°C

5.3 Total energy storage by PCM

The effect of varying inlet temperatures of HTF on cumulative/total energy storage by PCM is shown in Fig. 11. The total energy storage initially remained the same for both the cases, but after some time, there was higher energy storage for higher inlet temperature. The cumulative energy storage decreases with the decrease in the inlet temperatures of HTF, considered as 90°C, 80°C, and 70°C. The cumulative/total energy storage by PCM for without fin case, nearly 744.86 kJ, 768.29 kJ, and 789.36 kJ with an inlet temperature of 70°C, 80°C, and 90°C, respectively.

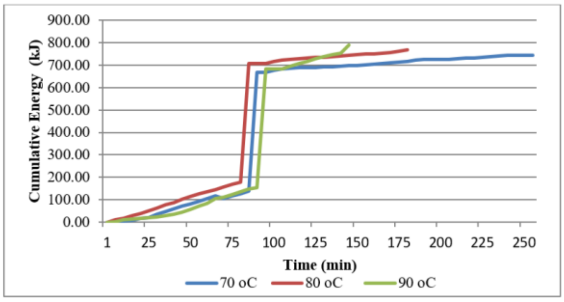


Fig. 11: Effects of varying HTF`s inlet temperature on the cumulative energy storage

The effect of longitudinal fins on total energy/cumulative energy storage in PCM is shown in Fig. 12.There was a drastic influence on cumulative energy storage in PCM with incorporation of longitudinal fins. A higher value of cumulative energy stored with the use of fins, which was around 767.57 kJ and without fins, was around 744.86 kJ at 70°C.

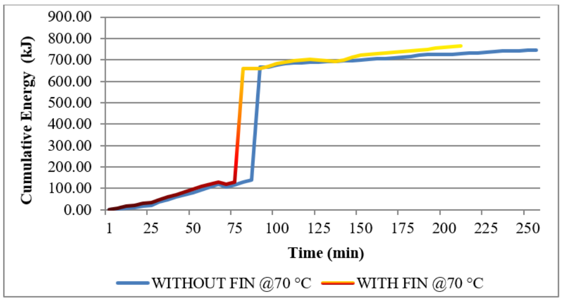
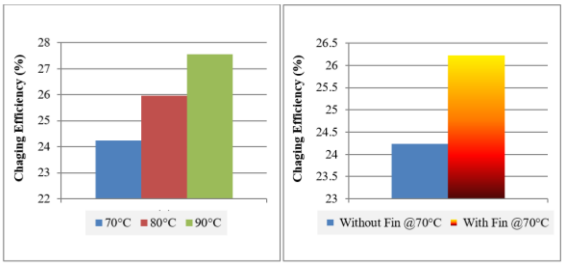


Fig. 12: Effects of longitudinal fins on the cumulative energy storage.



(a) (b)

Fig. 13: Effects of (a) varying HTF`s inlet temperatures and (b) with and without fin on charging efficiency at 70°C of HTF`s inlet temperature

5.4 Charging Efficiency

The effect of varying inlet temperatures of HTF on charging efficiency for both the cases, i.e., with and without fins, was found to be higher when inlet temperature was higher. The charging efficiency increases with the increase in inlet temperatures of HTF that were around 24.23%, 25.96%, and 27.56% with inlet temperatures of 70°C, 80°C, and 90°C, respectively. Apparently, with the use of fins, there was also an increase in charging efficiency from 24.23 % to 26.83% at 70°C of HTF inlet, as shown in Fig. 13.

5.5 System efficiency

The system efficiencies increase with the increase in inlet temperatures of HTF that was around 35.69%, 38.68%, and 41.32% with inlet temperatures of 70°C, 80°C, and 90°C, respectively. Moreover, with the use of fins, there was an increase in the system efficiency from 38.68% to 42.38% at 80°C of HTF inlet, as shown in Fig. 14.

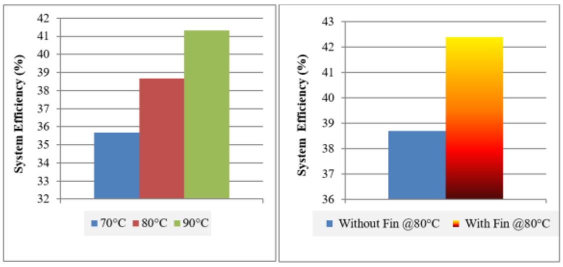


Fig. 14: Effects of (a) varying HTF`s inlet temperatures and (b) with and without fin on system efficiency at 80°C of HTF`s inlet temperature

6. Conclusions

There are various techniques to enhance the performance of the simple shell and tube type LHESS as PCM has low thermal conductivity. There is a significant enhancement in the performance of this system with longitudinal fins. Conclusion and recommendations drawn from a series of experiments carried out while varying two major parameters of the system, namely inlet temperature, and mass flow rates of HTF are discussed below.

Under this work, two different cases are studied, and a series of experiments are carried out while varying inlet temperature of HTF i e. (a) shell and tube type without fins and (b) shell and tube with longitudinal fins. Based on the experimental study following conclusions are draw;

i) During charging cycle, a layer near to HTF tube melt first followed radially to the nearby layer. In contrast, during the discharging cycle where layers near to HTF tube solidify first, followed by bordering layers radially.

ii) The inlet temperature of heat transfer fluid plays a vital role in governing the performance of this system. The performance in terms of thermal energy storage (744.86 kJ at 70°C and 789.36 kJ at 90°C) is higher at higher values of inlet temperatures with less charging time (255 minutes at 70°C and 150 minutes at 90°C) and higher system efficiency (35.69 % at 70°C and 41.32 % at 90°C)

References

[1] IEA, "EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia - Today in Energy," *U.S. Energy Information Administration (EIA)*. 2019.

[2] "Indian Renewable Energy Industry - Update." pp. 1–9, 2018.

[3] T. Alam, R. P. Saini, and J. S. Saini, "Experimental Investigation of Thermohydraulic Performance of a Rectangular Solar Air Heater Duct Equipped with V-Shaped Perforated Blocks," *Adv. Mech. Eng.*, vol. 2014, pp. 1–11, 2014.

[4] T. Alam, R. P. Saini, and J. S. Saini, "Heat and flow characteristics of air heater ducts provided with turbulators—A review," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 289–304, Mar. 2014.

[5] T. Alam, R. P. Saini, and J. S. Saini, "Use of turbulators for heat transfer augmentation in an air duct – A review," *Renew. Energy*, vol. 62, pp. 689–715, Feb. 2014.

[6] T. Alam and M. H. Kim, "A critical review on artificial roughness provided in rectangular solar air heater duct," *Renew. Sustain. Energy Rev.*, vol. 69, no. October 2016, pp. 387–400, 2017.

[7] T. Alam, R. P. Saini, and J. S. Saini, "Use of turbulators for heat transfer augmentation in an air duct – A review," *Renew. Energy*, vol. 62, pp. 689–715, Feb. 2014.

[8] Karmveer, N. Kumar, and T. Alam, "A Review on Augmentation in Thermal Performance of Solar Water Heater using Phase Change Material," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1116, no. 1, p. 12075.

[9] Karmveer, N. K. Gupta, and T. Alam, "Applications of Nanofluid in the thermal devices: A Review," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1116, no. 1, p. 12010.

[10] Karmveer, N. K. Gupta, and T. Alam, "A Review on Augmentation in Thermal Performance of Solar Air Heater," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1116, no. 1, p. 12064.

[11] T. Alam, R. P. Saini, and J. S. Saini, "Packed Bed Solar Energy Storage : A State-of-Art Review," *Int. Glob. J. Eng. Reasearch*, vol. 9, no. 1, 2014.

[12] T. Alam and K. Kulkarni, "Municipal Solid Waste Management and its Energy Potential in Roorkee City, Uttarakhand, India," *J. Inst. Eng. Ser. A*, vol. 97, no. 1, 2016.

[13] T. Alam and M. Kim, "Numerical study on thermal hydraulic performance improvement in solar air heater duct with semi ellipse shaped obstacles," *Energy*, vol. 112, pp. 588–598, 2016.

[14] T. Alam and M. Kim, "Heat transfer enhancement in solar air heater duct with conical protrusion roughness ribs," *Appl. Therm. Eng.*, vol. 126, no. 5, pp. 458–469, 2017.

[15] T. Alam and M.-H. Kim, "Thermohydraulic performance of solar air heater duct provided

with obstacles," 대한설비공학회 학술발표대회논문집, pp. 1047–1048, 2016.

[16] N. B. Balam, A. Gupta, T. Alam, and A. Kumar, "Numerical Solution to Natural Convection in Rectangular Enclosures."

[17] T. Alam, A. Kumar, and N. B. Balam, "Thermo-Hydraulic Performance of Solar Air Heater Duct Provided with Conical Protrusion Rib Roughnesses," in *Advances in Energy Research, Vol. 2*, Springer, Singapore, 2020, pp. 159–168.

[18] T. Alam and N. B. Balam, "Performance Evaluation of Double Glaze Flat Plate Solar Thermal Collector," *VW Appl. Sci.*, vol. 2, no. 1, pp. 59–63, 2020.

[19] N. B. Balam, T. Alam, and A. Gupta, "Transient Numerical Model for Natural Convection Flow in Flat Plate Solar Collector," in *Proceedings of the 7th International Conference on Advances in Energy Research*, 2021, pp. 371–381.

[20] T. Alam and M. H. Kim, "Performance improvement of double-pass solar air heater – A state of art of review," *Renew. Sustain. Energy Rev.*, vol. 79, 2017.

[21] T. Alam and M. H. Kim, "A comprehensive review on single phase heat transfer enhancement techniques in heat exchanger applications," *Renew. Sustain. Energy Rev.*, vol. 81, 2018.

[22] P. Charunyakorn, S. Sengupta, and S. K. Roy, "Forced convection heat transfer in microencapsulated phase change material slurries: flow in circular ducts," *Int. J. Heat Mass Transf.*, vol. 34, no. 3, pp. 819–833, 1991.

[23] R. Velraj, R. V. Seeniraj, B. Hafner, C. Faber, and K. Schwarzer, "Heat transfer enhancement in a latent heat storage system," *Sol. Energy*, vol. 65, no. 3, pp. 171–180, 1999.

[24] T. Alam, R. P. Saini, and J. S. Saini, "Heat Transfer Enhancement due to V-Shaped Perforated Blocks in a Solar Air Heater Duct," *Appl. Mech. Mater.*, vol. 619, pp. 125–129, Aug. 2014.

[25] T. Alam, R. P. Saini, and J. S. Saini, "Experimental investigation of thermohydraulic performance of a rectangular solar air heater duct equipped with V-shaped perforated blocks," *Adv. Mech. Eng.*, vol. 2014, 2014.

[26] T. Alam, R. P. Saini, and J. S. Saini, "Effect of circularity of perforation holes in V-shaped blockages on heat transfer and friction characteristics of rectangular solar air heater duct," *Energy Convers. Manag.*, vol. 86, pp. 952–963, Oct. 2014.

[27] T. Alam, R. P. Saini, and J. S. Saini, "Experimental investigation on heat transfer enhancement due to V-shaped perforated blocks in a rectangular duct of solar air heater," *Energy Convers. Manag.*, vol. 81, pp. 374–383, May 2014.

[28] T. Alam, R. P. Saini, and J. S. Saini, "Experimental investigation of thermo hydraulic performance due to angle of attack in solar air heater duct equipped with V–shaped perforated blockages," *Int. J. Renew. Energy Technol.*, vol. 6, no. 2, pp. 164–180, 2015.

[29] A. Agarwal and R. M. Sarviya, "An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material," *Eng. Sci. Technol. an Int. J.*, vol. 19, no. 1, pp. 619–631, 2016.

[30] Z. X. Gong and A. S. Mujumdar, "Finite-element analysis of cyclic heat transfer in a shell-and-tube latent heat energy storage exchanger," *Appl. Therm. Eng.*, vol. 17, no. 6, pp. 583–591, 1997.

[31] H. Cheng *et al.*, "Experimental study of a shell-and-tube phase change heat exchanger unit with/without circular fins," *Energy Procedia*, vol. 152, pp. 990–996, 2018.

[32] O. K. Yagci, M. Avci, and O. Aydin, "Melting and solidification of PCM in a tube-in-shell unit: Effect of fin edge lengths' ratio," *J. Energy Storage*, vol. 24, no. May, p. 100802, 2019.

[33] A. M. Abdulateef, J. Abdulateef, S. Mat, K. Sopian, B. Elhub, and M. A. Mussa, "Experimental and numerical study of solidifying phase-change material in a triplex-tube heat exchanger with longitudinal/triangular fins," *Int. Commun. Heat Mass Transf.*, vol. 90, no. December 2017, pp. 73–84, 2018.