Effect of Thermal Stratification and Insulation on the Performance of Parabolic Trough Collector

Prem Kumar T, Naveen C, Avinash Kumar R, N. Praveen Kumar

Abstract*: Parabolic trough collector (PTC) is a two dimensional solar focusing collector which collects beam radiation on tracking. In this research, closed parabolic trough solar collector of aperture area 0.6979 m^2, copper tube receiver with black powder coating of diameter 22.6 mm, surface area of 0.05996 m^2 is used. The concentration ratio (CR=Aa/Ar) of the PTC is 11.3. PTC is provided with top glass cover to induce greenhouse effect and to protect the reflector surface from dirt, weather, oxidation. The significance of insulation & thermal stratification and its effect on the performance of parabolic trough collector is studied. Non insulated storage tank led to high collection efficiency till 14:00 pm whereas it lead significant drop in system efficiency after that. Because of stirring the effect of thermal stratification was collapsed which reduces the thermo symphonic effect. This led to reduction in the system efficiency (difference of 16 %) of parabolic trough collector and also reduced the final temperature attained by water (difference of 4^{o}C) in the storage tank. Hence insulation of storage tank without stirring is preferred for higher efficiency (maximum storage efficiency of around 73.91 %) and higher final temperature of water (59.7 ^{o} C).

Index Terms*: Parabolic Trough Collector (PTC), Thermal stratification, insulation, Efficiency.

I. INTRODUCTION

Energy consumption per person is in the trend of increasing nature day by day. Hence the demand pulls the supply of energy source. Hence the dependence of fossil fuels could not be avoidable but it leads to global warming as well as depletion of its own. In order to meet the energy gap, it is essential to move towards the renewable energy. If certain amount of energy gap could be met by renewable energy, dependence on fossil fuels will come down. Hence energy dependence on other countries for energy source will come down, which can pave the way for sustainable development and energy security of one's own nation. Solar energy is one of the renewable energy sources and is widely used for many applications includes solar heating, solar drying, [1] [2] [3][4][5], anaerobic reaction [6], solar distillation [7] and power generation too. In the area of solar thermal applications contribution of flat plate collectors and parabolic trough collectors are remarkable [8, 9]. Many researches have been done to improve the efficiency of PTC like inclusion of glass covers over the aperture area [10], changing the material of receiver tube like steel, copper, aluminum and even alloys , changing the coating of the receiver tube like high absorptivity black paints, black powder[11] [8] etc.

Thermal stratification is the phenomena of formation of different layers of water in different temperature. Because of the density of difference the top layer will be occupied by the hot water and bottom will be occupied by high density cold water. These layers are separated by the layer called thermocline which is also called as region of rapid temperature range. Lot of researches has been carried over the thermal stratification, its effect and its benefits. The effect of position of phase change materials on thermal stratification in a solar water tank is analyzed in detailed manner. The impact of its position, diameter of PCM balls along with the water flow rate is analyzed and compared. [12][13][14]. The effect of thermal stratification is also compared with natural convection by certain researchers and also concluded such that both are interdependent with each other [15]. Apart from the study in solar water tanks, the effect of thermal stratification is studied in cryogenic tanks [16] , cooling channels for liquid rocket engines [17], pressurizer surge line [18], liquid metal pools [19], liquid hydrogen tank [20]. All the researchers reported the significance of thermal stratification in the different applications [21-25]. Hence it is decided to study the effect of thermal stratification and its effect on parabolic trough collector is analyzed in detail in this study along with the effect of insulation of storage tank.

II. EXPERIMENTAL SETUP

The closed loop setup was connected for the study of PTC over the day and it is shown in the figure 1. The inlet and outlet hose pipes (i.e. inlet and outlet of the receiver) were drilled and K type thermocouples had been inserted. It was calibrated by means of using standard air bath (AMETEK CT650B). Thermocouples (K-Type) were connected to data logger (Yokogawa GX20). Different temperature levels were fixed in the air bath and corresponding readings measured by thermocouples (data logger reading) were noted down. Difference between the two temperatures was calculated and appropriate calibration was carried out.

Revised Manuscript Received on April 26, 2019.

Mr.Prem kumar T, Assistant Professor, PSG Institute of technology and Applied research, Coimbatore, Tamil Nadu, India.

Dr.Naveen C, Assistant Professor, SRM Institute of science and technology, Kancheepuram,Tamilnadu , India.

Mr.Avinash kumar R, Assistant Professor, PSG Institute of technology and Applied research, Coimbatore, Tamil Nadu, India.

Mr. N. Praveenkumar, Assistant Professor, Dr. Mahalingam College of Engineering and technology, Pollachi, Tamil Nadu , India

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

The overhead tank was connected to the PTC by hoses through main inlet valve and T pipe. This tank was mainly used to fill the water in the storage tank initially or at the start of every experiment. The main valve also can be opened if the thermos phonic effect stopped at any point of time. The valve can be operated manually. The outlet of the PTC was connected to the storage tank top end with the help of hoses. The bottom of the storage tank is connected to the inlet of the PTC through connecting valve and T joint. The connecting valve should be closed whenever the main valve is opened. This is to ensure that the water from the overhead tank follows the path through the receiver of the PTC and hence first heating can be done there. The inlet, outlet and top cover of the storage tank were drilled to insert the thermocouples which were connected to the data logger for the measurement of the temperature.

Figure 1: Experimental setup (PTC)

III. RESULTS AND DISCUSSION

Experimentation without stirring and with insulation of storage tank

Figure 2 explained about the temperature distribution of water all over the storage tank (measured at four different places say top T1, upper middle T2, lower middle T3 and bottom T4) for the experimentation without stirring. The collector efficiency and system efficiency were calculated and it is shown in figure 3 . The efficiency analysis was done in figure 4 between different time interval and storage efficiency was found to be minimum at time interval 13.00-14.00 p.m. The heat analysis was done and shown in the figure 5 where the heat collected ,stored and input heat were mentioned in kJ.

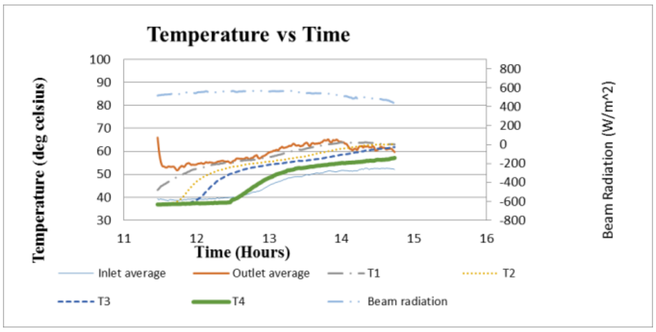

Figure 2: Temperature distribution over the time period

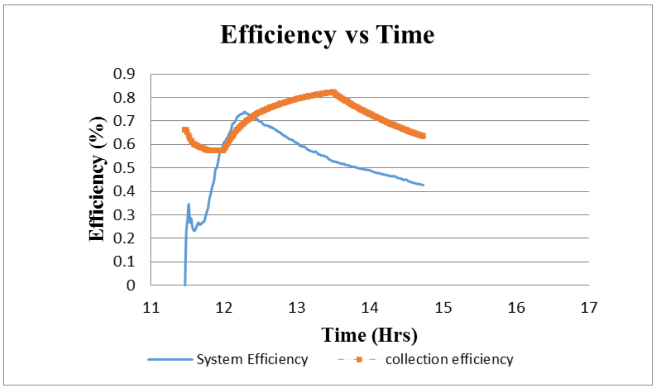

Figure 3: Comparison of collection efficiency and system efficiency

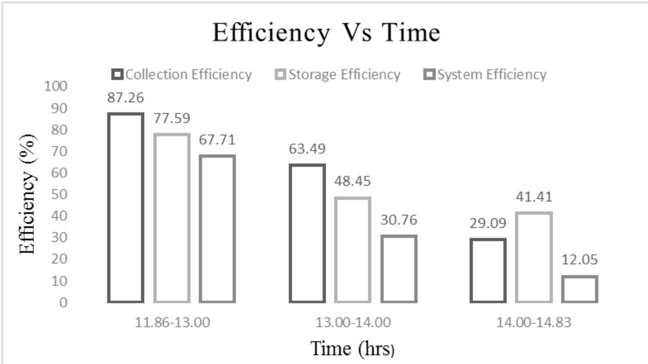

Figure 4: Efficiency analysis over the time period

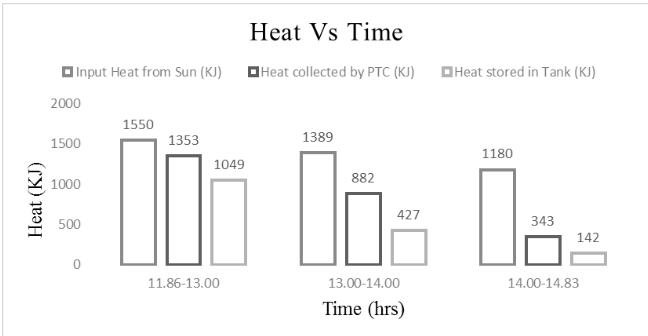

Figure 5: Heat analysis over the time period

Sudden steep in the temperature of the outlet water is noted up to 68 ^{o}C during initial startup of the experiment. This is mainly because initial time lag for the start of the thermo shyphon effect. Initially the water inside the receiver will be heated and there won't be any movement of water. Hence there is sudden increase in collection efficiency is also observed in figure 3. Once the water is heated (here up to 68 ^{o}C), the water become less dense. And this reduction in density and the relatively high inlet pressure of water due to water head in the storage tank caused the forward movement of water and the hot water reaches the top of the storage tank. This effect causes the effect of thermal stratification.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

It accelerates the effect of thermo syphon because of the temperature difference between the water at inlet of the PTC receiver and water at the top of the storage tank. Till the attainment of thermal stratification (till 11:50 am) there is some drop in collection efficiency is also observed and after that it increases. The effect is further witnessed by viewing the temperature distribution graph over the height of the storage tank. The temperature of top layer of water in the storage tank is increased at higher rate. Whereas the temperature of upper middle and lower middle moved at lower rate. The bottom layer water temperature is increased with lesser rate and even up to 12:20 pm the temperature is almost constant. Although it seems to be negative effect i.e. lesser average temperature of water in the storage tank, it paves the way for higher motive force i.e. thermal stratification which will be discussed in next section.

Because of the better motive force for themo syphon i.e. thermal stratification and high beam radiation till 13:30 pm the collection efficiency reached the maximum value of 81 %. The system efficiency too attained the maximum of 72.08 % at 12:20 pm. One of the main reasons for reduction in system efficiency after 12:20 pm is because of the temperature raise of water which is linearly proportional to heat losses to the atmosphere. Heat loss to atmosphere will be in increasing trend if the difference between water and atmospheric air is more. Even at the end of the experiment, the system efficiency is found to be 41 % which is appreciable. The heat stored during the 14.00 -15.00 p.m. time interval was very low i.e. 142 kJ whereas the amount of heat collected was around 343 kJ. One of the main reasons will be more heat loss from the system to surroundings as the temperature difference between hot water and atmosphere increases. During the time interval, collector efficiency was also very less due to decreasing trend of beam radiation after peak point. It is also observed the temperature difference between the outlet water temperature from PTC and inlet water is also in the decreasing mode which actually collapses the effect of thermal stratification. This is also one of the reasons for the reduction in collection efficiency as the time proceeds after 13:20 pm.

Effect of thermal stratification

In order to study the effect of thermal stratification, the same experiment is repeated but along with the stirring the water in the storage tank at regular intervals. Stirring is done four times at 12.00 pm, 12:30 pm, 13.00 pm and 13 .20 pm. Figure 6 explained about the temperature distribution of water in the storage tank.

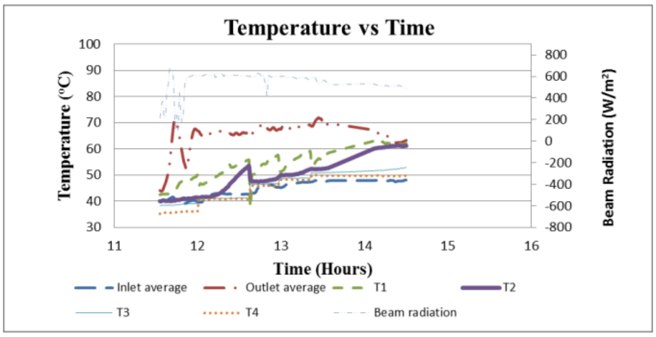

Figure 6: Temperature distribution over the time period

It is clear that effect of thermal stratification was reduced due to stirring. Immediately after the first stirring i.e. at 12:00 pm, the top layer temperature of water dropped down significantly from 50 °C to 46 °C. The upper middle temperature is almost constant whereas there is significant hype in lower middle and bottom layer temperature readings. Now the entire tank is at same temperature. This nullifies the effect of thermal stratification and hence the effect of thermo syphon is threatened. Then once again after certain time period the same pattern is repeated. It is observed that after each stirring of water in the storage tank the top layer temperature dropped down whereas the lower middle and bottom layer temperature increased up to average temperature. The upper middle layer water temperature almost maintained the constant value because of its closeness wither average temperature. Because of this fluctuation and collapse of thermal stratification at regular intervals, there is abrupt raise and fall in the system efficiency which is shown in figure 7. The collection efficiency maintained constant nature i.e. 70 % but attained less efficiency because of higher inlet temperature of water.

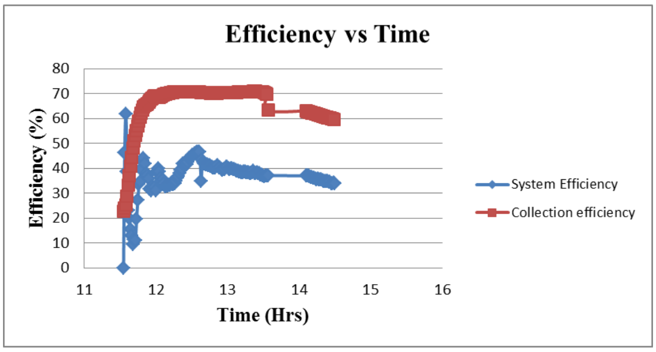

Figure 7: Comparison of collection efficiency and system efficiency

The summary of the effect of thermal stratification is listed in table 1 along with the insulation effect which will be explained later.

Table 1: Effect of insulation and stirring

Quantity of water (L)	Time (hrs)	Stirring (Y/N)	Insulation of tank (Y/N)	Maximum Temperature achieved by tank water (°C)	Final temperature at end of exp (°C)	Maximum System Efficiency at time interval (%)	Final efficiency at the end of exp (%)	Average beam radiation over the time period (W/m²)
18.3	3.14	Yes	No	65.7	54.9	51.54	26.56	535
18.8	3.27	No	Yes	63.9	59.7	67.71	42.65	536
18.8	2.95	yes	Yes	62.85	55.4	51.80	33.98	553

In spite of high average beam radiation on the stirring along with insulated tank experiment's maximum system efficiency (61.87 %) as well as maximum temperature (62.85 oC) could not exceeds without stirring along with insulated tank experiment's values. The final temperature (55.4 oC) and efficiency (34%) at the end of the experiment were also not higher than without stirring experiment's values.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Hence we can conclude that stirring of water will reduce the effect of thermal stratification in the aspects of both efficiency and temperature attained by water too.

Effect of insulation of storage tank

The storage tank was not insulated and two thermocouples were used to measure the tank temperature which kept at top and bottom of the storage tank. The inlet and outlet temperature of water from PTC were measured. The temperature distribution is captured in the figure 8. Stirring was done three times i.e. during 12.90, 14.00, 14.90 p.m. The instantaneous collection efficiency was calculated over the time period and the graph was plotted in the figure 9. The maximum collection efficiency was observed to 64 %. Heat analysis was done over the time interval of different time periods say 11.8-13.00, 13.00-14.00, 14.00-15.00 and graph was plotted in figure 10. Maximum amount of heat collected is stored during the timer interval of 11.80 -13.00 p.m. and effect of lack of insulation is not visible during this time period due to high outside temperature.

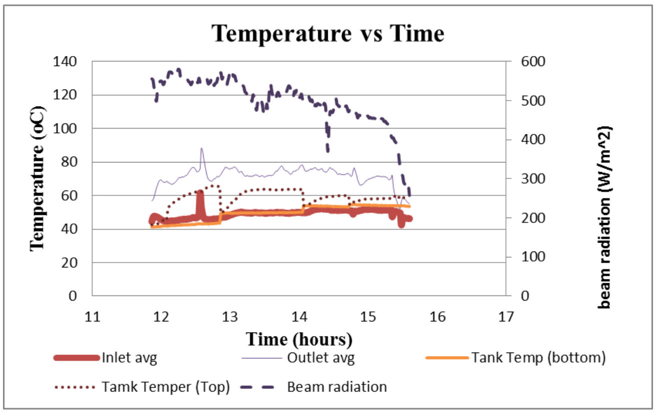

Figure 8: Temperature distribution over the time period

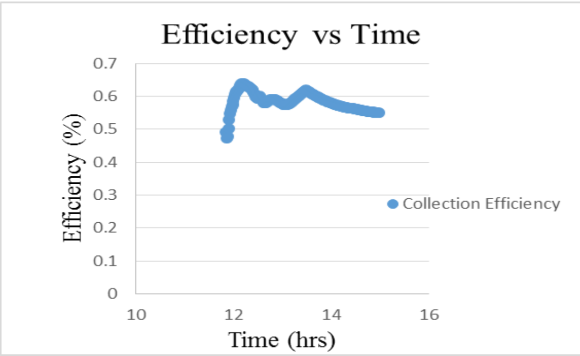

Figure 9: Collection efficiency over the time period

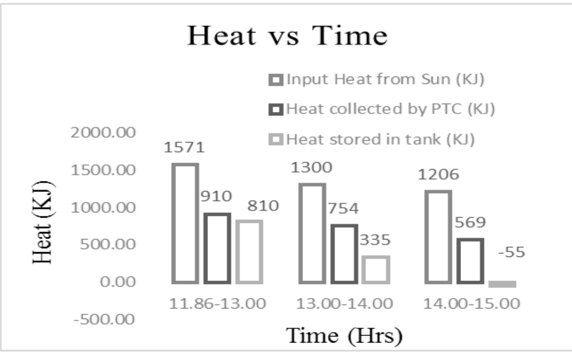

Figure 10: Heat analysis over the time period

After 13.00 pm significant drop in storage heat is found out. The negative storage after14.00 pm indicated the lack of insulation which results in negative storage efficiency as well as system efficiency too in the specific time interval which is shown in figure 11. The collection efficiency was constantly maintained around 50 – 60 % across the time intervals but the storage efficiency was maximum in 11.80-13.00 p.m. interval but minimum at 14.00-15.00 p.m. interval.

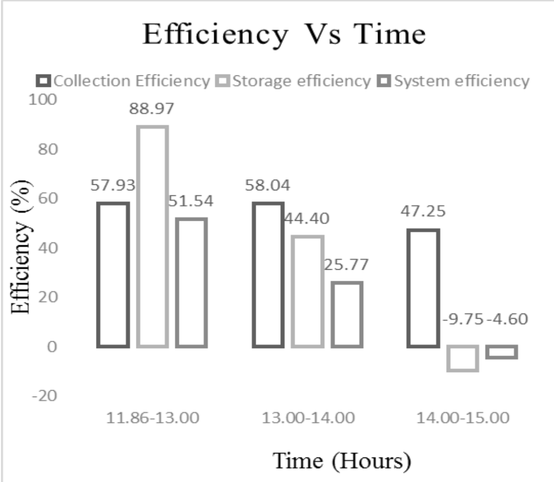

Figure 11: Efficiency analysis over the time period

The effect of insulation can be analyzed from previous figures and also with the help of Table 1. From figure 10 ,it is clear that the negative storage heat leads to reduction in the total system efficiency .Because of the absence of insulation, heat can be easily lost to the surroundings particularly during the late noon period and it is applicable to early noon period too. Out of three cases in table 1, without insulation experiment's final efficiency was very low i.e. 26.56 % compared to other day experiments. Hence insulation is preferable and suggested.

In the present set up, the hoses were not insulated. It is suggested to insulate the hoses too and hence considerable amount of heat can be saved which leads to increase in efficiency. The maximum temperature achieved in non-insulated storage tank is higher i.e. 65.7 ^{o}C than all other cases and it may due to the addition of extra heat from the surroundings particularly during the noon time period. It is also proved by high efficiency i.e. 89 % at that time interval 12.00-13.00 hours in figure 9. But at the same time final temperature attained by entire amount of water is less than all other cases which confirms the necessity of insulation.

IV. CONCLUSION

In this research closed loop circuit for PTC was done and the effect of insulation and stirring were carefully studied. It is concluded that by means of insulation considerable amount of heat can be saved from loss particularly at the time period after 14.00 p.m. By means of stirring the effect of thermal stratification was collapsed which reduces the thermo symphonic effect. This led to reduction in the system efficiency as well as final temperature of water.

Hence insulation of storage tank without stirring is preferred for higher efficiency. It was even proposed to insulate the hoses which connect the PTC with storage tank too in order to reduce the heat loss particularly when the fluid is at high temperature. Alternatively removable type of insulation (attach- retract type) in storage tank can also be incorporated and storage tank can be left non-insulated till 14:00 pm in order to attain maximum collection efficiency.

REFERENCES

[1] Pirasteh.G., Saidur.R., Rahman.S.M.A., Rahim.N.A., "A review on development of solar drying applications", Renewable and Sustainable Energy Review, vol. 31, pp. 133-148, 2014.

[2] Ekechukwua.O.V., Norton.B., "Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications", Energy Conversion & Management, vol. 40, pp. 657-667, 1999.

[3] S.Anil kumar, K.Sridhar, G. Vinod kumar, "Heat Transfer Analysis of Solar Air Heating System for Different Tilt Angles", Applied Solar Energy, vol. 54,no. 1, pp. 17–22, 2018.

[4] Abbasov.E.S., Umurzakova.M.A., and Boltoboeva.M.P., "Efficiency of solar air heaters", Applied Solar Energy, vol. 52, no. 2, pp. 97–99, 2016.

[5] Tyagi.R.K., Ravi Ranjan, and Kunal Kishore, "Performance studies on flat plate solar air heater subjected to various flow patterns", Applied Solar Energy J., vol. 50, no. 1, pp. 98–102, 2014.

[6] Zhenjieren, Zhili Chen, Li-an Hou, Wenbiao Wang ,Kaishengxiong, Xiao xiaowantuzhang, "Design investigation of a solar energy heating system for anaerobic sewage treatment", energy procedia, vol.14, pp. 255-259, 2012.

[7] Prem kumar.T, Moulieswaran.S, Pradeep.S, "Effect Of glazing and cooling on Solar Waste Water Still", IJRAR - International Journal of Research and Analytical Reviews (IJRAR), vol. 6, no. 1, pp.927-932, 2019.

[8] Rai.G.D., "Solar Energy Utilization", Khanna publishers, 2011.

[9] Tian.Y., Zhao.C.Y., "A review of solar collectors and thermal energy storage in solar thermal applications", Applied Energy, vol. 104, pp. 538-553, 2013.

[10] Alok Kumar, "Improvements in efficiency of solar parabolic trough", IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), vol. 7, no. 6, pp. 63-75, 2013.

[11] Rafael Almanza, Alvaro Lentz, Gustavo Jime´Nez, "Receiver Behavior In Direct Steam Generation With Parabolic Troughs", Solar Energy, vol. 61, no. 4, pp. 275–278, 1997.

[12] Zilong Wang, Hua Zhang Huajie Huang, Binlin Dou, Xiuhui Huang, Maria A.Goula., "The experimental investigation of the thermal stratification in a solar hot water tank", Renewable Energy, vol. 134, pp. 862-874, 2019.

[13] Karthick, S. "Semi supervised hierarchy forest clustering and knn based metric learning technique for machine learning system", Journal of Advanced Research in Dynamical and Control Systems, vol. 9, no. Special Issue 18, pp. 2679-2690, 2017.

[14] Huang, H., Wang, Z., Zhang, H., Dou, B., Huang, X., Liang, H., & Goula, M. A. (2019). An experimental investigation on thermal stratification characteristics with PCMs in solar water tank. Solar Energy, vol. 177, pp. 8–21.

[15] Weian Du., Yusheng Liu., Hongsheng Yuan., Shouxu Qiao., Sichao Tan., "Experimental investigation on natural convection and thermal stratification of IRWST using PIV measurement", International journal of Heat and mass transfer, vol. 136, pp. 128-145, 2019.

[16] Kang, M., Kim, J., You, H., & Chang, D., "Experimental investigation of thermal stratification in cryogenic tanks", Experimental Thermal and Fluid Science, vol. 96, pp. 371–382, 2018.

[17] Leonardi, M., Pizzarelli, M., & Nasuti, F., "Analysis of thermal stratification impact on the design of cooling channels for liquid rocket engines", International Journal of Heat and Mass Transfer, vol. 135,pp. 811–821, 2019.

[18] Wang, M., Feng, T., Fang, D., Hou, T., Tian, W., Su, G. H., & Qiu, S., "Numerical study on the thermal stratification characteristics of AP1000 pressurizer surge line", Annals of Nuclear Energy, vol. 130, pp. 8–19, 2019.

[19] Ward, B., Clark, J., & Bindra, H., "Thermal stratification in liquid metal pools under influence of penetrating colder jets", Experimental Thermal and Fluid Science, vol. 103, pp. 118–125, 2019.

[20] Liu.Z., Li.Y., & Zhou.G., "Study on thermal stratification in liquid hydrogen tank under different gravity levels", International Journal of Hydrogen Energy, vol. 43, no. 19, pp. 9369–9378, 2018.

[21] Karthick, S. "TDP: A novel secure and energy aware routing protocol for Wireless Sensor Networks", International Journal of Intelligent Engineering and Systems, vol. 11, no. 2, pp. 76-84, 2018. DOI: 10.22266/ijies2018.0430.09

[22] T. Sathish, and J. Jayaprakash, "Meta-Heuristic Approach to Solve Multi Period Disassembly-To-Order Problem of End-Of-Life Products using Adaptive Genetic Algorithm", International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol. 15, No. 3, pp. 59-67, 2015.

[23] T. Sathish, "Experimental investigation on degradation of heat transfer properties of a black chromium-coated aluminium surface solar collector tube", International Journal of Ambient Energy, Taylor and Francis Publishers, Vol. 39, doi: https://doi.org/10.1080/01430750.2018.1492456.

[24] Sathish, T., Jayaprakash, J. "Multi period disassembly-to-order of end-of-life product based on scheduling to maximise the profit in reverse logistic operation", International Journal of Logistics Systems and Management, vol. 26, no. 3, pp. 402-419, 2017.

[25] T. Sathish, "Heat Transfer Analysis of Nano-Fluid Flow in a converging Nozzle with different aspect Ratios", Journal of New Materials for Electrochemical Systems, Vol. 20, pp. 161-167, 2017.

[26] Sathish, T., and Karthick, S. "HAIWF-based fault detection and classification for industrial machine condition monitoring", Progress in Industrial Ecology, vol. 12, no. 1-2, pp. 46-58, 2018

AUTHORS PROFILE

Mr.Prem kumar T, Assistant Professor, Department of Mechanical Engineering, PSG iTech, Coimbatore, is having three years of teaching experience. He worked as Energy Auditor in Confederation of Indian Industry-GBC, Hyderabad for two years. He has worked in Supplier Quality Assurance department, RANE TRW for one year. His area of interest is Renewable energy, Energy auditing and Thermal sciences.

Dr. Naveen C, Assistant Professor, EEE, SRM institute of science and technology, kancheepuram,Tamilnadu-India. completed his masters and doctorate in energy engineering from NIT-Trichy He is having 3 year of teaching &research experience. His area of interest is in solar PV, thermal, waste to energy, energy efficiency and waste water treatment.

Mr Avinash Kumar R, **Assistant Professor, Department of Mechanical Engineering, PSG iTech, Coimbatore**, is having three years of teaching experience. He has worked as Assistant Professor in D Department of Automobile engineering, in Dr. Mahalingam college of engineering and technology, Pollachi before joining the present educational institution. His areas of interest are CFD, Thermal sciences and Aerodynamics.

Mr N. Praveenkumar, assistant professor in Department of Automobile engineering, in Dr. Mahalingam College of engineering and technology, Pollachi, completed his master of engineering in Thermal science. He is having 7 years of teaching and 1 year of research experience. His areas of interest are renewable energy, ic engine, alternative fuels, refrigeration and air conditioning

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication