

Theoretical Estimation of Dynamic Sol-Air Temperature in the Warm and Humid Region of India at Different Locations

LENIN V R[1]*, S AZHAGUVELAVAN[2], PRABU E[3]

[1] Department of Mechanical Engineering, Anil Neerukonda Institute of Technology and Sciences, Visakhapatnam, Andhra Pradesh, India – 531162.*

[2] Department of Mathematics, Dr. R.K. Shanmugam College of Arts and Science, Kallakurichi, Tamilnadu, India - 606213.*

[3] PG and Research Department of Mathematics, Erode Arts and Science College, Erode, Tamilnadu, India - 638009.

Corresponding authors

[1*] Lenin V R

[2*] S Azhaguvelavan

Abstract

Global warming has become a very important topic in the current context. The most important reason for this is considered to be greenhouse gases. Apart from this, a few other factors play an important role in global warming, one of which is the heat absorbed by the exterior walls of buildings. The heat thus absorbed increases the temperature of the environment and acts as a heat conductor through the walls of buildings, heating the indoor atmosphere. The primary purpose of this work is to estimate the sol-air temperature of buildings based on location, solar irradiance, absorptivity, and atmospheric temperature in warm and humid climatic conditions at different months of the year. The selected cities for this work are Chennai, Tiruchirappalli, and Visakhapatnam. In these cities, the sol-air temperature has been estimated in the month of January, July, July and October. At this location and month, the surface absorptivity has been considered in a wide range from 0.4 to 0.8. The results show that the increase in solar radiation, absorptivity and outdoor air temperature directly affects the sol-air temperature.

Keywords: *sol-air temperature, warm and humid, absorptivity, solar radiation*

Introduction

The building industry is considered to be the largest industry worldwide because housing is considered to be the most important to every human being, next to food and clothing. The maximum lifespan of a building is estimated to be 80 years [1, 2] in other countries and the lifespan of a well-maintained building in India is 75 years [3]. Buildings thus constructed are estimated to account for 89 to 93 percent of the amount of electricity and other energy consumed during its 75 years of operation. That is, the cost incurred by the beneficiaries to live inside the building after the building is completed and people have settled.

 https://doi.org/10.37896/pd91.5/91512

Assuming approximately 90% of the energy consumed during operational periods, most of that energy is used for the thermal comfort of the occupants. The amount of this energy consumption varies from continent to continent, country to country, place to place, building to building. Environmental factors such as ambient air temperature, solar radiation, wind speed, proximity to buildings, tall buildings around buildings, tree vines adjacent to buildings, and water sources nearer to buildings are also considered to be the most important factors [1, 4-6]. Factor in the building is considered to vary according to the orientation of the building, the shape of the building, the height of the building, its materials, its properties [7], the ratio of window and wall, the length and width of the room inside the building, the equipment used inside the building, the amount of its heat emission and the features made for ventilation. Apart from this, the energy consumption varies depending on the activities of the users inside the buildings door and window opening and closing[8], fan usage, fan location, AC usage, etc. The most important of these is the amount of solar radiation penetrating through windows and doors and the amount of heat energy transmitted through the wall.

Various researches have been done so far to reduce the energy consumption. Some of them are heat resistant coating on outer wall , increasing the thickness of the wall, designing the wall with various less heat absorbing materials (thermal mass) [9], constructing walls with different low heat transferring layers [10], expelling hot air naturally [7, 11-17], artificially expelling the hot air [18], identifying high heat generating equipment and replace with low heat emitting one with equivalent performance, increasing the air velocity [19] inside the building, some work is on reducing the moisture content in the atmospheric air [20-23], phase change materials [24, 25] also used to reduce the indoor heat generation [24] and lower the air temperature by means of HVAC equipment [26]. In order to estimating all the factors the main factor has to find to proceed is sol-air temperature [27]. The measured and estimated sol-air temperature comparisons have performed to find the variation among them. It was found there is a close relationship in hot-arid region [28-30]. For improving building energy efficiency on cooling load the ground temperature effect has performed in hot and dry region [31]. Some research done on adaptive indoor comfort with existing HVAC equipment [32]. The aim of this work is to predict the sol-air temperature theoretically perceived by buildings in various locations under same climatic conditions (warm & humid) with various environmental and building factors.

Methodology

The building wall material is considered to be a plane wall having different layers. It is assumed that a vertical wall has no inclination. The outside of the wall is exposed to the outdoor environment as well as solar radiation. Whereas the inside surface is exposed to an indoor environment where it is required to maintain desired low or high indoor air temperature according to the requirement. Heat transfer through the wall per square meter area is given below. It is the product of the convection heat transfer coefficient and the temperature difference between the sol-air temperature to the surface temperature.

 https://doi.org/10.37896/pd91.5/91512

ISSN: 0369-8963

$$\frac{q}{A} = h_0 \left(T_{Sol-air} - T_{Surface}\right)$$

Outdoor wall convection heat transfer coefficient is h_0.

$$T_{sol-air} = T_{Outdoor} + \frac{a\ I_{Total}}{h_0} - \frac{\varepsilon \Delta R}{h_0}$$

I_{Total} is the solar radiation, a is the absorptivity and $\frac{\varepsilon \Delta R}{h_0}$ is the correction factor which varies from 0°C (for vertical surfaces) to 4°C (for horizontal surfaces). Whenever there is inclined surface, the correction factor varies in-between values according to the inclination angle. The total solar radiation for the vertical surface can be calculated based on the below mentioned formula [33]. The ratio between the beam radiation (inclined surface) to the horizontal surface at any time is R_B.

$$I_{Total} = R_B I_{Be} + \frac{I_{Di} + I_{TH}\ \rho\ g}{2}$$

$$R_B = \frac{Cos\ \emptyset}{Cos\ \emptyset_Z}$$

I_{TH} is the total radiation, I_{Di} is the diffuse radiation and I_{Be} is the beam radiation. The ϕ_z and ϕ is the zenith angle and incidence angle, which can be estimated based on the below mentioned relations.

$$\emptyset = Sin\ \delta\ Sin\ \theta\ Cos\ \beta - Sin\ \delta\ Cos\ \theta\ Sin\ \beta\ Cos\ \gamma + Cos\ \delta\ Cos\ \theta\ Cos\ \beta\ Cos\ \omega + Cos\ \delta\ Sin\ \theta\ Sin\ \beta\ Cos\ \gamma\ Cos\ \omega + Cos\ \delta\ Sin\ \beta\ Sin\ \gamma\ Sin\ \omega$$

$$\emptyset_z = Cos\ \theta\ Cos\ \delta\ Cos\ \omega + Sin\ \theta\ Sin\ \delta$$

δ is the declination angle, θ is the latitude angle, γ is the surface azimuth angle, and ω is the hour angle. By considering all the above the final sol-air temperature relation is mentioned below where the wall is considered to be a vertical wall, hence the correction factor is zero.

$$T_{sol-air} = T_{Outdoor} + \frac{a\ I_{Total}}{h_0}$$

Hourly and monthly sol-air temperature are estimated at different locations.

Results and discussion

In this study, the impact of various factors on the south side vertical wall was considered to predict the sol-air temperature. The cities considered for this work are Chennai Tiruchirappalli and Visakhapatnam. In most cases, such cities will have many numbers of buildings with a significant population likely to be high, and these places have a uniform climate (warm and humid). Outdoor air temperature and solar radiation were measured at one-hour intervals in January, April, July,

 https://doi.org/10.37896/pd91.5/91512

ISSN: 0369-8963

and October. At the same time, the external vertical wall absorptivity is assumed to be from 0.4 to 0.8.

The sol-air temperature varies depending on the absorptivity properties of a building wall. More specifically when there is solar radiation, especially the higher absorptivity wall will have a higher sol-air temperature and the lower absorptivity wall will have a lower sol-air temperature. This is due to the fact that the solar radiation and the absorption are directly proportional to the sol-air temperature as mentioned in the formula. Its magnitude can be obtained by adding the outside air temperature to the product of the solar radiation and the surface absorptivity.

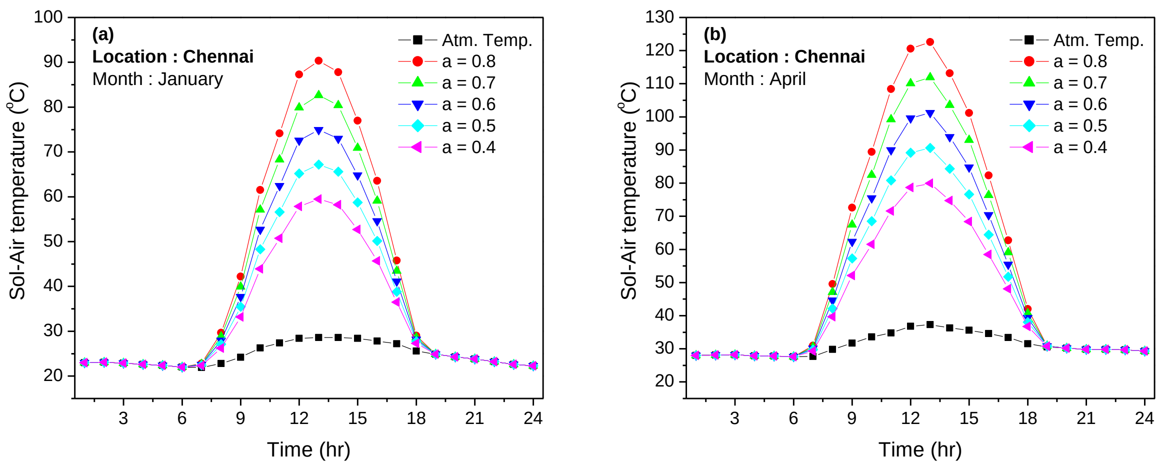
In the case of Chennai during January (Fig. 1 (a)), the amount of solar radiation recorded is 772 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 28.6°C. In this environment condition, the sol-air temperature is predicted as 59.48°C, 67.2°C, 74.92°C, 82.64°C and 90.36°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. During April (Fig. 1 (b)), the amount of solar radiation recorded is 1066 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 37.3°C. In this environment condition, the sol-air temperature is predicted as 79.94°C, 90.6°C, 101.26°C, 111.92°C and 122.58°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. During July (Fig. 1 (c)), the amount of solar radiation recorded is 666 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 33.4°C. In this environment condition, the sol-air temperature is predicted as 60.04°C, 66.7°C, 73.36°C, 80.02°C and 86.68°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. And for the October month (Fig. 1 (d)), the amount of solar radiation recorded is 724 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 31.6°C. In this environment condition, the sol-air temperature is predicted as 60.56°C, 67.8°C, 75.04°C, 82.28°C and 89.52°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. This variation is due to the fact that the amount of solar radiation falling on the ground varies with respect to zenith angle, declination angle and latitude angle. At other times the temperature of the sol-air is also lower as the amount of solar radiation is less for the rest of the hours in a day.

During January in Tiruchirappalli (Fig. 2 (a)), the amount of solar radiation recorded is 584 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 25.5°C which is 2.1°C lesser than the Chennai. In this environment condition, the sol-air temperature is predicted as 48.86°C, 54.7°C, 60.54°C, 66.38°C and 72.22°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. This temperature is also lower than the predicted value at Chennai, because solar radiation is directly proportional to the sol-air temperature. During April (Fig. 2 (b)), the amount of solar radiation recorded is 1004 W/m^2 (highest on that day) at 01.00 PM which is almost closer to the Chennai. At that time the outdoor air temperature was measured as 38.0°C. In this environment condition, the sol-air temperature is predicted as 78.16°C, 88.2°C, 98.24°C, 108.28°C and 118.32°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. During July (Fig. 2 (c)), the amount of solar

https://doi.org/10.37896/pd91.5/91512

ISSN: 0369-8963

radiation recorded is 979 W/m^2 (highest on that day) at 01.00 PM which is 300 W/m^2 higher than the Chennai. At that time the outdoor air temperature was measured as 36.1°C which is 2.7°C higher than the Chennai this is due to higher radiation in this location. In this environment condition, the sol-air temperature is predicted as 75.26°C, 85.05°C, 94.84°C, 104.63°C and 114.42°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. It is also noted that at least 15°C to 33°C temperature variation has noted due to the variation in solar radiation. And for the October month (Fig. 2 (d)), the amount of solar radiation recorded is 709 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 32.8°C. In this environment condition, the sol-air temperature is predicted as 61.16°C, 68.25°C, 75.34°C, 82.43°C and 89.52°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. This variation is due to the fact that the amount of solar radiation falling on the ground varies with respect to zenith angle, declination angle and latitude angle. At other times the temperature of the sol-air is also lower as the amount of solar radiation is less for the rest of the hours in a day.



https://doi.org/10.37896/pd91.5/91512

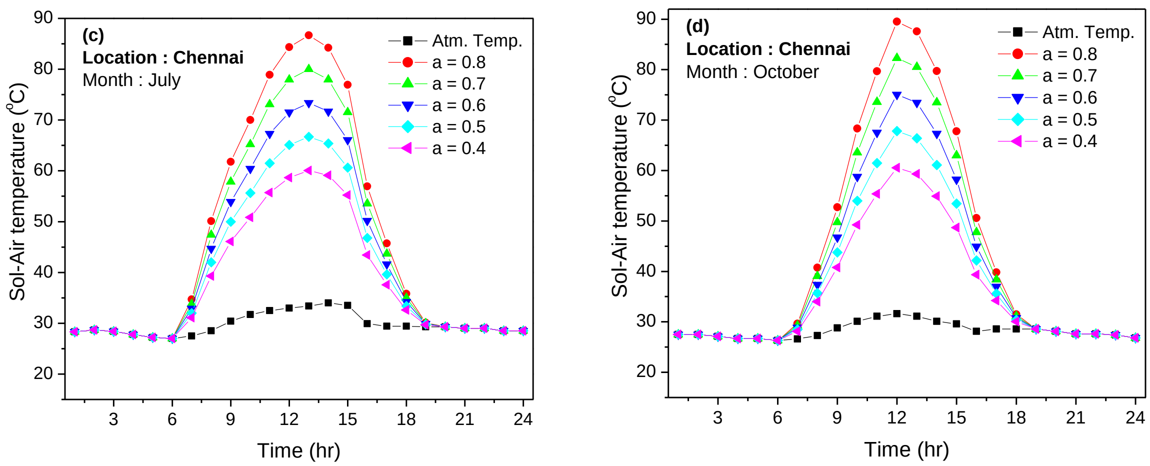


Fig. 1 Hourly variation of sol-air temperature at Chennai location

During January in Visakhapatnam (Fig. 3 (a)), the amount of solar radiation recorded is 747 W/m^2 (highest on that day) at 12.00 PM. At that time the outdoor air temperature was measured as 29.2°C which is 3.7°C greater than the Tiruchirappalli and slightly higher than the Chennai. In this environment condition, the sol-air temperature is predicted as 59.08°C, 66.55°C, 74.02°C, 81.49°C and 88.96°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. This temperature is also higher than the predicted value at Chennai as well as Tiruchirappalli, because solar radiation and outdoor air temperature is higher and is directly proportional to the sol-air temperature as mentioned in the equation. During April (Fig. 3 (b)), the amount of solar radiation recorded is 1034 W/m^2 (highest on that day) at 12.00 PM which is almost closer to the Chennai as well as Tiruchirappalli. At that time the outdoor air temperature was measured as 34.4°C. in this case there is large difference between above mentioned cities, the reason is that there are many factors associated with the outdoor air temperature such as micro climatic condition, vegetation, heat storage medium availability and so on. In this environment condition, the sol-air temperature is predicted as 75.76°C, 86.1°C, 96.44°C, 106.78°C and 117.12°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively.

 https://doi.org/10.37896/pd91.5/91512

ISSN: 0369-8963

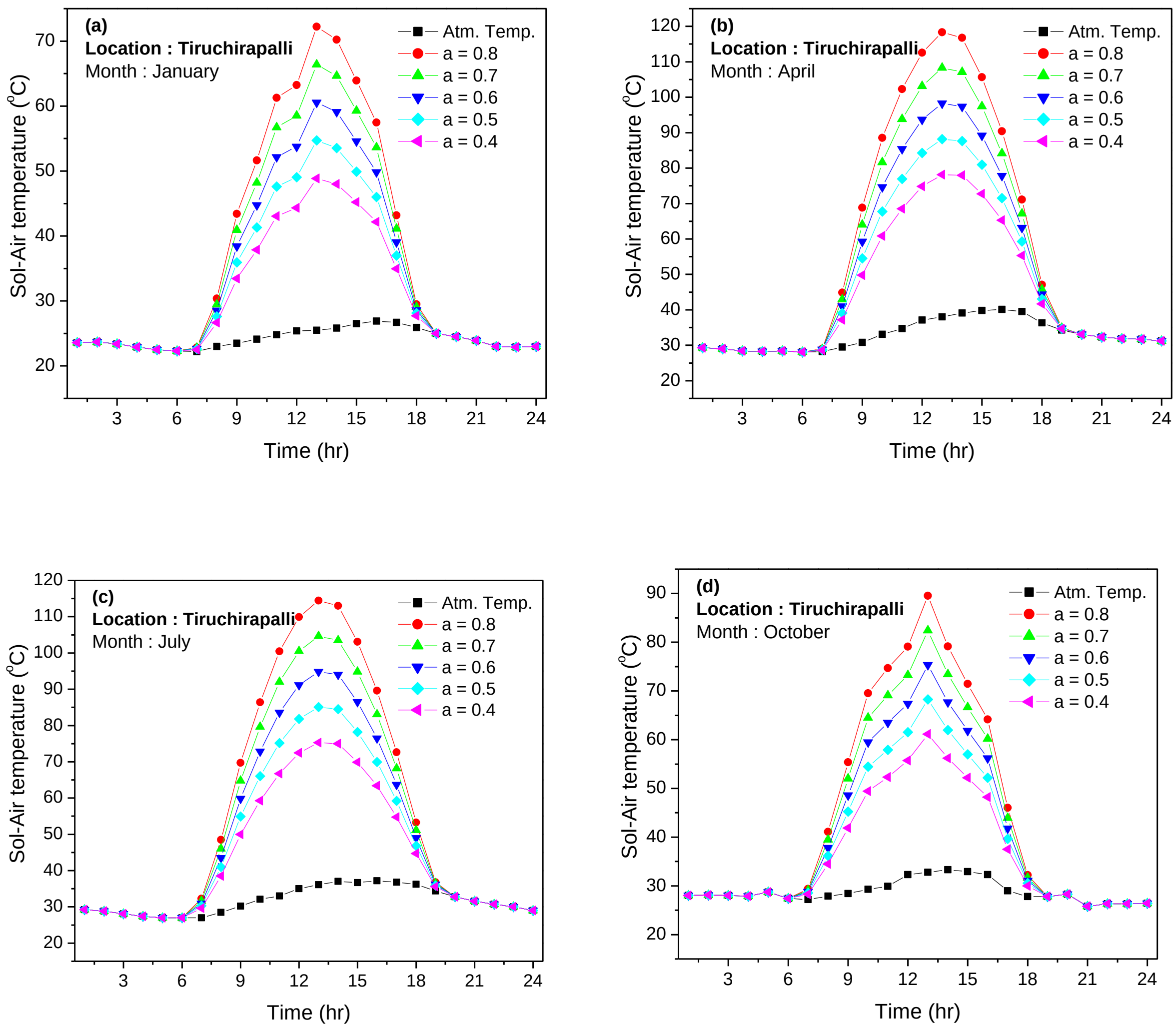


Fig. 2 Hourly variation of sol-air temperature at Tiruchirappalli location

During July (Fig. 3 (c)), the amount of solar radiation recorded is 680 W/m^2 (highest on that day) at 12.00 PM which is almost closer to the Tiruchirappalli and lower than the Chennai. At that time the outdoor air temperature was measured as 29.8°C which is having larger variation between cities this may be due to various reasons as mentioned above. In this environment condition, the sol-air temperature is predicted as 57.0°C, 63.8°C, 70.6°C, 77.4°C and 84.2°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. And for the October month (Fig. 3 (d)), the amount of solar radiation recorded is 777 W/m^2 (highest on that day) at 01.00 PM. At that time the outdoor air temperature was measured as 33.0°C. In this environment condition, the sol-air temperature is predicted as 64.08°C, 71.85°C, 79.62°C, 87.39°C and 95.16°C for the vertical wall surface absorptivity 0.4, 0.5, 0.6, 0.7 and 0.8 respectively. This variation is due to the fact that the amount of solar radiation falling on the ground varies with respect to zenith angle, declination

https://doi.org/10.37896/pd91.5/91512

angle and latitude angle. At other times the temperature of the sol-air is also lower as the amount of solar radiation is less for the rest of the hours in a day.

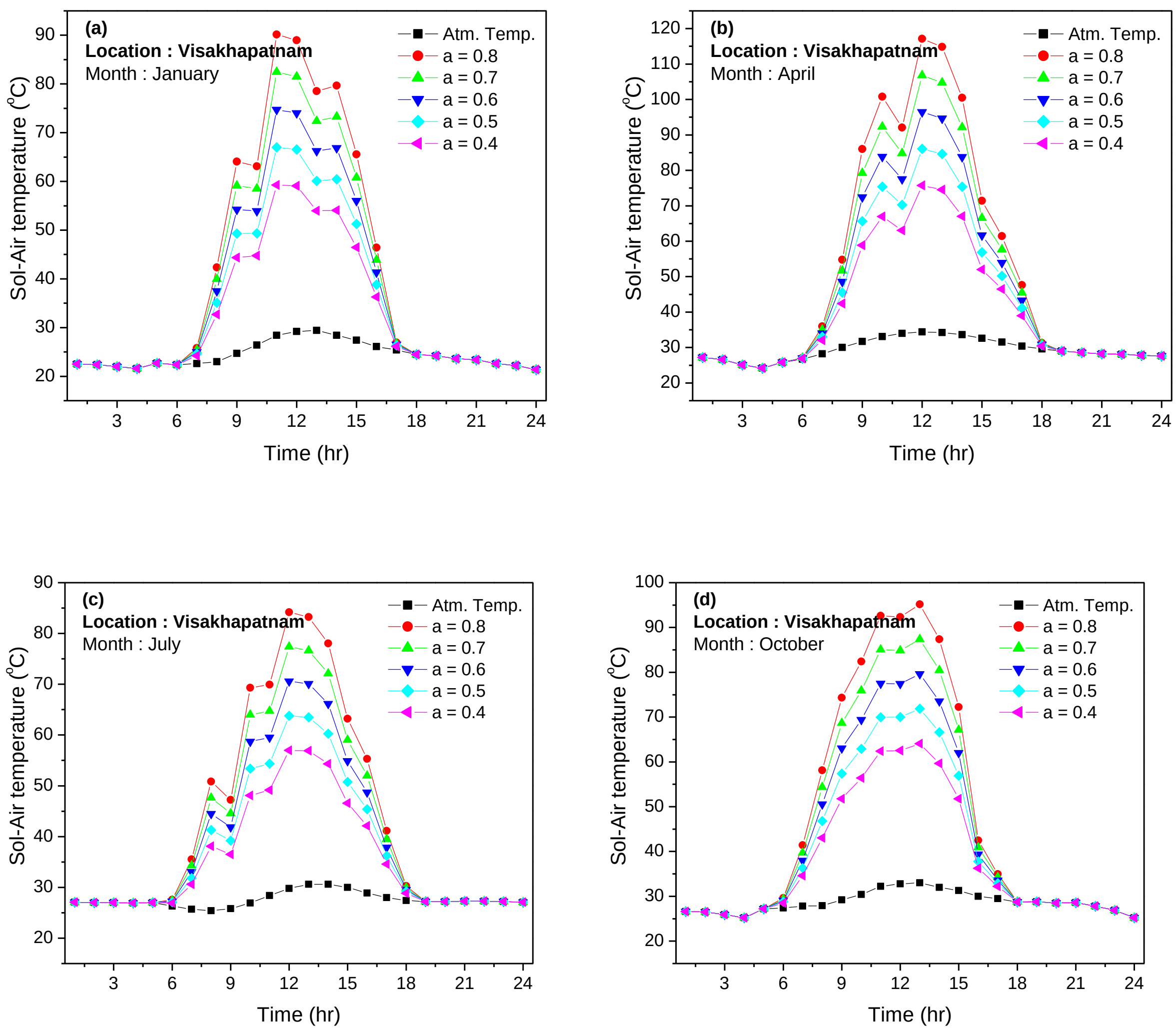


Fig. 3 Hourly variation of sol-air temperature at Visakhapatnam location

Conclusion

In this study the amount of sol-air temperature generated by buildings in different areas were predicted theoretically with various factors in warm and humid region. There are three main factors which are considered to be the most important factors for increase in sol-air temperature. Those are outdoor air temperature, solar radiation and absorptivity. The sol-air temperature varies greatly depending on the location, the main reason being the amount of solar radiation falling on that particular region. It can also be found that external absorption plays a major role in sol-air. The

 https://doi.org/10.37896/pd91.5/91512

sol-air temperature for the vertical wall was predicted for lower absorptivity (a=0.4) is that around 80°C during summer and 60° during winter in Chennai. In case of Tiruchirappalli 78°C during summer and 49°C during winter and for Visakhapatnam 76°C during summer and 54°C during winter. This temperature increases further as the absorptivity of the wall increases, and a maximum of 120°C was predicted for high absorptivity walls during summer. Therefore, the use of materials with low heat absorption capacity in buildings is used to prevent the heat being transferred into the building and to reduce the ambient temperature.

References

1. Khasreen, M.M., P.F. Banfill, and G.F. Menzies, Life-cycle assessment and the environmental impact of buildings: a review. Sustainability, 2009. **1**(3): p. 674-701.
2. Nematchoua, M.K., J. Teller, and S. Reiter, Statistical life cycle assessment of residential buildings in a temperate climate of northern part of Europe. Journal of Cleaner Production, 2019. **229**: p. 621-631.
3. Ramesh, T., R. Prakash, and K.K. Shukla, Life cycle approach in evaluating energy performance of residential buildings in Indian context. Energy and Buildings, 2012. **54**: p. 259-265.
4. Alwetaishi, M., Impact of building function on thermal comfort: A review paper. Am. J. Eng. Appl. Sci, 2016. **9**: p. 928-945.
5. Sartori, I. and A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings, 2007. **39**(3): p. 249-257.
6. Wang, Z., et al., Individual difference in thermal comfort: A literature review. Building and Environment, 2018. **138**: p. 181-193.
7. Vadugapalayam Rangasamy, L., S. Sivananthan, and R. Muthu, A study on the residential building construction information, thermal sensation and the behavior of households in Tamilnadu State – a questionnaire survey. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2020: p. 1-21.
8. Deme Belafi, Z., et al., Investigation on window opening and closing behavior in schools through measurements and surveys: A case study in Budapest. Building and Environment, 2018. **143**: p. 523-531.
9. Sharaf, F., The impact of thermal mass on building energy consumption: A case study in Al Mafraq city in Jordan. Cogent Engineering, 2020. **7**(1): p. 1804092.
10. Marino, B.M., N. Muñoz, and L.P. Thomas, Calculation of the external surface temperature of a multi-layer wall considering solar radiation effects. Energy and Buildings, 2018. **174**: p. 452-463.
11. Nawaf H, S. and W. Tan Jun, Effect of Periodic Variation of Sol-air Temperature on the Performance of Integrated Solar Collector Storage System. Engineering, 2010. **2010**.
12. Harish, R., Buoyancy driven turbulent plume induced by protruding heat source in vented enclosure. International Journal of Mechanical Sciences, 2018. **148**: p. 209-222.

13. Tanny, J., V. Haslavsky, and M. Teitel, Airflow and heat flux through the vertical opening of buoyancy-induced naturally ventilated enclosures. Energy and Buildings, 2008. **40**(4): p. 637-646.
14. Deng, X., et al., Numerical analysis of indoor thermal comfort in a cross-ventilated space with top-hung windows. Energy Procedia, 2017. **121**: p. 222-229.
15. Lenin, V.R., S. Sivalakshmi, and M. Raja, Optimization of window type and vent parameters on single-sided natural ventilation buildings. Journal of Thermal Analysis and Calorimetry, 2018.
16. Von Grabe, J., Flow resistance for different types of windows in the case of buoyancy ventilation. Energy and Buildings, 2013. **65**(1): p. 516-522.
17. Von Grabe, J., P. Svoboda, and A. Bäumler, Window ventilation efficiency in the case of buoyancy ventilation. Energy and Buildings, 2014. **72**(1): p. 203-211.
18. Song, Z., Studying the fan-assisted cooling using the Taguchi approach in open and closed data centers. International Journal of Heat and Mass Transfer, 2017. **111**: p. 593-601.
19. Du, C., et al., Quantifying the cooling efficiency of air velocity by heat loss from skin surface in warm and hot environments. Building and Environment, 2018. **136**: p. 146-155.
20. Kannan, V.S., T.V. Arjunan, and S. Vijayan, Experimental investigation of temperature swing adsorption system for air dehumidification. Heat and Mass Transfer, 2020. **56**(7): p. 2093-2105.
21. Kannan, V. and T. Arjunan, Optimization of process parameters of pressure-swing adsorption cycle in a silica gel desiccant dehumidification system. J Adv Chem, 2017. **13**(10): p. 6543-6551.
22. Sureshkannan, V., et al., Parametric study on pressure-based packed bed adsorption system for air dehumidification. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2021. **235**(5): p. 1351-1362.
23. Sureshkannan, V., S. Vijayan, and V.R. Lenin, Design and performance analysis of compressed air adsorption dryer with heatless regeneration mode. Heat and Mass Transfer, 2022. **58**(4): p. 631-641.
24. Alazwari, M.A., et al., Using phase change material as an energy-efficient technique to reduce energy demand in air handling unit integrated with absorption chiller and recovery unit–Applicable for high solar-irradiance regions. Journal of Energy Storage, 2021. **42**(1): p. 103080.
25. Kuznik, F., K. Johannes, and D. David, 13 - Integrating phase change materials (PCMs) in thermal energy storage systems for buildings, in Advances in Thermal Energy Storage Systems, L.F. Cabeza, Editor. 2015, Woodhead Publishing. p. 325-353.
26. Esfeh, M.K., et al., Visualized flow structure around and inside of one-sided wind-catchers. Energy and Buildings, 2012. **55**: p. 545-552.
27. O'Callaghan, P.W. and S.D. Probert, Sol-air temperature. Applied Energy, 1977. **3**(4): p. 307-311.

ISSN: 0369-8963

28. Al-Saud, K.A., Measured versus calculated roof peak sol-air temperature in hot-arid regions. Red, 2009. **29**: p. 95.
29. Chesser, G.D., et al. Comparison of Outside Air and Sol-air Design Temperatures for Estimating Insulation Needs. in 10th International Livestock Environment Symposium (ILES X). 2018. St. Joseph, MI: ASABE.
30. Forouzandeh, A., Comparative analysis of sol-air temperature in typical open and semi-closed courtyard spaces. Building Simulation, 2022. **15**(6): p. 957-973.
31. Mostafaeipour, A., et al., Energy efficiency for cooling buildings in hot and dry regions using sol-air temperature and ground temperature effects. Journal of Engineering, Design and Technology, 2019.
32. Kim, H.-H., K.-C. Lee, and S. Lee, Location-based human-adaptive air conditioning by measuring physical activity with a non-terminal-based indoor positioning system. Building and Environment, 2013. **62**: p. 167-173.
33. Ozel, M., Effect of insulation location on dynamic heat-transfer characteristics of building external walls and optimization of insulation thickness. Energy and Buildings, 2014. **72**: p. 288-295.