Thermal analysis of building roof assisted with water heater and insulation material

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Abstract. Traditional roof systems are constructed with concrete and weathering coarse layer and these roof systems absorb and reflect a certain amount of solar radiation. The absorbed solar energy is transferred into building indoor and causes significant discomfort to the occupants. Also, this solar energy gets dissipated without any useful energy conversion. Hence this paper is focused to use the available solar energy effectively through a novel solar water heating system and the transfer of heat in the building indoor is arrested by proper roof insulation material. The modified insulated roof with the solar water heater is designed and simulated numerically in commercial computational fluid dynamics code with validation. Through this study, the factors that affect the performance of solar water heating system and thermal insulation capacity are analysed and the best design of the modified roof system is identified. The modified roof system produces 25 L of hot water per day with a temperature raise of 60°C in the winter season. Also, the same roof system maintains the ceiling temperature at about 27°C for a complete day in a summer season.

Keywords. Thermal analysis; building roof; solar water heating system; roof insulation; numerical simulation.

1. Introduction

Nowadays, residential buildings are consuming a significant percentage of energy for lighting, cooling of buildings and for home appliances. Also, the ever-growing population increases the energy consumption rate and electrical energy demand. Among the many home appliances, water heater for bathing purpose is one of the most regularly used systems in winter and even in the summer season by children, aged, unhealthy and sick persons. Electrically operated water heating system consumes more energy and as an alternate, solar water heating systems are proving its effectiveness and identified as the economic solution to meet today's energy demand. Solar water heating system gains heat energy from the solar radiation and during clear sky conditions, up to 1 kW/m² of solar radiation can be incident on a roof surface, and between 20% and 90% of this radiation is typically absorbed [1]. These solar collectors use water or air as working medium and because of several benefits, such as its wide range of storage temperatures, high thermal capacity, nontoxicity, low-cost, and easy obtainability. Water is often used as a storage medium in domestic solar water heating (SWH) system [2–5]. Most solar water heating systems are thermosyphon type that consists of a grid of water carrying tubes bonded to the absorber plate, or with channels of fluid, together with a separate storage tank [6]. Usually, two types of collectors

are used in the domestic SWH system, namely flat plate and evacuated tube collectors. Flat plate collectors use both beam and diffuse solar radiation and do not require tracking of the sun, low maintenance, inexpensive and mechanically simple [7] and all evacuated tube solar collectors consist of a row of parallel evacuated glass tubes to reduce conduction losses and eliminate convection losses [8]. Yao *et al* studied the performance of all-glass evacuated tube solar water heater with twist tape inserts using CFD and observed that twist tape inserts reduce the velocity magnitude and make the temperature field more uniform [9]. Juanico designed a roof integrated solar water heater and heat is transferred from the solar radiation to the water through the glass, air gap, glass and water chamber [10]. Huang designed a new floor with capillary plait and micro packaged PCM and which saved the space for water tank and can reduce the night time heat loss [11]. Joudi and Farhan experimentally investigated the solar air heater attached to a green house, consists of a glass cover, corrugated plate, rear plate and back insulation material [12].

Sarachitti *et al* conducted the thermal performance analysis and economic evaluation for roof integrated with solar concrete collector integrated with a PVC pipe [13]. Lai *et al* attached the solar water heater in the curtain wall and analysed the heat transfer [14]. Nahar used water tubes embedded with a concrete terrace that exposed to the sun and also acts as a solar collector [15]. Krishnavel *et al*

analysed the concrete absorber solar water heating system by increasing the thermal conductivity of concrete by adding metal scraps and wire mesh [16]. Sokolov and Reshef analysed the thin concrete collectors with embedded tubes and suggested that collectors could also be used as building components for providing a low-cost energy collection means [17].

Varghese *et al* used the Compound Parabolic Concentrator in the solar water heater system and delivered hot water at an average temperature of 45–55°C [18]. Zhang *et al* studied the performance for water-in-glass evacuated tube solar water heaters and found the temperature rise of about 45°C after one day of heat collection [19]. Hamed *et al* integrated the phase change material with a solar collector and increased PCM thickness from 0.005 m to 0.025 m in turn the daily energy efficiency of storage collector raised from 76.98% to 82.42% [20]. The temperature difference across the collector was found to be 2–30°C [21] for domestic solar hot water storage system and 2–10°C for the conventional system [22]. Tank/box type integrated collector/storage solar water heater (ICSSWH) system supplies hot water at a temperature between 50–60°C and 60–75°C during winter and summer, respectively [23]. Mohsen and Akash tested a box type ICSSWH with single glazing and observed about 30°C raise in the tank water temperature [24]. Varghese reported that solar water heating system is the best method, if the system efficiency is comparable to other systems, despite the fact that nothing is provided to enhance the system performance like TIM, PCM so as not to add to the cost [18]. From this review, it is identified that the available SWH system raises the water temperature in the range of 30–75°C and the heat is gained through the assembly of a glass cover, absorber plate, air gap layer, a pipe containing water and back insulation. Solar concrete collectors without glass have the potential to meet the domestic energy needs and the need to develop suitable building-integrated solar water heating (BISWH) technology [16]. Also, in the above solar collectors, the maintenance required and the damage on glass cover are the crucial drawbacks. Hence, in this study a new solar water heating system is designed in which the water pipes are embedded in a highly conductive material called refractory carborundum brick which is directly exposed to the solar radiations. Since the modified system is not using glass cover, the system is free from damage and regular maintenance. The high thermal conductivity of refractory carborundum brick increases the heat gain of water passing through the pipe and also shoots the ceiling temperature. To avoid this undesirable heating of ceiling, the proper insulation material is needed to lay below the refractory carborundum brick layer. Some of the commonly used building insulating materials are polystyrene, polyurethane, expanded polystyrene and sustainable materials like straw bale, sugarcane bagasse, palm fiber, etc. Ekici *et al* chosen the fiber glass, extended polystyrene, foamed polyurethane on the external walls of the building as an insulation medium

and determined the optimum thickness [25]. Ozel *et al* studied the effect of the insulation location on dynamic heat transfer characteristics and also optimized the insulation thickness [26]. kayfeci *et al* used styrofoam as insulation on external walls [27]. Hence, in this modified roof with SWH system, wood wool and polyurethane are used as insulation material to avoid the undesirable heating on the ceiling.

2. Roof integrated with SWH system: model and CFD simulation

In the traditional residential building, roof system is made of concrete and weathering tile of thickness 0.15 m and 0.03 to 0.05 m, respectively. However, in the proposed modified roof system, the water flowing pipes are embedded in the refractory carborundum and this layer is directly exposed to the solar radiation. The embedded pipe system is having one upstream and downstream pipe, connected with 20 numbers of parallel copper pipes of length 4 m with diameter, d . The pipe system is tilted for an angle of 15° with reference to the ceiling to facilitate natural flow of water from the upstream side to the downstream side. Two thermal insulation layers, wood wool and polyurethane are laid below the chromium brick layer to reduce the transfer of heat into the building indoor. This roof system is designed for a residential building room of size 4 m x 4 m. The schematic representation of the modified insulated roof system with the solar water heating system is shown in figure 1.

The numerical simulation for the above roof model is made on a portion of roof system with one pipe and modelled in the GAMBIT software and solved in Fluent. The computational domain of a portion of modified roof system

1- Concrete: 2-Polyurethane: 3- Wood wool: 4-Refractory carborundum brick: 5- Water pipe

Figure 1. Exploded isometric view of modified roof system with water heating pipes and thermal insulation layer.

Figure 2. Isometric view and front view of computational domain of modified roof system.

Table 1. Material properties for roof materials and water pipe.

Material	Density (kg/m ³)	Specific heat (J/kg K)	Thermal conductivity (W/mK)	Size [X × Y × Z] (m)
Concrete	2300	1130	1.279	0.05 × 0.15 × 4
Polyurethane	32	1590	0.022	0.05 × t _p × 4
Wood wool	500	800	0.25	0.05 × t _{ww} × 4
Refractory carborundum brick	—	—	11.00	0.05 × t _{cb} × 4
Copper	8985	383	386	Pipe thickness = 0.001 m
Water	1000	4187	0.5978	—

for numerical simulation is shown in figure 2. The model meshes with the grid size of 0.01 m for concrete, 0.005 m for polyurethane, wood wool, refractory carborundum brick, and 0.0025 m for copper pipe and this grid system is checked for grid independent result. The computational domain is imported to the Fluent for solving the flow governing equations and the assumptions made in solving the numerical simulation are as follows. (i) The heat conduction across the composite roof is one-dimensional and the end effects are neglected.

(ii) The thermal conductivity of roof materials is considered as constant and not varying with respect to temperature. The material properties of various roof elements are given in table 1.

3. Boundary conditions

The boundary conditions employed for the numerical simulation are as follows.

The roof's exterior surface is exposed to the solar radiation and convection. The combined effect of solar radiation and convection is calculated through T_{solair} from Eq. (1) [28].

$$T_{solair} = T_a + (\alpha q / h_o) \quad (1)$$

where T_a is the ambient temperature, α , absorptivity, q , solar radiation. Solar radiation and ambient temperature in the month of May and December at Chennai are shown in figure 3.

The bottom surface of the roof system (ceiling) is nearer to the indoor environment and the boundary condition is given in Eq. (2).

$$-k_c \frac{\partial T}{\partial n} = h_{in}(T_c - T_{in}) \quad (2)$$

The water flowing through the pipe is specified with the mass flow rate and temperature equivalent to atmospheric temperature. At the outlet of the pipe outflow condition is specified.

Figure 3. Solar radiation, $T_{\text{sol-air}}$, atmospheric temperature data at Chennai [31].

3.1 Solution methodology

The roof domain is initially analysed under the steady state with double precision segregated solver. Later it is solved under a transient state for one complete cycle of 24 h with the second order implicit method. All the cases are iterated up to the convergence level of 10^{-6} . The above numerical simulation is validated with the experimental observations reported by Pasupathy and Velraj [29]. In this validation, the same roof model made is modelled in GAMBIT software and the same boundary conditions are applied. The CFD simulated temperature at the bottom of the roof surface is compared and validated with that of experimental prediction [30]. All the numerical simulations in the study

are simulated for 4 to 6 days to get the steady state of solution.

4. Results and discussions

The initial design of the modified roof with SWH system has the refractory carborundum brick layer thickness (t_{cb}) as 0.04 m, wood wool (t_{ww}) as 0.02 m and polyurethane (t_{p}) as 0.04 m with a pipe diameter of 0.02 m. Performance of this solar water heating system is studied by varying the mass flow rate of water (m), pipe diameter (d) and thickness of refractory carborundum brick layer and insulation layer. Generally, the pipe diameter for these kinds of applications are in the range of 0.01 m [32] to 0.016 m [33] and in this case, 0.02 m has been taken initially. The refractory carborundum layer thickness should be more than pipe diameter and hence it is taken as twice of pipe diameter initially. Mass flow rate is arbitrarily taken initially and later a trade-off is made between the water temperature rise and ceiling temperature.

4.1 Effect of mass flow rate on solar water heater performance

The mass flow rate of water passing through the pipe is varied from 7 kg/h to 13 kg/h with an increment of 2 kg/h and analysed for the conditions in May month for one complete 24 h. Water outlet temperature (T_{w}) and average ceiling temperature (T_{c}) are predicted as an outcome of the above analysis and plotted in 24 h scale in figure 4. The T_{w} begins to rise from the 6th hour and attains the maximum

Figure 4. Temperature of water outlet and ceiling for various mass flow rate of water flowing through the pipe ($t_{\text{cb}} = 0.04$ m; $t_{\text{w}} = 0.02$ m; $t_{\text{p}} = 0.04$ m; May month).

Figure 5. Temperature of water outlet and ceiling for various pipe diameters ($m = 5 \text{ kg/h}$; ($t_{cb} = 0.04 \text{ m}$; $t_w = 0.02 \text{ m}$; $t_p = 0.04 \text{ m}$; May month).

value at the 13th hour of 24 h cycle. This trend is unique for all the mass flow rate cases and this is due to the fact that solar radiation gets initiated at 6 AM and attains the peak value at about 12 PM. The heat gain of water up to the 12th hour is calculated as 732 kJ/h and 783 kJ/h for the mass flow rate of 7 kg/h and 13 kg/h, respectively. However, the heat gain per kg of water is maximum for the $m = 7 \text{ kg/h}$ as 104 kJ/h, since, the flow with low mass flow rate takes more time to travel the pipe and thereby gains more amount of heat in comparison with $m = 13 \text{ kg/h}$. This fact is clearly evident from figure 4, as reduction in the mass flow rate increases the water outlet temperature. Secondly, the flow with low mass flow rate influences high ceiling temperature in comparison with 13 kg/h, since, the total heat dissipation through water is comparatively less. But the variation of ceiling temperature is not significant among the analysed mass flow rate cases and the maximum variation is noticed as 0.2 K for $m = 7 \text{ kg/h}$. From this case, it inferred that single pipe discharges 7, 9, 11 and 13 L of hot water per hour at a temperature of 325 K, 320 K, 316 K and 313 K.

4.2 Effect of pipe diameter on solar water heater performance

In the previous section, the maximum water outlet temperature is achieved for the mass flow rate of 7 kg/h with a pipe diameter of 0.02 m. In this segment, the pipe diameter is varied as 0.02 m, 0.015 m and 0.01 m and the mass flow rate is reduced as 5 kg/h since, in the previous study, the

maximum temperature rise of the water is only about 25°C which is not hot enough to use for any application. The same simulation method is employed in the modified roof with the above-mentioned pipe diameters and the corresponding water outlet temperature and average ceiling temperature are plotted in figure 5.

The maximum T_w attained for the pipe diameter 0.02 m, 0.015 m and 0.01 m is noticed as 330 K, 350 K and 380 K, respectively. For smaller diameter pipe, the cross-sectional area of water channel is minimum and hence, the heat gains are more than from a larger diameter pipe. The difference in maximum T_w , achieved among the pipe diameters is radical and this infers that pipe diameter is the key parameter that influences more on the temperature rise of the water. On the other hand, the average ceiling temperature for one complete 24 h is higher for $d = 0.01 \text{ m}$, since, the heat carried by water is minimum as 670 kJ/h and for the pipe diameter of 0.02 m it is 1680 kJ/h. However, the variation of ceiling temperature for pipe diameter = 0.01 m case is not significant in comparison to the pipe diameter of 0.02 m. From this study, pipe diameter of 0.01 m is identified as suitable for the modified roof with SWH system. Conversely, for the $d = 0.01 \text{ m}$ at time = 12 h, the water outlet temperature is nearing to the boiling point. This transformation of water to steam is not preferable for bathing applications. To avoid this phase transformation, the mass flow rate of water can be increased from 5 kg/h and hence, in continuation to this study, the mass flow rate is again varied as 7, 9 and 11 kg/h with the pipe diameter of 0.01 m and the corresponding water outlet temperature and average ceiling temperature are plotted for

Figure 6. Temperature of water outlet and ceiling for various mass flow rate ($d = 0.01\text{ m}$; $t_{cb} = 0.04\text{ m}$; $t_w = 0.02\text{ m}$; $t_p = 0.04\text{ m}$; May month).

Figure 7. Temperature of water outlet and ceiling for various mass flow rate ($d = 0.01\text{ m}$; $t_{cb} = 0.04\text{ m}$; $t_w = 0.02\text{ m}$; $t_p = 0.04\text{ m}$; January month).

the condition of May month in figure 6. From this figure, the peak T_w obtained for the mass flow rate 7, 9 and 11 kg/h are 370, 365 and 360 K, respectively, and the mass flow rate in the range of 9 to 11 kg/h is sufficient to heat the water during the month of May. Even though, the same mass flow in the range of 9 to 11 kg/h is not guaranteed to

achieve the same peak temperature in the month of January. Hence the performance of same solar water heating system is analysed for the condition in January month and the water outlet temperature and ceiling temperature for the pipe diameter of 0.01 m is shown in figure 7. It is observed that the mass flow rate of 9 kg/h fails to rise a temperature

Figure 8. (a), (b). Temperature of water outlet and ceiling for various refractory carborundum brick layers ($d = 0.01\text{ m}$; $t_w = 0.02\text{ m}$; $t_p = 0.04\text{ m}$; $m = 7\text{ kg/h}$; January month). (c) Temperature of water outlet and ceiling ($d = 0.01\text{ m}$; $t_{cb} = 0.02\text{ m}$; $t_w = 0.02\text{ m}$; $t_p = 0.04\text{ m}$; May month).

even by 40°C in the month of January. Hence the mass flow rate of water is further reduced as 7 and 5 kg/h and the peak temperature of outlet water are noticed as 350 and 357 K, respectively. From this study, it is concluded that the mass flow rate in the range of 5 to 7 kg/h and 9 to 11 kg/h is suitable for the month of January and May for a pipe diameter of 0.01 m. In all the above cases the variation of ceiling temperature is not significant.

4.3 Effect of refractory carborundum brick layer thickness

Generally, refractory carborundum brick material have high thermal conductivity and effectively transfer the

absorbed solar radiation to the water passing through the pipe. The thickness of refractory carborundum brick layer may influence the heat gain of water and hence its effect on SWH performance is studied by varying the thickness as 0.04, 0.03 and 0.02 m. These cases are analysed for the month of December and their corresponding T_w and T_c are plotted in figure 8. The water outlet temperature of the roof with refractory carborundum brick thickness (t_{cb}) of 0.02 m is risen by 4°C with reference to 0.04 m and no significant difference is observed for the refractory carborundum brick thickness of 0.03 and 0.04 m. Since the thickness of refractory carborundum brick layer is reduced, the resistance to heat transfer also gets reduced and hence the water outlet temperature is higher for $t_{cb} = 0.02\text{ m}$.

Figure 9. Ceiling temperature for various thickness of wood wool and polyurethane ($d = 0.01$ m; $t_{cb} = 0.02$ m; $m = 7$ kg/h; May month).

On the other hand, $t_{cb} = 0.02$ m case rises the ceiling temperature, but the variation is not significant in comparison with other cases. Hence refractory carborundum brick thickness of 0.02 m is identified as suitable, also the material requirement is relatively less and in turn weight of roof system gets lowered. The same SWH roof system with $t_{cb} = 0.02$ m is analysed for the month of May and the variation of water outlet temperature and ceiling temperature are shown in figure 8c. The maximum water outlet temperature and ceiling temperature in the month of May are predicted as 375 and 301 K, respectively.

4.4 Study on roof insulation

In the previous studies, the utilization of solar energy is enhanced by various measures and the presence of refractory carborundum brick amplifies the heat transfer to the water passing through the pipe. This also leads to the additional rise of ceiling temperature in comparison to the traditional roof system. To pull down the ceiling temperature rise, thermal insulation material is laid below the refractory carborundum brick layer. Insulation material restricts the flow of heat into the indoor and also indirectly enhances the temperature rise of water passing through the pipe. In this study, two different insulation materials, wood wool and polyurethane are used and the effect of their thickness are studied. The wood wool layer thickness and polyurethane layer thickness are varied simultaneously and the ceiling temperature is plotted for the condition of May month in figure 9.

In figure 9, the thickness of the wood wool (t_w) and polyurethane (t_p) layer are represented as w_xp_y where x and y are the thickness of wood wool and polyurethane,

respectively. From this figure, it is observed that increasing the wood wool layer thickness and reducing the polyurethane layer thickness will not reduce the ceiling temperature comparatively, since, the thermal resistance of the wood wool material is lesser than polyurethane. Alternatively, roof insulation by only polyurethane shows comparatively lower ceiling temperature for a complete 24 h, also the variation in ceiling temperature is not significant and maintained almost constant at 300.75 K which is very much closer to the atmospheric condition. However, in the case of w5p1, the variation of ceiling temperature is in the range of 301.5 to 302 K which is also considered to be closer to atmospheric condition. By considering the economic aspects, it is good to choose the w5p1 insulation system, since the cost of wood wool is lower than polyurethane. Hence, roof insulation with wood wool of 5 cm and polyurethane of 1 cm (w5p1) is selected as the best insulation pattern for the proposed SWH system. Meanwhile, heat transfer analysis across the w5p1 insulation pattern is made and compared with the traditional room having concrete and weathering tile of thickness 15 cm and 2 cm, respectively. The corresponding temperature plots at the time between 10 AM and 6 PM are shown in figure 10. The ceiling temperature of the traditional roof is increasing from 301.3 K to 306.4 K, whereas, for the insulated roof system (w5p1) the ceiling temperature is almost constant at about 301 K.

5. Conclusion

In this study, an insulated roof system with the solar water heater arrangement is developed and analysed through numerical simulation method. The numerical simulations are performed in Fluent software and validated with experimental results. The modified roof system consists of a series of pipes embedded in refractory carborundum brick, wood wool layer and polyurethane layer along with concrete. The various design factors like mass flow rate of water, pipe diameter, the thickness of refractory carborundum brick, wood wool and polyurethane are varied and the water outlet temperature and ceiling temperature are predicted for one complete 24 h in the months of January and May. The modified roof system is analysed for various mass flow rate, pipe diameter and thickness of carborundum brick, wood wool and polyurethane layer. The pipe diameter of 0.01 m, carborundum brick layer thickness of 0.02 m, wood wool of 0.05 m and polyurethane of 0.01 m are identified as suitable values for the mass flow rate of 5 to 7 kg/h and 9 to 11 kg/h in the months of January and May, respectively. This roof system produces approximately 25 L of hot water per day with a temperature rise of 60°C and maintains the ceiling temperature at 27°C for a complete 24 h in the months of January and May, respectively.

Figure 10. Temperature plot across traditional and modified roof system with w5p1 insulation pattern ($d = 0.01$ m, $t_{cb} = 0.02$ m; $m = 7$ kg/h; May month).

List of symbols

d	pipe diameter
t_p	polyurethane layer thickness
t_w	wood wool layer thickness
t_{cb}	refractory carborundum brick layer thickness
T_a	ambient temperature
α	absorvity
q	solar radiation
T_{solair}	temperature of the combined effect of radiation and convection
T_{in}	indoor temperature
k_c	thermal conductivity of ceiling
h_o	convective heat transfer coefficient of the exterior surface of the roof

h_{in}	convective heat transfer coefficient of indoor
T_w	water outlet temperature
T_c	ceiling temperature
m	mass flow rate

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