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Dharmasastha K
IIT Madras, India, dharmasirkazhi@gmail.com

Maiya M P
IIT Madras, India, mpmaiya@iitm.ac.in

Shiva Nagendra S M
IIT Madras, India, snagendra@iitm.ac.in

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Dharmasastha K[1]*, Maiya M P[2], Shiva Nagendra S M[3]

[1, 2]Department of Mechanical Engineering, IIT Madras,
Chennai, Tamilnadu, India
Email: [1]dharmasirkazhi@gmail.com, [2]mpmaiya@iitm.ac.in
Phone: [2]+91 4422574665

[3]Department of Civil Engineering, IIT Madras,
Chennai, Tamilnadu, India
[1]Phone: +91 4422574290, Email: snagendra@iitm.ac.in

* Corresponding Author

ABSTRACT

Globally, building sector consumes a large amount of energy both for construction and operation. Especially, heating, ventilation and air conditioning contribute for 40 – 50% of total building energy consumption. Thermally Activated Building System (TABS), which is an energy efficient alternative to conventional mechanical air conditioning, can reduce the energy consumption of building operation. TABS is a radiant cooling technology, which utilizes the thermal mass of the building to achieve thermal comfort of the indoor space. In TABS, chilled water circulates through the pipes, which are embedded in the building structure. Chilled water removes the heat from the indoor and provides a comfortable indoor to the occupants. In addition to TABS, use of appropriate building material can enhance the energy-saving potential of buildings not only by reducing the cooling/heating load but also by reducing the embodied energy of the building. A sustainable and eco-friendly building material, namely Glass Fibre Reinforced Gypsum (GFRG) can be integrated with the TABS. The combination of TABS and GFRG is named as Thermally Activated Glass Fibre Reinforced Gypsum (TAGFRG). The present study aims to analyze the impact of various design and operating parameters on the performance of TAGFRG roof. A TAGFRG roof has been designed by embedding water flowing copper pipes along with the provision of air gaps in the structure. A commercial CFD tool has been used to simulate the TAGFRG roof. The design and operating parameters analyzed are diameter, wall thickness and thermal conductivity of pipe, pipe spacing, and temperature and flow rate of supply water.

1. INTRODUCTION

Increase in global temperature, urbanization and economic growth make air conditioning essential for living which increases the energy consumption in building sectors. The natural and passive cooling technologies are not much effective in the dense hot cities during peak summers. Therefore, it is necessary to discover some alternatives for the conventional air conditioning system. Thermally Activated Building System (TABS) is a promising technology to provide better thermal comfort with considerable energy saving. The use of appropriate building material with the suitable architectural designs for cooling will enhance the cooling performance and energy saving potential of the building by reducing the external solar loads. Currently, the reduction of CO_2 emission is getting more attention as it is rising globally. TABS indirectly helps to reduce CO_2 emission due to its energy-saving potential. The use of alternative building material called Glass Fibre Reinforced Gypsum (GFRG) helps to reduce the embodied energy and CO_2 emission associated with the building construction. GFRG, when combined with the TABS is named as Thermally Activated Glass Fibre Reinforced Gypsum (TAGFRG). The detailed explanation of TABS, GFRG and TAGFRG are discussed in the following subsections.

1.1 Thermally Activated Building System

Thermally Activated Building System is an energy efficient alternative to conventional air conditioning system. In TABS, pipes are embedded in the building structures, and chilled water is circulated through the pipes to remove the heat from the building structure, in turn, from the indoor space. The cooling energy is transferred to the indoor heat sources, i.e., occupants and electrical appliances by radiative heat transfer, and to the indoor air by convective heat transfer. It is also termed as radiant cooling system as more than 50% of heat load is removed by radiative heat transfer (ASHRAE handbook, 2016).

The main advantages of the TABS are larger radiant surface areas for the heat transfer, shifting of the peak load demand to off-peak load period, usage of water as energy transporting medium and higher supply water temperature that improves the coefficient of performance (COP) of the chiller. Passive cooling techniques such as evaporative cooling and nocturnal cooling can be utilised to cool the water supplied to TABS. In addition, TABS provides same comfort level at a higher indoor air temperature compared to the conventional air conditioning. Noise and draft problems associated with the fans/blowers are minimized because of downsized fans/blowers as the quantity of air handled is less in TABS.

The main limitation of the TABS is that it can treat sensible load only. The limitation is overcome by adopting dehumidification system such as desiccant dehumidification and dedicated outdoor air system (DOAS) to treat latent load. The large thermal inertia of TABS makes the control difficult and slow down the response time. Therefore, an instantaneous surge in cooling loads cannot be treated immediately. Condensation may occur at the surfaces if the radiant surface temperature falls below dew point temperature of the indoor air.

1.2 Glass Fibre Reinforced Gypsum

GFRG, made of glass fiber and gypsum, is an eco-friendly alternative to conventional building material. Gypsum is abundantly available industrial waste from the fertilizer industry. Around 7 million tons of gypsum was generated from the fertilizer industry in India for the year 2013- 14 (IFA Handbook, 2016). GFRG is more economical than conventional building construction. It is suitable for rapid constructible and mass housings. The embodied energy and CO_2 emission associated with the GFRG building is lower compared to the conventional building. GFRG material is not only the greenest product due to the industrial waste utilization and also recyclable. GFRG construction reduces the utilization of natural resources such as river sand and water.

1.3 Thermally Activated Glass Fibre Reinforced Gypsum (TAGFRG) Roof

The integration of TABS in the GFRG construction is named as TAGFRG. The heat penetration through the sunlit roof is higher than the sunlit walls (Vijaykumar *et al*., 2007). Therefore, this study is focused on reducing the solar heat penetration and improve the performance of TAGFRG sunlit roof. Reinforcements are provided at every third cavity of the panel to enhance the structural strength. Copper pipes are embedded in the GFRG panel cavities with the provision of air gap, and also in the cavity with reinforcements as shown in Figure 1. The pipe specifications are mentioned in Table 1.

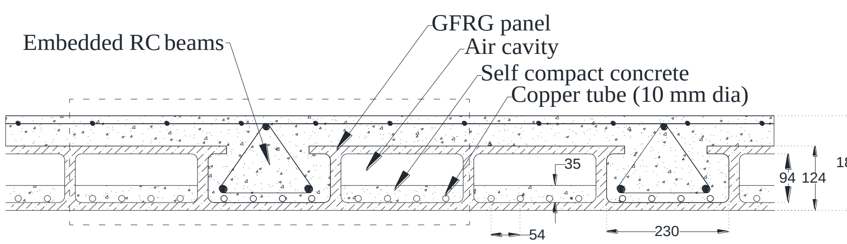

Figure 1: TAGFRG roof

Table1: Piping specification

SI.No.	Description	Specification
1	Pipe material	Copper
2	Pipe inner diameter	0.01 m
3	Pipe wall thickness	0.001 m
4	Pipe spacing	0.055 m
5	Pipe arrangement	Serpentine
6	No. of row per cavity	4
7	Pipe length embedded per cavity	12 m

2. NUMERICAL SIMULATION

A numerical model for TAGFRG (Figure 2) is developed using a commercial Computational Fluid Domain (CFD) software, which solves the governing equations by Finite Element Method (FEM). The dotted rectangular box mentioned in Figure.1, i.e., reinforcement zone (RZ) in the middle of two air-cavity zones (AZ), is considered as the computational domain as this segment is repeated over and over. This section briefs the governing equations, initial and boundary conditions, assumptions, physical model and validation. The validated model is used to study the influence of design and operating parameters on the thermal performance of TAGFRG roof.

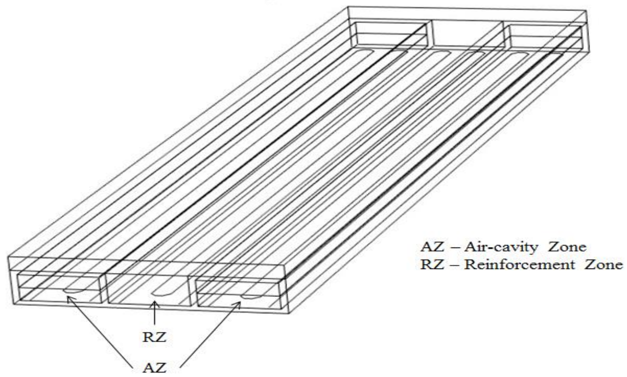

Figure 2: Computational domain of TAGFRG roof

2.1 Initial and Boundary Conditions

The top surface of TAGFRG roof is considered to be exposed to sunlight, therefore time-varying sol-air temperature with a constant heat transfer coefficient is given as the boundary condition. The sol-air temperature is calculated for the peak summer day of the year 2015, shown in Figure. 3, for the location of IIT Madras (13°00’19”N, 80°14’31” E). The data required for the sol-air temperature is obtained from Continuous Ambient Air Quality Monitoring Station (CAAQMS) located in IIT Madras.

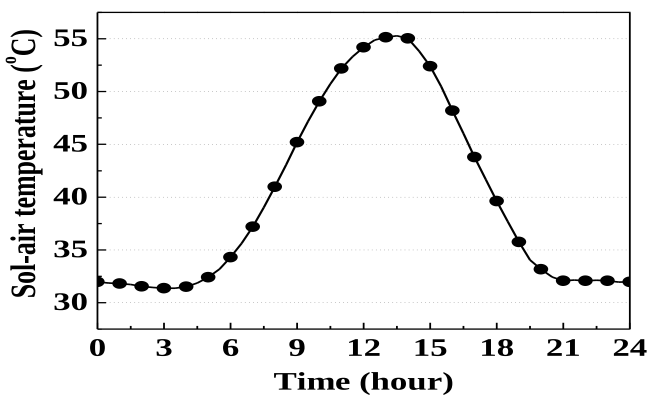

Figure 3: Sol-air temperature for 24th May 2015

The bottom surface of the roof is considered to be exposed to indoor space. Therefore, its boundary condition is specified by a constant air temperature and a constant heat transfer coefficient. All vertical surfaces of the model are assumed to be adiabatic. The numerical values of boundary conditions are mentioned in Table 2.

Table 2: Boundary conditions

SI.No.	Surface	Boundary Condition
1	Vertical sides	Adiabatic
2	Top surface	h_o = 30 W/m^{2}K (Leo Samuel *et al.*, 2016), $T_{Sol\text{-}air} = T(\tau)$
3	Bottom Surface	h_i = 13.2 W/m^{2}K (Causone *et al.*, 2009), T_{room} = 30°C

As the initial conditions are unknown, they are obtained by an iterative method. The simulation is marched repeatedly until the consecutive days' results are the same, i.e., the difference between the results of consecutive days for a particular time of the day is within the prescribed limits.

2.2 Assumptions

The sol-air temperature, which is given as the boundary condition in the top surface, is calculated for every half an hour of the day and assumed to be varying linearly between the time steps. Constant heat transfer coefficients are considered in both top and bottom surfaces. The pipe flow is assumed to be 1D flow, as the flow is fully developed due to high length to diameter ratio of the pipe.

The GFRG material properties are measured in IIT Madras and they are specified as inputs for the simulation. A few properties of air and water are specified as a function of temperature. The critical material properties are mentioned in Table 3.

Table 3: Thermal Properties of materials

Material \ Property	Density (Kg/m^3)	Specific heat capacity (J/kgK)	Thermal conductivity (W/mK)
GFRG	1292	1177	0.54
Concrete	2300	880	1.4
Air	ρ(T)	1005	k(T)
Water	1000	4178	k(T)

2.3 Governing Equations

The governing equations are specified for three domains, i.e, air, solid domain (concrete and GFRG) and water. The mass, momentum and energy equations for the air domain are as follows.

$$\frac{\partial \rho}{\partial \tau} + \nabla.(\rho u) = 0 \tag{1}$$

$$\rho\left[\frac{\partial u}{\partial \tau} + (u.\nabla)u\right] = -\nabla p + \mu\nabla^2 u + \frac{\mu}{3}\nabla(\nabla.u) \tag{2}$$

$$\rho Cp\left(\frac{\partial T}{\partial \tau} + u.\nabla T\right) = \nabla.(k\nabla T) + q \tag{3}$$

For the concrete and GFRG, energy equation only applicable as U=0. The pipe flow is simplified to 1D along the center of the pipe and governing equations for the pipe flow (Basmaid, 1996) is as follows.

$$\frac{\partial A\rho}{\partial \tau} + \nabla.(A\rho\bar{u}) = 0 \tag{4}$$

$$\rho\frac{\partial u}{\partial \tau} = -\nabla p - f\,\frac{\rho}{2d}\bar{u}\,|\bar{u}| \tag{5}$$

$$\rho ACp\frac{\partial T}{\partial \tau} + \rho ACp\bar{u}.\nabla T = \nabla.Ak\nabla T + f\,\frac{\rho A}{2d}|\bar{u}|^3 + q + Q \tag{6}$$

2.4 Physical Model

Experiment room of 3.46 m x 3.46 m x 3.15 m is constructed in IIT Madras, Chennai. The location experiences tropical wet and dry climate. In order to study the performance of TABS in real-world condition, the experiment room is constructed in an outdoor environment (uncontrolled condition) i.e., all the outdoor surfaces exposed to solar radiation. The room has 2 single glazing windows in north and south walls and partly glazed wooden door in the west wall. The walls are constructed using concrete blocks and flooring is done using concrete. The specifications of experiment room are mentioned in Table 4.

The roof is constructed using GFRG panel with copper pipes embedded in all of its cavities. The specifications and configurations of piping are mentioned in Table 1. TAGFRG roof has 13 cavities out of which 5 cavities, i.e., every third cavity, are provided with the reinforcements, and the remaining cavities have the provision of air gap as shown in Figure 1. The internal heat load is 400 W from the computer and monitoring instruments and there is no latent load. The chilled water required is supplied by a mechanical water chiller.

Table 4: Specification of experiment room

SI. No.	Building Element	Material	Dimension (m)
1	Room size	–	3.46 (L) x 3.46 (B) x 3.15 (H)
2	Wall	Concrete blocks	0.23 (t)
3	Roof	GFRG	0.164 (t)
4	Floor	Concrete	0.15 (t)
5	Window	Glass	2 (W) x 1.2 (H)
6	Door	Glass and wood	0.98 (W) x (0.87 (glass)) + 0.93 (wood)) (H)

2.5 Model Validation

The model is validated with the experimental results of the physical model described above. TABS can directly control the room surface temperature; therefore, the mean radiant temperature and operative temperatures are essential to study the thermal comfort. The bottom surface (ceiling surface) temperature of the roof is considered as the performance parameter as it directly influences the mean radiant temperature and operative temperature of the room. The bottom surface temperature is validated for without cooling and with cooling cases (Figure. 4). The solar heat penetration varies between RZ and AZ; hence, the temperature of both zones is validated.

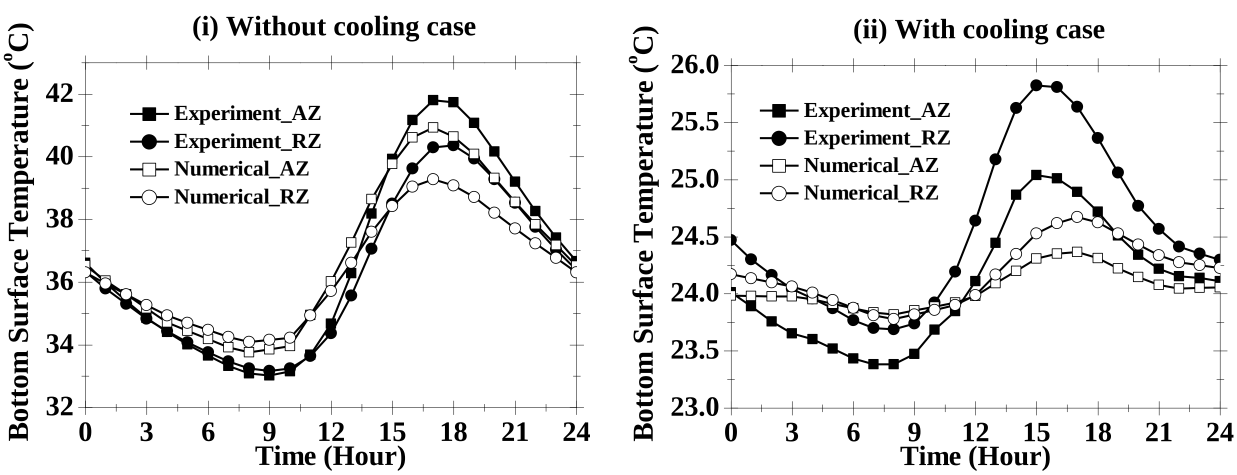

Figure 4: Validation **(i)** without cooling case for RZ and AZ, **(ii)** with cooling case for RZ and AZ

The percentage error is calculated using the Equation 7 and is tabulated in Table 5. The error is minimal for both the cases of without and with cooling.

$$\text{Percentage error } (\varepsilon) = \frac{|T_{Simu} - T_{Meas}|}{T_{Meas}} \times 100\% \qquad (7)$$

Table 5: Percentage error for model validation

% Error range	Without cooling	With cooling
Air-cavity Zone (AZ)	0.06 – 3.9 %	0.1 – 3%
Reinforcement Zone (RZ)	0.2 – 3.9%	0.1 – 5%

2.6 Parameters Investigated

The parameters investigated listed in Table 6. The influences of piping parameters and operating parameters are investigated on the performance of TAGFRG roof.

Table 6: Investigated parameters

Sl. No.	Parameter, Unit	Range	Increment	Default
1	Pipe inner diameter, m (Constant flow rate = 600 L/h)	0.007 to 0.017	0.002	0.010
2	Pipe inner diameter, m (Constant velocity = 2.13 m/s)	0.007 to 0.017	0.002	0.010
3	Pipe spacing, m	0.25 to 0.85	0.3	0.55
4	Pipe wall thickness, mm	1 to 4	4	1
5	Pipe thermal conductivity, W/mK	0.14, 0.45, 1.4 and 384	-	384
6	Water inlet temperature, °C	18 to 24	2	18
7	Water flow rate, L/h	25, 50, 100, 200, 400, 800 and 1600	x 2	600

3. RESULTS AND DISCUSSION

The performance of TAGFRG is analyzed in terms of bottom surface temperature, which is responsible for the mean radiant temperature of indoor space. The parameters listed in Table. 6 are investigated and the quantitative influences of these parameters on the bottom surface temperature of TAGFRG are presented in this section. The bottom surface temperature presented is the area-weighted average values of RZ and AZ.

3.1 Pipe inner diameter

Pipe inner diameter is varied from 7 to 17 mm with the arithmetic progression step of 2 mm. Its influence is analyzed for the cases of constant flow rate and constant velocity.

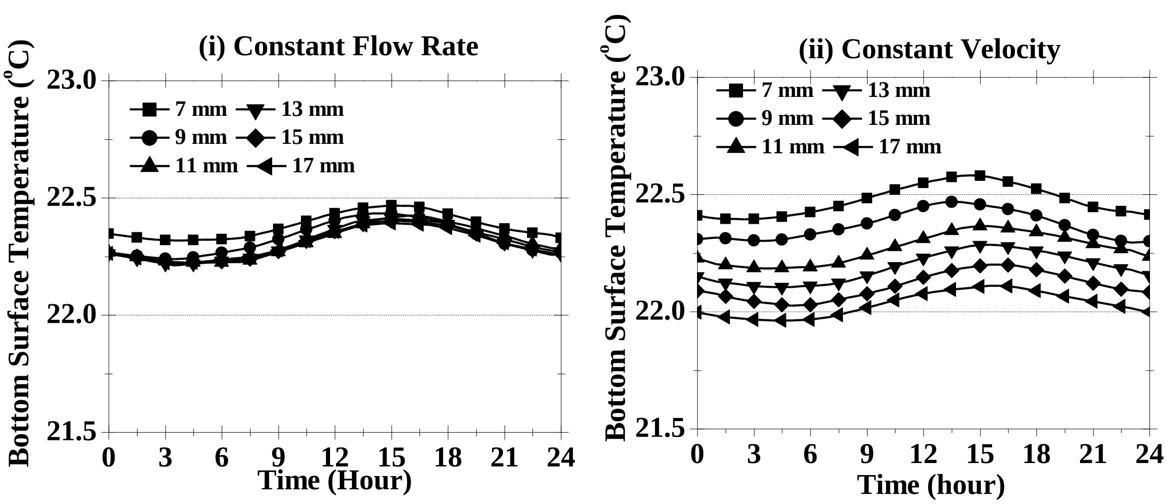

Figure 5: Diurnal variation of average bottom surface temperature for various pipe inner diameters with **(i)** constant flow rate **(ii)** constant velocity of cooling water

Figure 5(i) depicts the diurnal variation of bottom surface temperature for various pipe inner diameters with a constant flow rate of cooling water. Varying the pipe inner diameter from the 7 to 17 mm has a low influence on the performance of TAGFRG, the reduction in average bottom surface temperature is not even 0.5°C. Increase in pipe inner diameter increases the heat transfer area between water and the pipe and also the pipe and their embedded building structures. These enhance the heat removal from the indoor space. However, increase in inner diameter with constant flow rate reduces the water velocity and increases its residence time in the pipe. Increase in residence time, i.e., additional time spent by water results in increased water temperature. Therefore, for higher diameter pipes, the heat transfer potential of the water decreases more rapidly along the pipeline. Hence, the impact of an increase in pipe inner diameter without an increase in water flow rate is less significant on the cooling performance of TAGFRG. The average bottom surface temperature for the pipe inner diameter of 7 mm is 22.4°C. This reduces only by 0.1°C when the pipe inner diameter is increased to 17 mm. In both the cases, the solar heat penetration through the RZ reduces with the increase in pipe inner diameter as the space between the pipes decreases. This results in a more uniform temperature at the bottom surface of the roof.

Figure 5(ii) shows the diurnal variation of bottom surface temperature for different pipe inner diameter with constant velocity. Increase in pipe diameter with constant velocity increases the flow rate of water, i.e., a large volume of water is utilized to remove the heat from the indoor. This improves the performance of the TAGFRG roof because of the increased heat transfer potential for the larger inner diameter pipes. The heat transfer potential drops slower in larger diameter pipes as a high quantity of water is available for the heat absorption. The average bottom surface temperature is 22.5°C for the pipe inner diameter of 7 mm and it is reduced to 22°C for 17 mm. This reduction is not significant due to the low thermal conductivity of GFRG material at the bottom layer. This temperature reduction will only have a minimal influence on the mean radiant temperature of indoor space. Hence, for both the cases, increase in pipe inner diameter has no significant influence on the performance of TAGFRG roof.

3.2 Pipe Spacing

Pipe spacing of 25, 55 and 85 mm are analyzed for the performance of TAGFRG roof. Increase in pipe spacing allows more solar heat through the roof. However, in TAGFRG roof 2/3 of the area has the provision of the air gap, which acts as a thermal insulation and remaining 1/3 of the area allows the solar heat penetration through it. The decrease in pipe spacing increases the number of rows or pipe length to be embedded in each cavity. This increases the residence time of water. The decrease in pipe spacing decreases the bottom surface temperature due to increase in the heat transfer area of piping. The average bottom surface temperature of 22.6°C for the 85 mm pipe spacing decreases to 22.3 and 21.8°C for 55 and 25 mm of pipe spacing respectively (Figure.6). The diurnal fluctuation is reduced with the decrease in pipe spacing as it reduces the solar heat penetration between the two pipes. The difference in average bottom surface temperature between 85 and 25 mm pipes is 0.8°C.

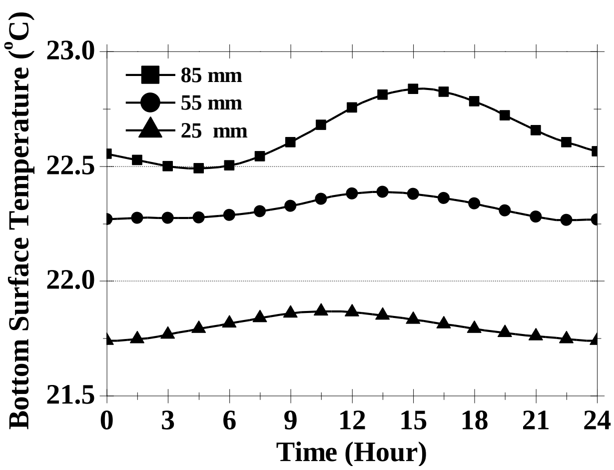

Figure 6: Diurnal variation of average bottom surface temperature for various pipe spacing

3.3 Pipe Wall Thickness

Pipe wall thickness is varied between 1 and 4 mm with the increment of 1 mm. Increase in pipe wall thickness increases the thermal resistance between the cooling water and building fabrics. Increase in pipe wall thickness decreases the heat transfer rate of water, which in turn increases the bottom surface temperature. However, the difference in the bottom surface temperature between the wall thickness of 4 and 1 mm is 0.2°C, which is not significant. (Figure 7(i)). Therefore, the influence of pipe wall thickness is negligible on the performance of TAGFRG roof. Hence, the thickness of pipe chosen must be based on the resistance to puncture or other damages throughout their lifetime, particularly during the construction phase.

3.4 Pipe Thermal Conductivity

The impact of pipe thermal conductivity is evaluated for the materials of chlorinated polyvinyl chloride (CPVC) (k = 0.14 W/mK), Cross-linked polyethylene (PEX) (k = 0.45 W/mK), concrete (k = 1.4W/mK) and copper (k = 384 W/mK). The thickness is considered as 1 mm and the thermal resistance offered by the pipe material is negligible compared to the thermal resistance of GFRG layer at the bottom side. Therefore, the bottom surface temperature is almost same for all the pipe material as shown in Figure 7(ii). The pipe material will impact the cooling performance only when its thermal conductivity is lower than the thermal conductivity of slab material (Jin *et al.*, 2010). However, due to the low thermal conductivity of GFRG layer, the impact of pipe parameters has a negligible effect on the cooling performance of TAGFRG. The pipe material should be finalized by factors such as considering corrosion resistance, scale resistance, leak-proof and flexibility to work.

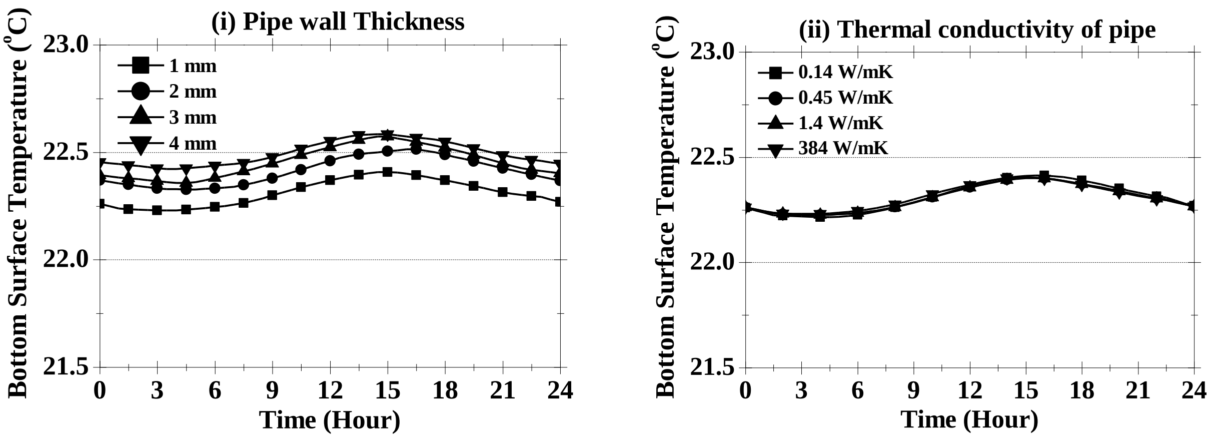

Figure 7: Diurnal variation of bottom surface temperature for various **(i)** pipe wall thicknesses **(ii)** pipe thermal conductivities

3.5 Supply Water Temperature

Figure 8(i) depicts the diurnal variation of bottom surface temperature for the supply water temperatures from 16 to 24°C with the increment of 2°C. Decreases in supply water temperature increase the temperature potential, which results in a decrease in bottom surface temperature. The average temperature of roof bottom surface for the supply water temperature of 24°C is 26.2°C and is decreased to 21°C for the supply water temperature of 16°C. The temperature difference between the supply water temperature and the average temperature of the bottom surface is 5°C for the supply water temperature of 16°C and decreases to 2.2°C for 24°C. The range of supply water temperature is finalized by the dew point temperature of the air. The supply water temperature below the dew point temperature cause condensation on the indoor surfaces. The average heat removal rate is 49.6 W/m^2 for the supply water temperature 24°C. This increases to 118 W/m^2 for the supply water temperature of 16°C. Among the parameters investigated, supply water temperature has the highest influence on the cooling performance of the TAGFRG roof slab.

3.6 Supply Water Flow Rate

The cooling performance of TAGFRG is analyzed for the supply water flow rates between 25 and 1600 L/h with the geometric progression step of 2. For lower flow rates, increase in water flow rates decreases the bottom surface temperature. The difference in the bottom surface temperatures among the lower flow rates (25, 50, 100 and 200 L/h) is significant (Figure 8(ii)). The decrease in flow rates affects the cooling performance of the TAGFRG roof as the residence time of water in the pipe increases, in turn, the temperature of water increases along the pipe length which reduces the heat transfer potential between the indoor space and water. The average bottom surface temperature for the flow rate of 25 L/h is 24.5°C and is decreased to 22.4°C for the flow rate of 200 L/h. For higher flow rates (400,800 and 1600 L/h), the difference in bottom surface temperature is not significant. The difference in average temperature of bottom surface between 400 and 1600 L/h is 0.1°C only. Hence, an increase in flow rates above a certain range does not influence the cooling performance; however, the power consumption of pump increases. Therefore the optimum flow rates need to choose with the consideration of cooling performance and also power consumption of the pump.

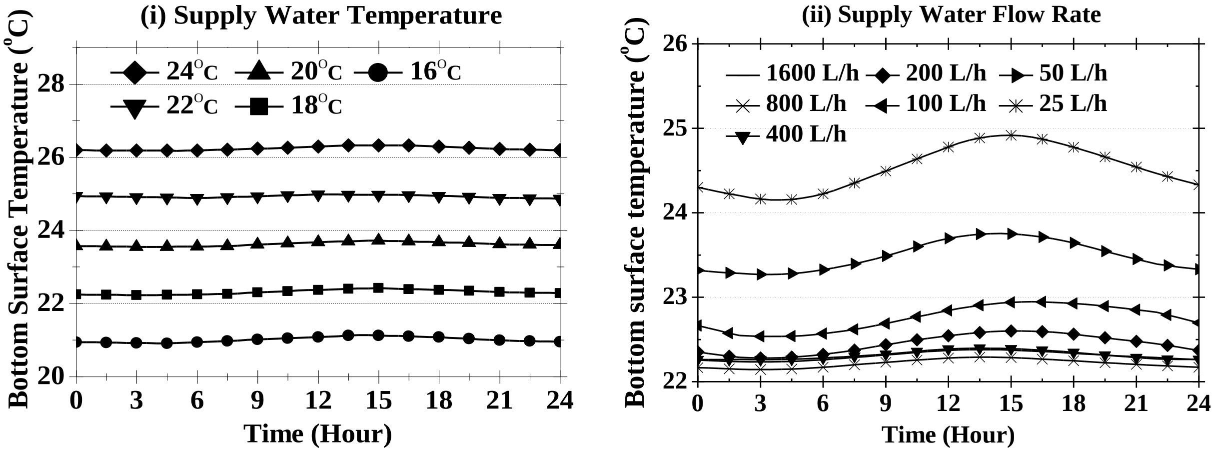

Figure 8: Diurnal variation of bottom surface temperature for various **(i)** temperature **(ii)** flow rate of supply water

4. CONCLUSION

The influence of various design and operating parameters on the performance of Thermally Activated Glass Fibre Reinforced Gypsum (TAGFRG) roof is analyzed. The decrease in pipe spacing from 85 to 25 mm decreases the bottom surface temperature by 0.8°C. Other pipe parameters (inner diameter, wall thickness and thermal conductivity) have no significant influence on the performance. Operating parameters, i.e., temperature and flow rate of supply water, have a significant effect on the performance of TAGFRG roof. The decrease in supply water temperature from 24 to 16°C decreases the bottom surface temperature from 26.2 to 21°C. For the lower flow rates, an increase in flow rate from 25 to 400 L/h decrease the bottom surface temperature by 2.1°C. A further increase in flow rate has no significant impact on the performance of TAGFRG roof.

NOMENCLATURE

A	area of cross section	(m^2)
B	breadth	(m)
Cp	specific heat capacity	(J/kgK)
d	hydraulic diameter	(m)
ε	percentage error	(%)
f	darcy friction coefficient	
H	height	(m)
h	heat transfer coefficient	(W/m^2K)
k	thermal conductivity	(W/mK)
L	length	(m)
μ	dynamic viscosity	(Ns/m^2)
p	pressure	(pa)
ρ	density	(kg/m^3)
q	heat source	(W/m^2)
Q	heat transfer through wall	(W/m)
T	Temperature	(K)
τ	time	(s)
t	thickness	(m)
u	velocity vector	(m/s)
$\bar{u}$	cross-section averaged fluid velocity along the tangent of the center line of a pipe	(m/s)
W	width	(m)

Subscript

i	inner surface
Meas	measured
o	outer surface
Simu	simulated

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