Indian Journal of Engineering & Materials Sciences
Vol. 29, June 2022, pp. 345-354

Thermal performance evaluation of cellulose fibre as building insulation material

Ravinder Kumar Pal[a], Parveen Goyal[b], & Shankar Sehgal[b*]

[a]Mechanical Engineering Department, Panjab University, Swami Sarvanand Giri Regional Centre, Hoshiarpur, Punjab 146 020, India
[b] Mechanical Engineering, University Institute of Engineering and Technology, Panjab University, Chandigarh 160 014, India

Received: 25 January 2022; Accepted: 16 February 2022

Space cooling has utilized lots of electricity in summers which has to be reduced by insulating inside of buildings. This has potential to reduce the environment pollution caused by higher expenditure of energy. The present work has the scope to evaluate thermal performance of a test model house providing cellulose fibre based cardboard insulation and compare the performance with an uninsulated model. The addition of heat through roof, walls and net heat gain during the day has remained lesser for insulated test model than uninsulated test model. The temperature of indoor air has stayed lesser in case of insulated test model than the uninsulated test model during the day particularly in the interval from 12 hrs to 19 hrs The indoor air temperature for the insulated test model has remained lesser by 7°C from 14 hrs till 16 hrs in comparison to uninsulated test model. The energy and financial savings obtainable for summers has value of 144 kWh and Rs 864 respectively for insulated test model. The carbon dioxide emitted has reduced for summers by 226 kg for insulated test model. Hence better thermal comfort conditions have existed in the insulated buildings.

Keywords: Cellulose fibre, Thermal insulation, Indoor air temperature, Thermal comfort, Thermal performance, Cooling load

1 Introduction

A lot of energy has to be spent to maintain comfort conditions inside a building in hot summers. This high expenditure of energy has caused a lot of pollution to the environment and has produced greenhouse gases. Space heating or cooling load in the buildings has greatly reduced by applying insulation with a low payback period in the past[1–5]. Insulation materials has been used in building for improving the comfort in both space heating and cooling[6]. Thermal diffusivity of the insulation material has great importance under dynamic heat flow conditions like variation of outdoor air temperature as it tells us that how fast the heat will flow in a particular material. Synthetic insulation materials like polystyrene based insulations, glass wool and rock wool has not been environment friendly and have large embodied energy[1,7,8]. Utilization of plastic based unnatural materials have caused damage to the environment[9]. Natural fibres have been environment friendly and saved energy when utilized in place of synthetic fibres[10]. Natural fibres based on agriculture wastes have been utilized to prepare composite materials also[11,12]. Natural fibre based materials have replaced wood as a construction material currently[13]. Interest in natural biobased materials for buildings construction has increased to mitigate the climate impacts of inorganic materials[14]. Natural biobased materials have caused lesser environmental pollution as compared to non-biobased materials[15,16]. Natural insulation materials like cotton, wood fibre, coconut and cellulose has been utilized as replacements for inorganic insulation materials[6]. These materials have comparable thermal properties and a lower environmental and health impact[17]. Thermal diffusivity has been lower for natural insulations than mineral and manmade insulations and these have been more suitable under dynamic heat transfer conditions[18,19]. The hygroscopic properties of the natural materials have helped in decreasing energy consumption for buildings[20]. The hygroscopic materials have balanced the indoor air humidity by absorbing, storing and releasing the water vapour from indoor room air[21–23]. Cellulose fibre insulation has been an environment friendly material prepared from recycled paper and has very low embodied energy and has not been much used as compared with traditional insulating materials[8]. Cellulose fibre has properties suited for insulating purpose beside having low thermal conductivity[8]. Cellulose fibre insulation has the least thermal diffusivity than other insulations like glass wool, recycled glass, cork, polyurethane and recycled cotton and hence has been most suitable for transient heat flow[18]. The cardboard has been

*Corresponding author (E-mail: sehgals@pu.ac.in)

prepared from cellulose fibre by separating it from wood fibre and has very low thermal conductivity and diffusivity. The literature available on the performance of cellulose fibre as an insulation for the buildings has been scarce.

The suitability of cardboard prepared from cellulose fibre for insulation purpose has to be investigated here. The cardboard insulation has to be applied on the roof and walls of a test model house and actual experiments has to be conducted on a test model. The temperature of the indoor air for an uninsulated and insulated test model has to be measured and net heat flow has to be computed in each case. The savings of money, energy and decrease in emission of carbon dioxide for the insulated test model also has to be calculated. The heat flow for both the cases for the test model has to be compared.

2 Materials and Methods

Various resources and techniques utilized for current investigation are presented within coming sections.

2.1 Materials

In the present work insulation layer of cardboard made of cellulose fibre was utilized on the roof and walls of the test model of a single-story house made from cardboard. The use of cardboard as an insulation was expected to reduce indoor temperature of the test model due to its lower thermal conductivity and thermal diffusivity. The life span of good quality cardboard as building material was around 25 years[24]. The dead load added to the building was only 5% of the load bearing capacity of the cement-concrete roof. Hence load bearing capacity of the building was not much affected. The performance of cardboard made from cellulose fibre as an insulation was evaluated by applying it on the roof and walls of a test model house in the month of May and June. White exterior color was best for keeping lower indoor temperature of a building. The combined effect of cardboard insulation and white color of the exterior of the test model was evaluated. Actual experiments were conducted and the temperature of the indoor air was gauged for uninsulated and insulated test model on the roof and walls. The indoor temperature and various heat flows in case of uninsulated and with cardboard insulation layer were also compared for both the cases. Parameters like savings in the form of energy, money and reduction in emission of carbon dioxide were computed in both cases. The schematic sketch and dimensions of the set of test model used for the study was presented in Fig. 1. The test model prepared for the study was a scaled down miniature model of an actual house. The actual picture of the test model was presented in the Fig. 2.

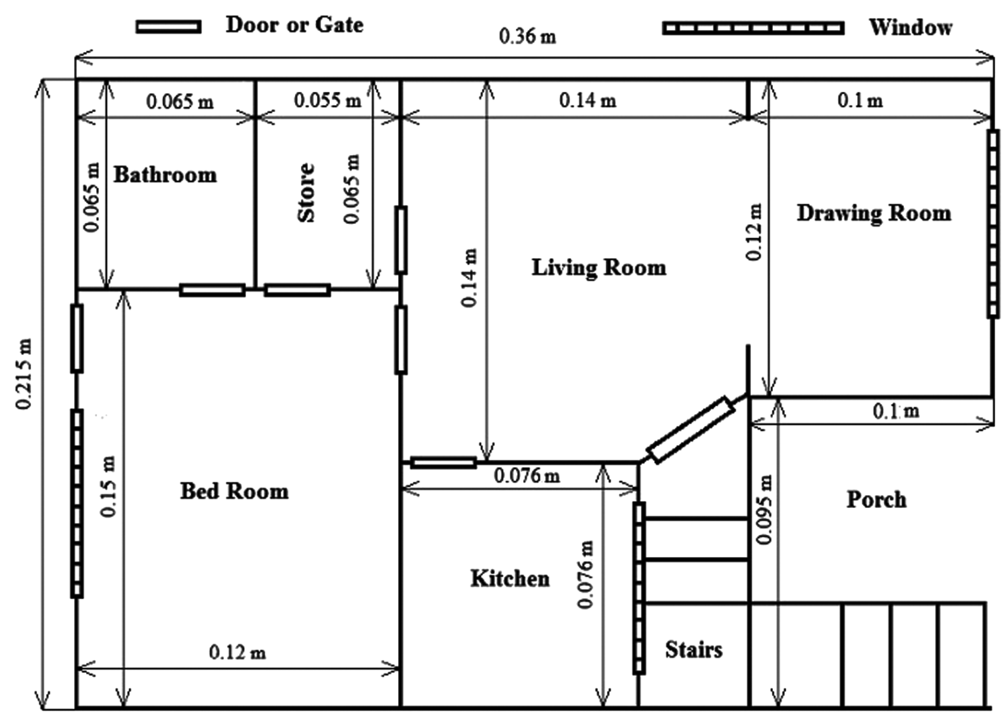

Fig. 1 — Experimental set-up.

Fig. 2 — Actual experimental set-up.

Various parameters of the test model and other factors used related to the current study were as follows. Outside film coefficient, inside film coefficient, density of the air and cost of electricity were taken as 22.8 W/m^{2}K, 6 W/m^{2}K, 1.14 kg/m^3 and 6 Rs/kWh respectively for the insulated and uninsulated test model[25]. Thermal conductivity for cardboard lagging was 0.055 W/mK for insulated and uninsulated test model [26]. Solar absorptance for the uninsulated and insulated test model was 0.45 and 0.21. Test model area, test model height and size of the windows were 0.77 m^2, 0.12 m and 0.0016 m^2 for both the cases. Thickness of the cardboard layer for roof and all walls was 0.0054 m for the uninsulated test model. Thickness of the cardboard layer for roof, southern, eastern, western and northern walls was 0.03 m, 0.0222 m, 0.0216 m, 0.0192 m and 0.0138 m respectively in case of insulated test model.

The mathematical model already tested was used to figure out the value of indoor air temperature mathematically and compare it with experimental value. Various heat interactions were also worked out and compared for both the cases.

2.2 Methods

The different parameters used in the study were figured out by various methods. These methods were presented in this section.

2.2.1 Solar air temperature

It was calculated using Eq. (1). It was calculated from factors like ambient air temperature, part of radiation absorbed etc.[25,27]

$$T_{sl} = T_{ab} + \alpha_s \frac{I_{sl}}{h_{ou}} - \frac{\varepsilon\delta R}{h_{ou}} \quad \text{... (1)}$$

where, T_{sl} solar air temperature (°C), T_{ab} was ambient temperature (°C), h_{ou} was outside film coefficient/ Wm^{2}°C), α_s is surface solar absorptance and $\varepsilon\delta R/h_o$ Longwave radiation factor.

2.2.2 Heat transfer coefficients

These were calculated from the film coefficient for indoor air & ambient air and thermal resistance of layer by means of Eqs. (2 and 3).

$$U_{ro} = \frac{1}{\frac{1}{h_{in}} + \frac{\delta_1}{K_1} + \frac{1}{h_{ou}}} \quad \text{... (2)}$$

$$U_{wa} = \frac{1}{\frac{1}{h_{in}} + \frac{\delta_2}{K_1} + \frac{1}{h_{ou}}} \quad \text{... (3)}$$

where, $U_{ro,}$ U_{wa} were overall heat transfer coefficients roof, walls respectively (W/m^2°C), $h_{in,}$ h_{ou} were inside and outside film coefficients respectively (W/m^{2}°C), K_1 was cardboard layer conductivity (W/m°C) and δ_1, δ_2 are thickness of cardboard for roof, wall (m).

2.2.3 Heat interactions

The heat interaction from the roof was the first term of right side in Eq. (4). Similarly second term represent heat interaction from walls, sum of third and fourth term represent the heat flow from the windows and the fifth term represent the heat interaction due to ventilation.

The net heat interaction was worked out from Eq. 4 from the sum of heat flow from roof, wall, window and due to ventilation.

$$Q_{net} = U_{ro} * A_r(T_{ro} - T_i) + U_{wa} * A_{wa}(T_{wa} - T_i) + A_w * \tau_g * I_{sl} + U_w * A_w * (T_w - T_i) - \frac{\rho_i * V_i * C_i * N_a * (T_i - T_{ab})}{3600} \quad \text{... (4)}$$

where, Q_{net} was net heat interaction (W), U_w was overall heat transfer coefficient for windows, A_r, $A_{wa,}$ A_w were area of the roof, wall and window oftest model (m^2), $T_{ab,}$ T_i were ambient and indoor air temperature (°C), T_{ro} was solar air temperature for model roof (°C), T_w, T_{wa} solar air temperature of window, wall (°C), ρ_i was density of indoor air (kg/m^3), τ_g glass transmissivity, V_i was indoor air volume (m^3), C_i specific heat of indoor air (kJ/kg°C) and N_a was air charges (h^{-1}).

2.2.4 Indoor temperature

Inside air temperature was computed from net heat flow (Eq. (4)) to the buildings as given in Eq. (5).

$$M_i * C_i\left(\frac{dT_i}{dt}\right) = Q_{net} \quad \dots (5)$$

The indoor temperature for next hour was worked from Eq. 5[25,27]using MATLAB software using function (ode45) based on Runge-Kutta 4th and 5th order method. The solution is given below: -

$$T_i(t+1) = T_i(t) + \left(\frac{C_1+2C_2+2C_3+C_4}{6}\right) * h \quad \dots (6)$$

The coefficients for Runge-Kutta method[25,27] in Eq. (6) were worked out using expressions given below in Eqs.(7)-(10).

$$C_1 = (bT_i(t) + \mathrm{v}(t)) * h \quad \dots (7)$$

$$C_2 = (b(T_i(t) + \frac{C_1}{2}) + \mathrm{v}(t)) * h \quad \dots (8)$$

$$C_3 = (b(T_i(t) + \frac{C_2}{2}) + \mathrm{v}(t)) * h \quad \dots (9)$$

$$C_4 = (b(T_i(t) + C_3) + \mathrm{v}(t)) * h \quad \dots (10)$$

where, M_i was mass of indoor air (kg),bwas room air temperature coefficient, $C_{1,}$ C_2 were First and Second Runge-Kutta coefficient, $C_{3,}$ C_4 was Third and Fourth Runge-Kutta coefficient, $v(t)$ was time function of transient terms and h was time interval in hour (h).

2.2.5 Optimum thickness of insulation

The optimum thickness was worked out from the total cost (Eq. (13)) which was sum of the insulation cost (Eq. (11)) and energy cost (Eq. (12)). Thickness was optimum at a point where the total cost was minimum.

$$P_i = (M_{in} * C_{in})/L_{in} \quad \dots (11)$$

$$P_e = (Q_{net}/E_{pr}) * C_e \quad \dots (12)$$

$$P_t = P_i + P_e \quad \dots (13)$$

where, $P_{i,}$ $P_{e,}$ P_t was insulation, energy and total cost (Rs/y), M_{in} was mass of insulation (kg), C_{in} was cost of insulation (Rs/kg), E_{pr} energy performance ratio of cooling device and C_e cost of energy (Rs/kWh).

2.2.6 Energy, money savings and reduction in carbon dioxide

Energy savings were figured out by difference of algebraic sum of heat gain for the uninsulated and insulated test model. Technique utilized for working out energy savings was given in Eq. (14).

$$E_{sa} = (Q_{nu} - Q_{ni})*30/1000 \quad \dots (14)$$

where, Q_{ni} was net heat flow for insulated test model (W), Q_{nu} was net heat flow for uninsulated model (W) and E_{sa} was energy savings for insulated model (kWh).

Money savings for the insulated test model were worked out by the product of energy savings and cost of energy per unit. The method for computing money savings were given in Eq. (15).

$$M_{sa} = E_{sa} * C_e \quad \dots (15)$$

where, C_{er} were carbon dioxide emission reduction (kg) Carbon dioxide decrease were figured out from the savings in energy. The carbon dioxide emission reduction calculation technique was presented in Eq. (16).

$$C_{er} = E_{fc} * (1 + L_{dn} + L_{tn}) * E_{sa} \quad \dots (16)$$

Where E_{fc} was emission factor carbon dioxide (kg/kWh), L_{in} was life span of insulation (years), $L_{dn,}$ L_{tn} were distribution losses and transmission losses and M_{sa} was money savings for insulated model (Rs.)

3 Results and Discussion

The outcomes computed as indoor temperature measured experimentally and worked out using the mathematical model, parameters like solar temperature, various heat interactions, savings in the form of energy and money and decrease in carbon dioxide computed from Eqs. (1-16) were given here.

3.1 Solar air temperatures

These temperatures in case roof, wall and window of the test model were presented in Fig. 3 for without and with insulation. The solar air temperature was equal for all cases and decreased from 00 hrs to 05 hrs due to absence of sun. The solar air temperature increased for all surfaces of the test model without and with insulation from 06 hrs to 16 hrs This was as a result of falling of sun rays on the exterior of test model and absorption of heat by the test model according to its absorptivity for sand and white color.

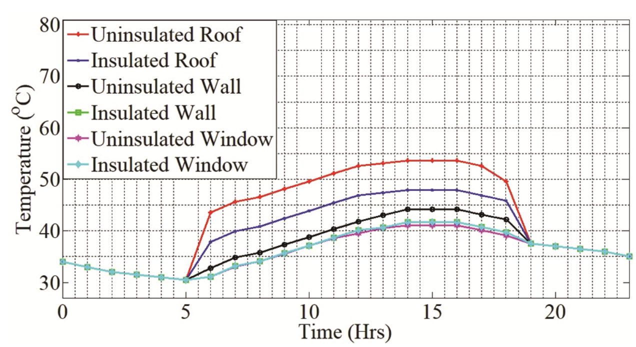

Fig. 3 — Solar air temperature for both test model.

The increase in solar temperature was maximum for roof, lesser for the wall and least for the window during this period. This was because the radiation falls on the roof throughout the day and for wall it falls for a certain period on a particular wall and solar absorptivity was least for the window. Solar air temperature of rooftop and wall was higher in case of the test model without insulation owing to higher absorptivity of sand colour used on exterior as compared to white color used on the test model with insulation. The solar air temperature of all the surfaces decreased from 16 hrs to 23 hrs This was firstly because of fall in sun radiation and then complete disappearance of sunlight after 19hrs The solar air temperature for test model without insulation was more for the roof and wall for this period due to reason already explained. The solar air temperature becomes equal for all surfaces in both the cases after 19-23 hrs because of absence of solar radiation due to night. The solar air temperature for the window was equal in both cases throughout the day and night.

In literature also lower solar air temperature was reported for colour with lower solar absorptivity as compared to colour with higher solar absorptivity[28]. Which was similar to the results obtained in the present study. In another study lower surface temperature was observed for light colours as compared to dark colours this means a lower solar air temperature[29].

3.2 Heat transfers

Different heat transactions for the test model were through roof, wall, window, ventilation and the net heat interaction which was the algebraic sum of the first four heat interactions. The variation of heat interaction from roof, wall, window, ventilation and net heat transfer for the test model without insulation and with insulation were discussed in the following sub-sections.

3.2.1 Heat flow from roof

The variation of heat interaction from roof for the test model without insulation and with insulation was presented in Fig. 4. The test models do not lose or gain heat due to equilibrium between inside and outside temperature from 00 hrs to 05 hrs The heat flow from the roof of uninsulated test model remained almost constant from 06 hrs in morning to 13 hrs in the afternoon due to constant difference of temperature between solar air temperature for the roof and indoor air temperature which was responsible for heat flow from the roof. The amount of heat transfer from the roof was high due to falling of solar radiation and high difference in temperature during this period. The heat transfer from the roof decreased from 13 hrs onwards up to 18 hrs in the evening due to decrease in difference of outdoor temperature and indoor temperature. The test model lost heat from the roof from 19 hrs to 22 hrs due to negative temperature difference of solar air temperature and indoor temperature. The test model did not lose or gain heat due to equilibrium between inside and outside temperature after 22 hrs in the night to 23 hrs In case of insulated test model the heat gain from the roof was very less as compared to the uninsulated model. This was because lesser heat gets transferred inside due to more thermal resistance offered by the insulation material employed. The heat gain from roof remained constant from 06 hrs to 18 hrs as a result of constant difference of solar air, indoor temperature. The heat gain reduced from 18 hrs to 19 hrs owing to sun set and decrease of solar temperature. No heat gain or loss took place from 19 hrs in the evening till 23 hrs as the outdoor and indoor temperature remained equal during this interval.

Lower heat gain was reported in literature also from the roof of a room insulated with antisolar insulation system[30]. In another study it was found that heat gain can be reduced by insulating the roof of a building[31]. This was similar to the result obtained for the heat flow from roof in the present work.

3.2.2 Heat flow from walls

The variation of heat interaction from walls for the test model without insulation and with insulation was presented in Fig. 4. No heat gain or loss takes place for walls from 00 hrs till 05 hrs for both cases as the outdoor and indoor temperature remained equal during this interval. The heat flow from the walls of uninsulated test model remained almost constant from 06 hrs in morning to 14 hrs in the afternoon due to

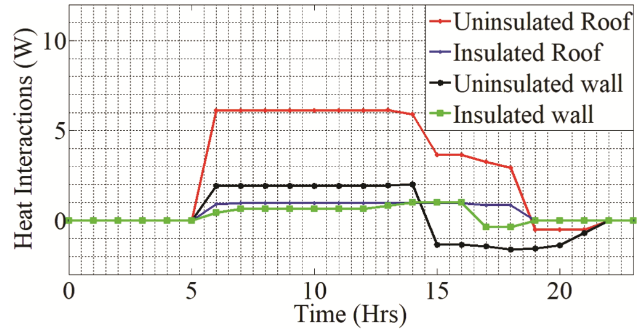

Fig. 4 — Heat interactions from roof and wall oftest model without and with insulation.

constant difference of temperature between solar air temperature for the walls and indoor air temperature which was responsible for heat flow from the walls. The amount of heat transfer from the walls was low as compared to roof due to falling of lesser solar radiation and lower difference in temperature than the roof. The test model lost heat from the walls from 14 hrs to 22 hrs because of negative differential of solar air and indoor temperature. The uninsulated test model did not lose or gain heat due to equilibrium between inside and outside temperature after 22 hrs to 23 hrs In case of insulated test model the heat gain from the walls was lesser as compared to the uninsulated model. This was because lesser heat gets transferred inside due to more thermal resistance offered by the insulation material employed. The heat gain from walls increased slightly from 06 hrs to 07 hrs and remained constant from 07 hrs to 12 hrs because of slight increase in difference between solar, indoor air temperature from 06 hrs to 07 hrs and thereafter it remained constant up to 12 hrs The heat transfer increased slightly 12 hrs to 13 hrs due rise in temperature difference of outdoor and indoor air as the indoor temperature did not rise as much as the outdoor temperature. Heat gain remained constant from 13 hrs to 16 hrs as a result of constant differential of solar air temperature and indoor temperature. The heat loss occurred from 16 hrs to 19 hrs because of sun set and decrease of solar air temperature. No heat gain or loss took place from 19 hrs in the evening till 23 hrs as the outdoor and indoor temperature remained equal during this interval.

In literature also it was reported that heat flow reduced from 0.0259 kW to 0.0102 kW for an internally insulated wall comprised of red clay bricks as compared to uninsulated wall for a building due to reduction in thermal conductivity of the wall by around 50%[32]. It was reported in another study that insulated walls have lower overall heat transfer coefficient up to 60% this means lower heat transfer to the inside of building through walls[33]. In the present work also the decrease in heat flow for insulated walls was observed which is in agreement with the available literature.

3.2.3 *Heat flow from window*

The variation of heat interaction from windows for the test model without insulation and with insulation was presented in Fig. 5. The heat flow from the windows of uninsulated and insulated test model was same throughout the day and night. The test models did not lose or gain heat due to equilibrium between inside and outside temperature from 00 hrs to 05 hrs The heat gain by the test model remained almost constant from 06 hrs morning to 16 hrs in the afternoon due to constant difference of temperature between solar air and indoor temperature and constant falling radiation. The amount of heat gained from the windows was low as compared to roof as a result of smaller differential of solar air temperature for window and indoor temperature than the difference in case of roof. The heat gain by test model from the window reduced from 16 hrs to 19 hrs owing to decrease in temperature difference of solar air and indoor temperature and decreased solar radiation. Uninsulated test model did not lose or gain heat due to equilibrium of solar air, indoor temperature after 19 hrs to 23 hrs

3.2.4 *Heat flow due to ventilation*

The variation of heat interaction due to ventilation for the test model with insulation and without insulation was presented in Fig. 5. No heat gain or loss takes place for both models from 00 hrs till 05 hrs as the outdoor and indoor temperature remained equal during this interval. The heat gain due to ventilation for uninsulated test model was zero and remained almost constant from 06 hrs in morning to 12 hrs in the afternoon due to same outdoor and indoor air temperature difference during this interval. The uninsulated test model started losing heat from 12 hrs onwards up to 22 hrs in the evening due to higher indoor temperature than outdoor temperature. The heat loss from test model increased from 12 hrs to 18 hrs and decreased from 18 hrs to 22hrs due to increase in temperature difference first and then due to decrease in temperature difference. The test model did not lose or gain heat due to equilibrium between

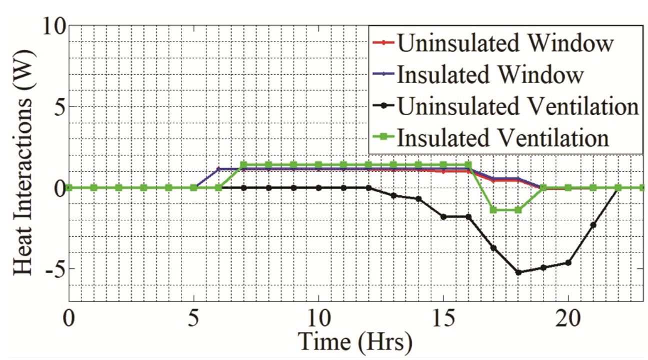

Fig. 5 — Heat interactions from window andventilation for insulated and uninsulated model

inside and outside temperature after 22 hrs to 23 hrs In case of insulated test model the heat gain due to ventilation was somewhat higher as compared to the uninsulated model due to lower indoor air temperature for insulated test than uninsulated model. The heat addition because of ventilation increased for the period 06 hrs to 07 hrs and then remained constant for the period 07 hrs to 16 hrs due to first rise and then constant temperature differential between outside and inside temperature. Heat gain decreased after 4 pm and then it lost heat after 17 hrs to 19 hrs due to rise in indoor temperature as compared to outdoor temperature. No heat gain or loss took place from 19 hrs in the evening till 23 hrs the outdoor and indoor temperature remained equal during this interval.

3.2.5 Net heat flow

The total heat flow for the test model without insulation and with insulation was shown in Fig. 6. Neither total heat gain nor total heat loss took place for the period 00 hrs to 05 hrs for both cases as the outdoor and indoor temperature remained equal during this interval The net heat gain for uninsulated test model remained almost constant from 06 hrs in morning to 12 hrs in the afternoon due to same outdoor and indoor air temperature during this interval. The uninsulated test model net heat gain increased slightly from 12 h onwards up to 14 h due to higher outdoor temperature and falling of more solar radiation during this period. The total heat addition in uninsulated test model remained much higher than insulated test model from 06 hrs to 14 hrs due to lower thermal resistance in case of uninsulated test model. The net heat gain from uninsulated test model decreased from 14 hrs to 16 hrs due to decrease in temperature difference. The test model lost net heat due to higher indoor temperature than the outside temperature after 16 hrs till 22 hrs Net heat gain was lower for uninsulated test model than insulated model from 14 hrs till 22 hrs owing to higher indoor temperature in the former. Neither heat gain nor heat loss occurred after 22 hrs till 23 hrs as a result of thermal equilibrium between indoor and outdoor temperature. In case of insulated test model the net heat gain increased from 06 hrs to 07 hrs and was almost constant from 07 hrs till 16 hrs due to rise in outdoor temperature from 06 to 07 hrs and constant indoor and outdoor temperature difference from 07 hrs till 16 hrs The net heat gain decreased after 16 hrs as indoor and outdoor temperature decreased and it lost heat slightly from 17 hrs till 19 hrs as a result of higher indoor temperature than outdoor temperature. Neither total heat gain nor total heat loss took place for the period 19 hrs to 23 hrs on the next morning as the outdoor and indoor temperature remained equal during this interval.

Lower heat gain was also reported for an insulated building in the available literature[30–33]. The observations in the literature for the heat gain were similar in trend with the present work.

3.3 Indoor air temperature

In this section experimentally measured inside temperature and the temperature of indoor air determined by simulation method were presented in separate sub-sections and compared.

3.3.1 Experimental indoor air temperature

The experimentally measured inside temperature decreased from 00 hrs to 6 hrs for both models due to absence of sun as shown in Fig. 7. The temperature increased from 06 hrs in the morning till 16 hrs in the afternoon. Which was owing to net heat addition during the interval to both test models. The inside temperature decreased from 16 hrs till 23 hrs This was as a result of decreased in net heat gain in the late afternoon and then due to net heat loss from the test models in the evening and early part of night and

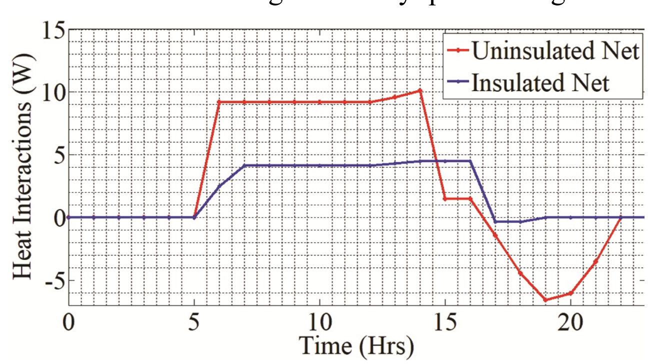

Fig. 6 — Net heat interactions for both test model.

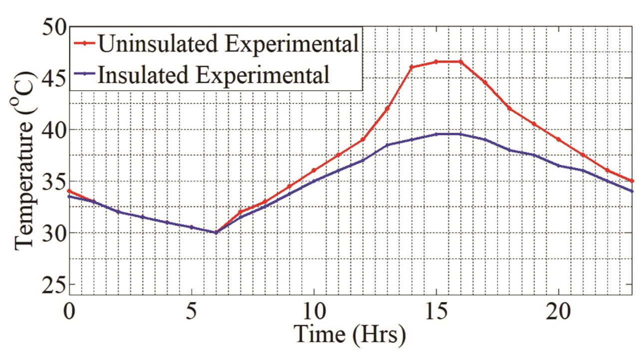

Fig. 7 — Experimental indoor temperature for insulated and uninsulated model.

because of fall in outdoor temperature and thermal equilibrium between the indoor and outdoor temperature in the late night and early morning. Indoor temperature was lower in insulated test model than uninsulated test model at most of the time of the day and night and was same only during the early morning from 01 hrs to 06 hrs This was due to higher thermal resistance and lower net heat flow in case of insulated test model. The difference in indoor temperature of insulated and uninsulated test models was more in the 12 hrs till 19 hrs Which was owing to more sun rays falling on the test model during, the outdoor temperature was also higher during this interval of time and the insulated model had higher thermal resistance. The maximum difference between indoor air temperature of the two test models was 7°C from 14 hrs till 16 hrs in the afternoon and the lower indoor temperature existed in the insulated test model than the uninsulated test model.

In the literature also a reduction of 2.0-2.5°C in the indoor air temperature and around 6.5°C decrease in difference of outdoor and indoor temperature was reported due insulation of roof of the building with antisolar system[30]. Another study reported lower indoor temperature by 0.6°C in insulated roof building than uninsulated roof of same building[34]. The decrease in temperature was more in present study than other studies as both the roof and walls were insulated along with white exterior colour of the test model used for the trials. Hence applying the cellulose fibre insulation to the roof and walls along with white exterior color was more preferable.

3.3.2 Simulated indoor temperature

Variation of the inside temperature obtained by simulation method for both the uninsulated and insulated test models and their comparison with the experimental results was revealed in Fig. 8. The variation of the simulated indoor air temperature for uninsulated and insulated test model was similar with the experimental results respectively. The variation of the simulation results from the experimental results was less than 5% for each case. This was within acceptable limits and the model can be used to predict the results very accurately.

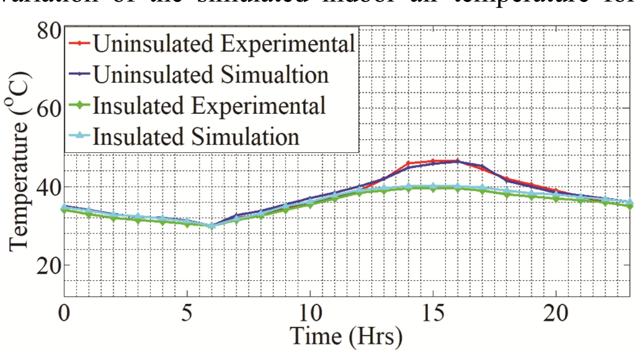

Fig. 8 — Simulated and experimental indoor temperature for uninsulated and insulated model.

3.4 Optimum thickness of insulation

The variation of insulation cost, energy cost and total cost was shown in Fig. 9. The insulation cost increased with increase in thickness of insulation as more materials was employed at higher thickness. The energy cost for cooling decreased with increase in thickness due to lesser heat inflow at higher thickness. However the reduction in energy cost decreased constantly and become very less after thickness of 0.03 m. The total cost decreased up to 0.03 m thickness and after that it started increasing. Hence the optimum thickness of insulation in this case was 0.03 m.

3.5 Energy, money savings and decrease in emitted carbon dioxide

Energy savings, money saving and carbon dioxide reduction due to employing cellulose fibre insulation and white exterior color of the test model were presented in Fig. 10. Energy savings were obtained due to the fact that cooling load was much lower because of lower net heat flow to the indoor of test

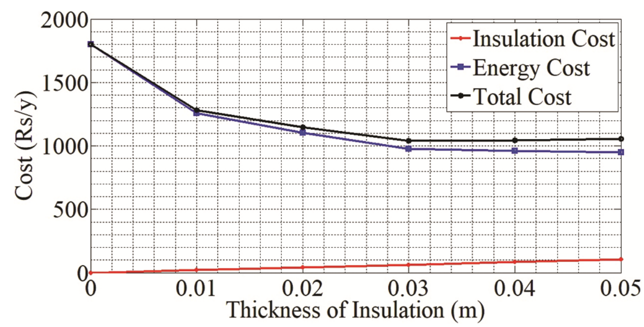

Fig. 9 — Optimum thickness of insulation.

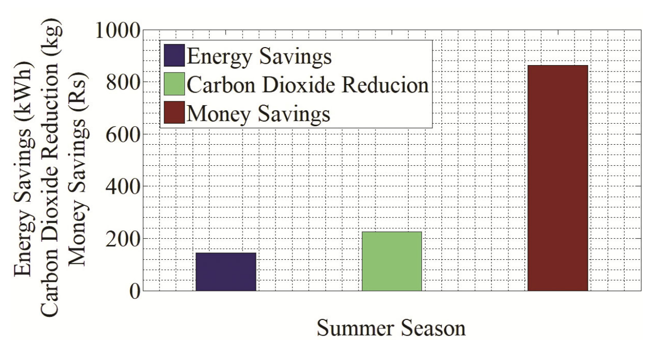

Fig. 10 — Energy, money savings and carbon dioxide reduction for insulated test model.

model and the lower indoor temperature as compared to uninsulated test model. The energy savings for a month was 24 kWh and for the summer season (from mid-April to mid-October) was 144 kWh. The money savings were obtained for the insulated test model because of energy savings achieved during the summer season. The amount of savings attained for a month was Rs 144 and for the full summer season was Rs 864. The energy savings and money savings obtainedwere significant considering the fact that it was only for a small test model and for a full scale building it will be very large.

In literature also savings of 26.62 kW were reported for an insulated red brick building as compared to uninsulated building[32]. Another study observed that energy savings around 27% was attainable applying optimum thickness of insulation[35]. Money savings of 1.33-2.13 USD were reported in the literature for an internally insulated red brick building[32]. Savings in terms of money were also reported in another study using insulation in the buildings[36]. The value for the energy and money savings in the literature were quite high on monthly basis as these were for the full scale building.The carbon dioxide emission reduction was obtainable as a result of energy savings in case of insulated test model as lesser amount of electricity will need to be used for the space cooling which will reduce the carbon dioxide produced for production of electricity. The carbon dioxide emission reduction for a month is 37.67 kg and for the full summer season was 226 kg. This reduction was significant as it is only for a small test model and for the full scale building it will be very large.

A reduction in annual carbon dioxide emission of around 150 kg/m^2 of floor area was reported for a roof insulated room[30]. The reduction was more in the present study as both walls and roof were insulated with cellulose fibre based insulation and the solar absorptivity of the exterior colour was also least. A reduction of 27% in carbon dioxide emission was reported in another study using optimum thickness of insulation[35].

4 Conclusion

In the current work, trials have been performed on a scaled down test model of a house in uninsulated and insulated conditions. Indoor air temperature of the test models has been experimentally found out and also calculated by simulation technique and compared. Heat flow from roof, wall, window and due to ventilation has been also worked out and net heat gain computed from the algebraic sum of these. The conclusions drawn from the study have been presented here.

- The heat flow from the roof has been much higher as compared to heat flow from the walls, window and ventilation in the uninsulated test model. The difference has not been so prominent in the insulated test model due to higher thermal resistance.
- The heat gain from the roof and walls has been lesser for insulated test model than uninsulated test model because of insulation provided in the former. The reduction in heat flow from the roof has been more evident than that for the walls in case of insulated test model. The net heat gain during the day has been generally more in uninsulated test model than insulated test model.
- Inside temperature has been lesser for insulated test model than uninsulated test model during the day. The difference in indoor temperature of insulated and uninsulated test models has been higher in the interval from 12 h to 19 h. The indoor air temperature for the insulated test model has been lesser by 7°C from 14 pm till 16 h in the afternoon than the uninsulated test model.
- Optimum thickness of insulation has been found out to be 0.03 m for the insulated test model in the present case.
- Significant energy and money savings have been obtainable along with reduction in carbon dioxide emission. The energy savings obtainable have been 24 kWh/month and for the summer season have been 144 kWh for the test model. The money savings attained have been Rs 144/month and for summer season have been Rs 864 for the test model. The carbon dioxide emission reduction has been 37.67 kg/month and for summer season has been 226 kg for the test model.
- The indoor air temperature worked out using simulation technique for uninsulated and insulated test model has analogous experimental results with high level of accuracy. Therefore the simulation method has potential to be utilized for working out inside air temperature in actual building with cardboard insulation.
- Further research has to be carried out to simulate indoor temperature to figure out effect of providing insulation inside actual building in the form of cellulose fibre insulation.

References

1 Asdrubali F, D'Alessandro F, & Schiavoni S, *Sustainable Mater Technol*, 4 (2015) 1.
2 Lechtenböhmer S, & Schüring A, *Energy Effic,* 4 (2011) 257.
3 Nyers J, Kajtar L, Tomić S, & Nyers A, *Energy Build*, 86 (2015) 268.
4 Alam M, Singh H, & Limbachiya MC, *Appl Energy*, 88 (2011) 3592.
5 Ahmad EH, *The 6th Saudi Engineering Conference, KFUPM*, (2002) 21.
6 Cetiner I, & Shea AD, *Energy Build*, 168 (2018) 374.
7 Wang H, Chiang P-C, Cai Y, Li C, Wang X, Chen T-L, Wei S, & Huang Q, *Sustainability (Switzerland)*, 10 (2018) 1.
8 Lopez Hurtado P, Rouilly A, Vandenbossche V, & Raynaud C, *Build Environ*, 96 (2016) 170.
9 Sinha R, Kumar S, Garg S, & Prasad N M, *Indian J Eng Mater Sci*, 28 (2021) 36.
10 Singh BG, Singari RM, & Mishra RS, *Indian J Eng Mater Sci,* 27 (2020) 866.
11 Dhawan V, Debnath K, Singh I, & Singh S, *Indian J Eng Mater Sci*, 27 (2020) 649.
12 Ahlawat V, Parinam A & Kajal S, *Indian J Eng Mater Sci*, 25 (2018) 295.
13 Singh R, Singh B, Gupta M &Tarannum H, *Indian J Eng Mater Sci*, 27 (2020) 137.
14 Lundmark T, Bergh J, Hofer P, Lundström A, Nordin A, Poudel BC, Sathre R, Taverna R, & Werner F, *Forests*, 5 (2014) 557
15 Buyle M, Braet J, & Audenaert A, *Renewable Sustainable Energy Rev*, 26 (2013) 379.
16 Cabeza LF, Rincón L, Vilariño V, Pérez G, & Castell A, *Renewable Sustainable Energy Rev*, 29 (2014) 394.
17 Sutton A, Black D & Walker P, *Building Research Establishment (BRE), UK,* BRE IP: IP18/11. (2011)
18 Pal RK, Goyal P & Sehgal S, *Mater Today: Proc*, 45 (2021) 5778.
19 Pal RK, Goyal P & Sehgal S, *Artificial intelligence, machine learning, and data science technologies: Future impact and well-being for society 50*, Chapter 9 (2021) 173.
20 Osanyintola OF, Talukdar P & Simonson CJ, *Energy Build*, 38 (2006) 1270.
21 Korjenic A, Teblick H, & Bednar T, *Build Simul*, 3 (2010) 295.
22 Shea A, Lawrence M, & Walker P, *Constr Build Mater*, 36 (2012) 270.
23 Simonson CJ, Salonvaara M, & Ojanen T, *J Therm Envelope Build Sci*, 28 (2004) 63.
24 Cripps A, *Build Res Inf*, 32 (2004) 207.
25 Pal RK, *J Eng Sci Technol*, 13 (2018) 1090.
26 Asdrubali F, Pisello AL, Alessandro FD', Bianchi F, Cornicchia M, & Fabiani C, *Energy Procedia*, 78 (2015) 321.
27 Chel A, & G N Tiwari, *Energy Build*, 41 (2009) 56.
28 Al-Khawaja MJ, *Appl Therm Eng*, 24 (2004) 2601.
29 Synnefa A, Santamouris M, & Apostolakis K, *Sol. Energy*, 81 (2007) 488.
30 Ahmad I, *Renewable Energy*, 35 (2010) 36.
31 Qin Y, Zhang M, & Hiller J E, *Energy*, 129 (2017) 138.
32 Alghamdi A A, *Int J Ambient Energy*, 42 (2021) 1428.
33 Walker R, & Pavía S, *Build Environ*, 94 (2015) 155.
34 Dabaieh M, Wanas O, Hegazy MA, & Johansson E, *Energy Build*, 89 (2015) 142.
35 Çomakli K, &Yüksel B, *Appl Therm Eng*, 24 (2004) 933.
36 Al-Sallal KA, *Renewable Energy*, 28 (2003) 603.