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IMPACT OF CEILING MATERIALS' THERMAL PROPERTIES ON THE FLOWFIELD AND HEAT TRANSFER WITHIN A COMPLEX-SHAPED ATTIC

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ABSTRACT

Beyond insulation, consideration of the effect of the thermal properties of the ceiling materials on the airflow and heat distribution within the attic are important in building design. This study examines this impact for asbestos, particle board, plywood and PVC ceilings under a complex-shaped pitched roof heated from below using ANSYS Fluent V(18) package. Results showed multicellular flow patterns for all the materials. Air speed within the attic increases with the use of asbestos, PVC, particle board and plywood. Generally, pressure is lowest at the upper vertex and highest near the bottom corners. The pressure maximum value is lowest in the particle board ceiling and highest in the asbestos ceiling. Therefore, on the flowfield, asbestos makes the best choice and plywood the least. In terms of thermal performance, particle board ceiling is best recommended, then the PVC, the asbestos and plywood. In a sample building, the rate of heat loss into the attic through a plywood ceiling is found to be about 7% higher than when particle board is used. This has huge building energy-saving and air-conditioning implications.

Keywords: Ceiling materials, thermal properties, attic, heat transfer, natural convection

NOMENCLATURE

AR	Aspect ratio, AR (2H/W)
g	Acceleration due to gravity, m/s^2
H	Height of enclosure, m
k	Thermal conductivity, W/mK
P	Dimensionless pressure
p	Pressure, N/m^2
Pr	Prandtl number
Ra	Rayleigh number
T	Temperature, K
T_C	Temperature at the cold wall, K

T_H	Temperature at the hotwall, K
u	Velocity in x-axis, m/s
U, V	Dimensionless velocity
v	Velocity in y-axis, m/s
W	Width of enclosure, m
X, Y	Dimensionless Cartesian coordinates

Greek symbols

α'	Thermal diffusivity, m^2/s
β'	Coefficient of thermal expansion, K
θ	Dimensionless temperature
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
α, β	Pitch angle, degrees

INTRODUCTION

The heating and cooling load for a building envelope depend largely on the thermal properties of the constituent building materials. According to ASHRAE (2005), building envelope sensible load is above 50% of the total and about 20% of it is across the ceiling. Ceiling boards are generally lightweight and made from a wide variety of natural and synthetic materials (Suman and Srivastava, 2009; George *et al.*, 2010). Nowadays, common ceiling materials are made of plastic, fiberglass, mineral fiber, wood-fiber, vinyl-coated gypsum, plaster, mineral fiber, and synthetic plastic polymer such as polyvinyl chloride (PVC). Ceiling constructions are often classified as galvanized ceiling, stretched ceiling, corrugated ceiling, cathedral ceiling and fall (dropped) ceiling.

Over the years, to improve thermal comfort within building envelope without the use of mechanical means, research efforts have concentrated on technologically improving the thermal properties of building insulation materials especially those used for the ceiling. In 2011, Yahay and Ahmad (2011) integrated PCM into gypsum board ceiling panels to effectively reduce energy consumption through active cooling systems. In an attempt to establish the suitability of PVC ceiling sheets for building construction in tropical environment, Onyeaju *et al.*, (2012) studied its thermal properties in comparison with those of asbestos. The properties were found to be within the same range. Li *et al.* (2015) investigated the thermal performance of different kinds of ceiling with and without phase change material (PCM). The PCM was applied to enhance the thermal energy storage capacity of the building envelope thereby decreasing the building energy consumption and improve thermal comfort within the building. Berardi and Naldi (2017) examined the effect of varying the thermal conductivity of inorganic fiber board, petrochemical-foamed board and a hybrid of the two on the thermal performance of a building envelope. Eric and Hensley (2018) compared the thermal insulation properties of conventional POP, plywood, Masonite ceiling boards and those embedded with rice husk. They found the performance decreasing in order of POP, rice husk, plywood and the Masonite. Dirisu *et al.*, (2018) carried out a review of the techniques employed to improve the properties of building ceiling products.

As a result of the importance of ceiling in building design, a number of authors carried out experimental investigations of the heat transfer characteristics of common ceiling materials in different parts of Nigeria (Alausa *et al*., (2011); Gesa *et al*., (2014); Ettah *et al*., (2016); Oyekunle *et al*., (2018) and Adepitan *et al*., (2019). Sinacka and Szczechowiak (2021) experimentally determined the convective and radiant heat flux density, convective and radiant heat transfer coefficient at the surface of suspended ceiling panels embedded with PCM. Balogun *et al*., (2022) used digital logic method to estimate the thermal insulation value of ceiling tiles with polymeric materials reinforced with natural fibers. They found that polypropylene mixed with bargasse fiber performed best. Hamid *et al*., (2022) produced a ceiling board made from waste paper mixed with urea formaldehyde glue and compared its density, moisture content and water absorption properties with those of asbestos and gypsum boards. The new ceiling board was found lighter but the moisture content was about the same as others. Mechanical and thermal properties of eco-friendly ceiling board produced with sugarcane leaves were investigated by Etuk *et al*., (2022). Values obtained for these properties were found to compare favourably with extant ceiling panels.

It is worthy of note that these research efforts have focused on estimating the effectiveness or thermal performance of the ceiling materials. But beyond insulation, it is necessary to know the implication of the use of these materials on the air flow and heat distribution within the attic. This study attempts to fill this gap. The findings of such study will guide in rooftop storage of sensitive materials and drying of agricultural produce (still common in the villages of developing countries in the tropics). Four different common ceiling materials, viz, asbestos, particle board, polyvinyl chloride (PVC) and plywood with their unique thermal properties and same roof boundary conditions are used in the simulation.

METHOD OF SOLUTION

Two-dimensional, finite-volume numerical simulation of natural convective heat transfer through the ceiling into the attic was performed using computational fluid dynamics approach. In Fig. 1, the 2-D physical model of the roof, which coincides with the computational domain, is shown. Depending on the roof architecture, the ceiling of the roof is subtended at about one-third of its length to one-third of the height which implies angle α is two-third of the pitch angle β (18° for this study).

For this complex geometry, unstructured tetrahedral mesh was used; with special attention paid to the skewed bottom corners to properly resolve the flow and thermal fields there. For proper discretization, the mesh was well refined (Fig. 2).

Using the following dimensionless variables,

$$X = \frac{x}{H};\ Y = \frac{y}{H};\ \ U = \frac{uH}{\alpha'};\ V = \frac{vH}{\alpha'};\ \theta = \frac{T - T_c}{T_H - T_C};\ P = \frac{pH^2}{\rho\alpha'^2};\ Ra = \frac{g\beta'\Delta T H^3}{\nu\alpha'};\ Pr = \frac{\nu}{\alpha'}$$

and, applying Boussinesq approximation, the dimensionless forms of the governing equations for steady natural convective heat transfer are expressed as:

Conservation of mass:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

Conservation of momentum:

U-momemtum:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

V-momemtum:

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + RaPr\theta \tag{3}$$

Conservation of energy:

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{4}$$

The boundary conditions are:

Velocity:

$U = V = 0$ (no slip condition along the walls).

Temperature (winter season):

$\theta = 1$ (isothermal hot ceiling)
$\theta = 0$ (isothermal cold inclined walls)

Air within the roof enclosure was assumed to be dry (Pr=0.71), incompressible, viscous and Newtonian. No heat is generated within the enclosure. Hot air within the space below heats up the ceiling to a temperature that is slightly above that of the room and snow covers the upper walls. For the geometry and boundary conditions considered, the Rayleigh number results in 7.88×10^7.

The governing equations, equation (1) to (4), were iteratively solved using the ANSYS FLUENT (Version 18) package. The pressure-velocity coupling in the governing equations was resolved using the SIMPLE algorithm. The pressure interpolation was performed with the PRESTO scheme. The equations were spatially discretized with the third-order Quadratic Upstream Interpolation for Convective Kinematics (QUICK) finite-volume scheme. The target convergence for the continuity equation was 10^{-5} and that for the U-momentum, V-momentum and energy equations was 10^{-7}. With very fine mesh, these combined to sufficiently minimize the discretization and linearization errors to acceptable level for reliable results.

To ensure the results obtained were not sensitive to grid, the elemental size of the mesh was varied. The results for the maximum velocity relative to the number of elements are presented in Table 1. Since the value of U_{max} change insignificantly (1.3%) as the number of elements increased from 57,394 to 70,813 (23%), it is concluded that 57,394 elemental grid will produce grid independent results for the problem.

Using ANSYS FLUENT for a similar problem, Yesiloz and Aydin (2013) analyzed numerically the natural convection in a right-angled triangular enclosure heated from below for the laminar Rayleigh number range of 10^3 to 10^7. They compared the results obtained with that of an experiment performed for the same configuration and found good agreement. The present study therefore relied on this for validation of the methodology.

RESULTS AND DISCUSSION

The numerical results obtained for the simulation are presented in form of airflow structure in Figs. 3-7, temperature distribution in Fig. 8 and heat transfer rate across the ceiling materials in Figs. 9-11. The results enable technical analysis of the effect of each ceiling material on the thermal and flow fields within the attic. The velocity, pressure and temperature contours are shown dimensionless for generalization of application to varying roof pitch and winter boundary condition configuration.

Streamlines

Typical of the flow structure within enclosure heated from below, almost similar multicellular flow pattern was observed for all the ceiling materials. The streamlines for the asbestos ceiling (Fig 3a) and plywood ceiling (Fig 3b) are as shown. The figures appear very similar but a closer look shows some differences in pattern especially towards the bottom corners. In each half, there are about nine counter-rotating cells with two large cells at the midsection where there is enough space for the cells to grow and manoeuvre. The size of a cell reduces from the midsection to the bottom corners as the distance between the upper walls and the base wall diminishes. The closeness of the hot and cold walls leads to increased heat exchange that results in further breakdown of the cells. Air is quiescent within about one-fifth of each half from the bottom corners; conductive heat transfer prevails within these areas. This conduction area coverage varies slightly as the ceiling material changes.

Velocity Distribution

In Fig. 4, the variation of air velocity within the attic with asbestos ceiling (Fig. 4a) and plywood ceiling (Fig. 4b) are presented in contour form. The pattern in the roof with other materials are not too different. Similar to a forced vortex velocity profile, the rotational speed of air particles within a cell reduces inwardly towards its centre. The velocity is highest around the outer edges of the two largest cells at the middle; indicating high fluid motion within the area. Depending on the size of the roof, this may become turbulent.

The maximum value of air velocity, U_{max}, within the roofs is found to depend on the buoyant force propelling the air particles which correlates with the heat flux from the ceiling. As shown in Fig. 5, the values of U_{max} within the attic was plotted. The results show that asbestos with the highest thermal mass and low heat capacity would lose less heat into the space to drive the fluid movement. On the other hand, plywood with the highest heat capacity and low thermal mass would release more heat into the attic. In Fig. 5, the U_{max} for asbestos ceiling is 1.2% lower than that for plywood ceiling. The implication of these results is that, for a vented roof in a highly humid environment, using plywood for the ceiling will require high quality coating in order to prevent early degradation. Asbestos, despite being the material with the lowest air circulation speed, is also not advisable because of its health risk. Therefore, for air circulation consideration, PVC, which causes less air circulation than particle board, is recommended. On the other hand, because of the relatively high circulation speed of high volume of air at the roof midsection, high pitch roofs should be avoided when using some of these materials.

Pressure Distribution

Air pressure distribution in the roof is presented in Fig. 6 for asbestos and PVC ceilings. In line with Bernoulli's principle, pressure is low at the upper vertex area where velocity is relatively high and high near the bottom corners where heat exchange is high and movement of air is limited. As the heat from the basewall increases, the air pressure becomes higher. This knowledge is useful in the design of ceiling insulation. Also, to prevent pressurizing the attic, it is advisable to place a vent or an exhaust fan near the bottom corners.

The plot of the maximum value of the air pressure within the attic is shown in Fig. 7 for all the ceiling materials. Pressure is high at the bottom corners of the roof. Asbestos ceiling has the highest value and the lowest when particle board ceiling is used.

Temperature Field

The isotherms within the attic for the roof with the plywood ceiling and the particle board ceiling are shown in Fig. 8; representing the temperature field for other materials. The values of temperature are high along the plumes arising from the basewall and low along the jets descending from the upper walls; both acting as the driving tangential forces that rotate the cells. As a result, the cells have relatively isothermal core. This is more pronounced within the large cells at the midsection. Due to the shape of the roof, the heat flow between the ceiling and the roof is high near the bottom corners. The pattern of temperature variation is symmetrical about the midsection for all the ceiling materials.

Heat Transfer

The heat transfer characteristics of the ceiling have been of immense importance in order to accurately estimate the quantity of heat flow across it. These characteristics are found to depend largely on the thermal properties of the ceiling material (Adepitan et al., 2019). In Table 2, the thermophysical properties of the selected ceiling materials considered in this study are presented. The thermal conductivity value shows the rate at which the material would permit heat to flow across it while the specific heat indicates the extent of its heat storage. The combination of these determines how quickly and how long the air within the attic is heated.

The heat transfer rate from the ceiling into the attic is presented in the form of the variation of local Nusselt number and mean Nusselt number along the hot ceiling. The local Nusselt number is defined using the local surface heat flux from the hot ceiling as (Bejan, 2013):

$$Nu_x = \frac{q_x H}{k_f \Delta T} \qquad (5)$$

where k_f is the thermal conductivity of air, q_x is the local surface heat flux and height H as the characteristic length. Taking after Cui *et al.* (2019), about 0.04L part of the base wall is cut off at the bottom corners to exclude the point of singularity there. It has been observed that such adjustment has no significant effect on the convection within the enclosures (Saha, 2011).

Fig. 9 shows the Nusselt number variation along the hot ceiling when asbestos is used. The pattern of the Nusselt number variation for other ceiling materials are not too different from this. The multicellular flow structure within the attic encouraged the sinusoidal variation of the Nu_x along the hot horizontal ceiling and the cold upper inclined walls. Near-zero heat transfer was experienced at the points where hot air rises from the hot ceiling and cold jet detached from the upper cold walls as a result of almost zero thermal gradient at the points. Heat transfer rate was high along the ceiling at the points where cold jets from the upper inclined walls impinged on the hot basewall and at the points where the rising hot plumes from the ceiling impacted on the upper inclined walls. This high heat exchange between the ceiling and the upper inclined walls was more noticeable within the bottom corner regions.

Fig. 10 shows the average Nusselt Numbers which defines the overall heat transfer across the ceiling. The average Nusselt number is defined as (Bejan, 2013):

$$\overline{Nu} = \frac{\bar{q}\, W}{k_f\, \Delta T} \qquad (6)$$

where $\overline{q}$ is the mean surface heat flux and W is the characteristic length which, in this case, is the width of the ceiling.

The average Nusselt number varies directly with the convective heat transfer rate from the ceiling surface. For the materials considered, the heat transfer rate from the ceiling is generally low; indicating their insulating quality. In Fig. 10, the highest average Nusselt number is obtained when the plywood material is used. Having the highest specific heat and lowest thermal conductivity among the selected materials, plywood retains much of the heat that comes to it and releases the heat at a slower rate thereby heating the attic longer than other materials.

Heat Load

The mean Nusselt number plot shown in Fig. 10 for the ceiling materials is better appreciated when the heat intensity per unit time, Q, is estimated for a cathedral ceiling of size 10m width and 30m long is assumed installed with the same roof pitch and each of the selected materials. The plot of the average Q for each of the ceiling material is as presented in Fig. 11. The rate of heat loss from the cathedral into the attic through the ceiling when plywood was used was found to be about 7% higher than when particle board was used. Besides other environmental consequences, the energy implications of this over the annual operational period of the heating systems is definitely huge.

CONCLUSIONS

Impact of thermal properties of four ceiling materials on the flowfield and heat transfer within a complex-shaped attic has been considered using finite volume based ANSYS FLUENT. Results showed multicellular flow patterns for all the materials. The air velocity profile across adjacent cells depict those of forced vortices spinning in opposite directions. Air speed within the attic increases with the use of asbestos, PVC, particle board and plywood. Generally, in line with Bernoulli's principle, pressure is lowest at the upper vertex area where velocity is relatively high while pressure is highest near the bottom corners that air movement is limited. The pressure maximum value is lowest in the particle board ceiling and highest in the asbestos ceiling. Temperature is uniformly distributed within the attic for all the materials. Heat convection rate from the ceiling is generally low. In terms of thermal performance, particle board ceiling is best recommended, then the PVC, the asbestos and plywood as the least. Asbestos ceiling makes the attic calm while plywood produce vortices with the highest speed, thereby making it the least recommended.

FIGURES AND TABLES

Figures

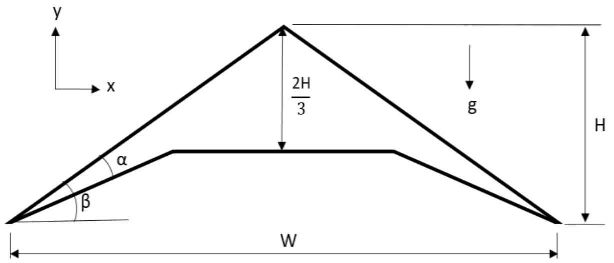
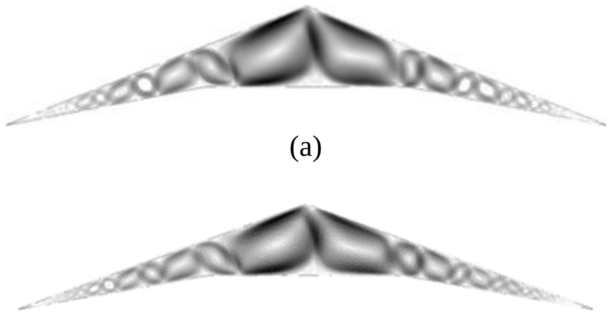


Fig.1. Physical model

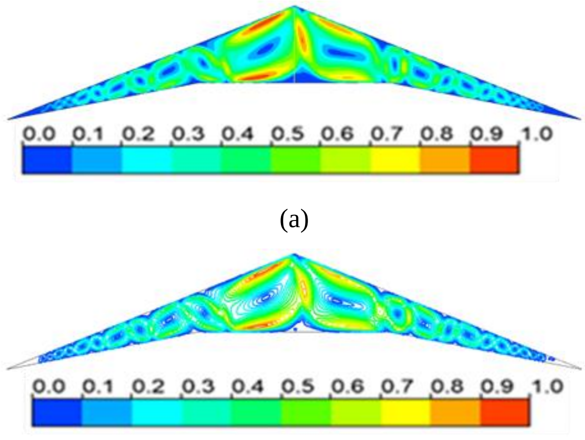
Fig.2. Computational mesh



(a)

(b)

Fig.1. Streamlines for roof with (a) asbestos ceiling; (b) plywood ceiling



(a)

(b)

Fig.4. Air velocity contour plots for (a) asbestos; (b) plywood ceilings

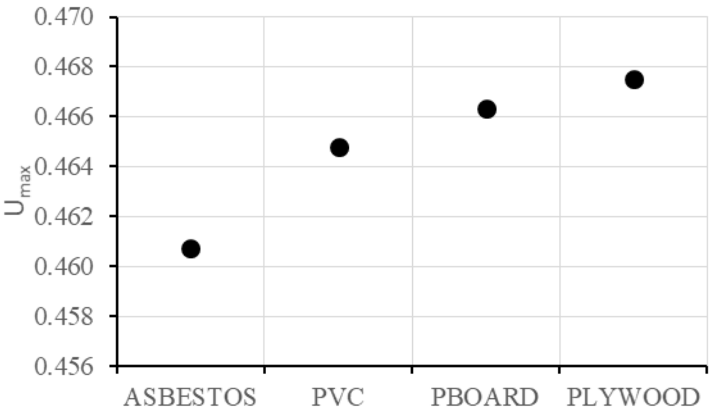
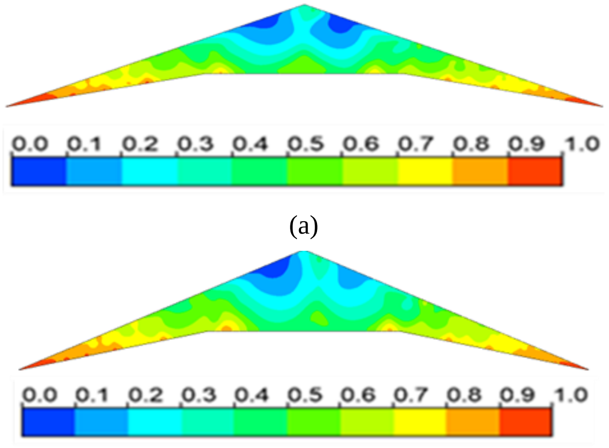


Fig.5. Plot of maximum dimensionless velocity for different ceiling materials



(a)

(b)

Fig.6. Air pressure contour plots for (a) asbestos; (b) PVC ceilings

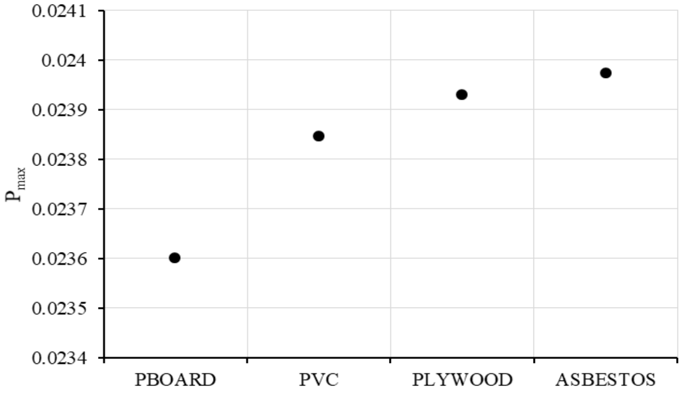
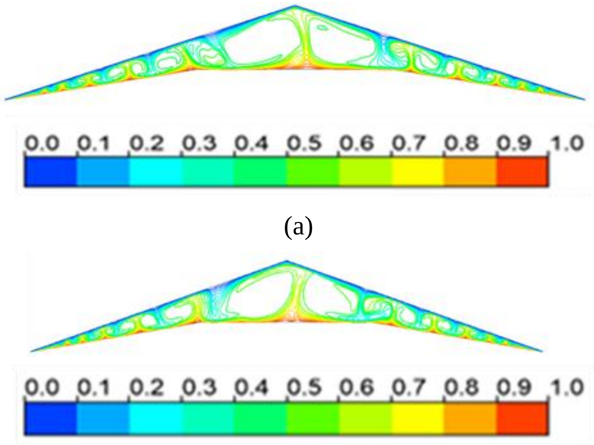


Fig.7. Plot of maximum dimensionless pressure for different ceiling materials



(a)

(b)

Fig.8. Isotherms within the roof with (a) plywood; (b) particle board ceilings

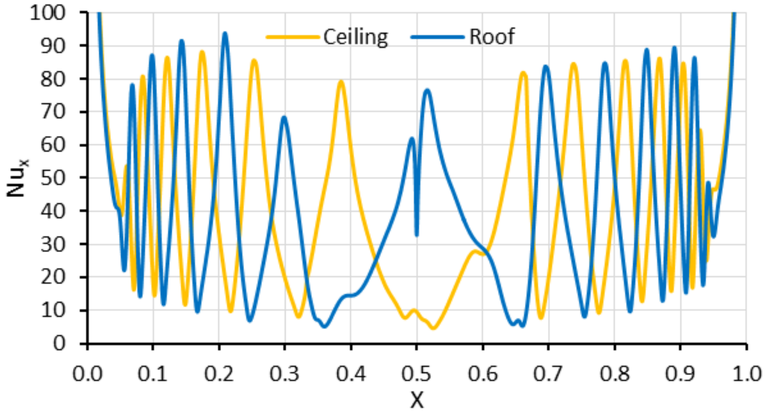


Fig.9. Local Nusselt number plot for asbestos ceiling

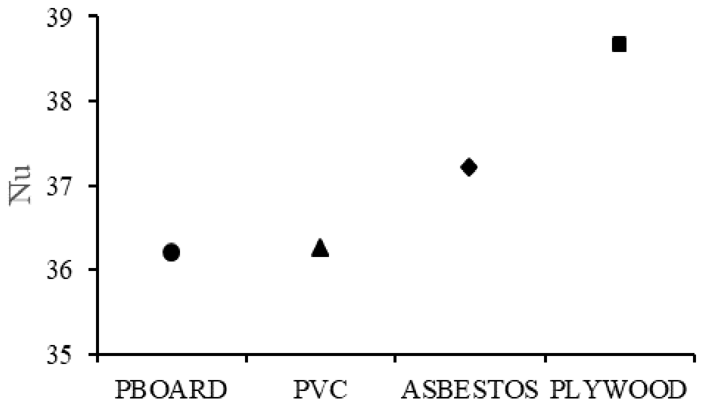


Fig.10. Average Nusselt number for different ceiling materials

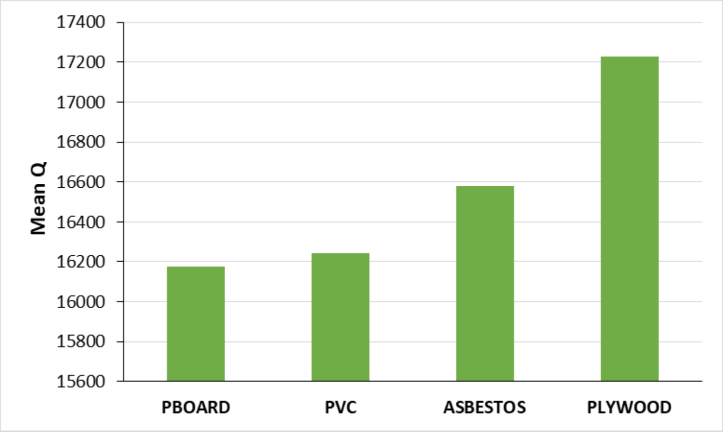


Fig.11. Average heat flow intensity across different ceiling materials

Tables

Table 1. Grid independence test results

Number of elements	47,400	57,394	70,813
U_{max}	0.1445	0.1558	0.1579

Table 2. Thermophysical properties of the selected ceiling materials

Materials	**Density** (kg/m^3)	**Specific Heat** $(kJ/kg\ K)$	**Thermal Conductivity**

			$(W/m\ K)$
Asbestos	1600	840	0.140
Particle Board	650	1450	0.164
PVC	1330	880	0.200
Plywood	570	2500	0.134

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