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Thermal Emission and heat transfer characteristics of ceiling materials: a necessity

J.O. Dirisu[a]*, O.S.I. Fayomi[a,b], S.O. Oyedepo[a]

[a]*Department of Mechanical Engineering, Covenant University. P.M.B 1023, Ota, Ogun State, Nigeria*
[b]*Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, P.M.B. X680, Pretoria, South Africa*

Abstract

The investigation of the thermal insulation properties of ceiling materials in comparison to the heat transfer constituent is a necessity because materials recommended as building ceiling due to their excellent thermal insulation nature may not necessarily reflect their heat transfer nature. This will eventually give insight to all building stakeholders on factors to consider in ceiling design from initiation to final stage thereby yielding excellent and enviable building ceiling products.

Keywords: thermal insulation; ceiling; heat transfer; design; products.

1. Introduction

Ceiling is the structure located at the base of a roof. It is the surface that is directly opposite the floor and the covering for roof which prevent thermal influx to the room thereby preventing discomfort. The materials for ceiling are either natural or synthetic. The natural ones are originated from plant such as thatches, plywood, cardboard, and particleboard. Nature will realize that the solution to human comfort is in understudying the origin such as the cooling system of clay pot which gives comfort to users without the use of a refrigerator. Clay building gives

* Corresponding author. Tel.: +2348036886783; fax: +27835828119.
E-mail address: ojo.fayomi@covenantuniversity.edu.ng

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thermal comfort to dwellers unlike other building materials. This natural approach is awesome because the synthetic may come with its associated disadvantages such as health threat. The synthetic types are asbestos, plaster of Paris (POP), polyvinylchloride (PVC) and hybrid types. PVC is the most recent type and now widely used due to probable aesthetics and flexibility of application to buildings [1].It shields the occupant from the direct heat absorbed by the roof from the external environment and usually designed for the purpose of comfort, aesthetic and protection from probable leaking roof [2]

1.2 History of Ceiling

Clay tile is one of the oldest form of roofing[3][4]. It was used as roof in the 17th century. It was used to inhibit fire such as the London fire in 1666 and scorched Boston in 1679. Pan tile or curved type clay tile was said to be used at Virginia. The plain or flat rectangular tiles most commonly used from the 17th through the beginning of the 19th century measured about 10" by 6" by 1/2," and had two holes at one end for a nail or peg fastener. Sometimes mortar was applied between the courses to secure the tiles in a heavy wind. It was used between 17 and 19th century. It was replaced in the mid 19th century by sheet metal roof type due to its lighter weight, ease of maintenance and easy to install [2]. Slate was spotted in the ruin of mid-17th century Jamestown. This roofing type is the innovation of settlers. It was popular for its durability, fireproof qualities, and aesthetic potential. Slate continued to be used till date [2]. Shingles has been throughout history. The list of shingles include carriage house, slateline, royal sovereign, standard 3 tab, Truslate[5] and asphalt shingle[6]. The first asphalt shingle was introduced in 1893[7]. "The size and shape of the shingles as well as the detailing of the shingle roof differed according to regional craft practices. People within particular regions developed preferences for the local species of wood that most suited their purposes. In New England and the Delaware Valley, white pine was frequently used: in the South, cypress and oak; in the far west, red cedar or redwood. Sometimes a protective coating was applied to increase the durability of the shingle such as a mixture of brick dust and fish oil, or a paint made of red iron oxide and linseed oil" [2]. Wood shingles survived the technological advancement of metal in the nineteenth century. Metal roofing came up in the 19th century such as the use of lead and copper as seen in Christ Church in 1727-1744. Sheet metal was developed by Robert Morris in 1794. Corrugated iron came up in 1834 by William Strickland. Galvanization with zinc to serve as protection against corrosion was developed in France in 1837. Tin plate iron was improvised in the 18th century while zinc came up in 1820. "Asphalt shingles and roll roofing were used in the 1890s. Many roofs of asbestos, aluminium, stainless steel, galvanized steel, and lead-coated copper may soon have historic values as well"[2].

1.3 Classes of Ceiling

The classification of ceiling is due to artwork done on it and its aesthetics[8]. Technological renaissance gives insight to ceiling materials selection, however, there is the observed failure to inspect the combustion and emission characteristics of these ceilings at the instance of fire[9].

1.3.1 Dropped Ceiling: refer to suspended ceiling, grid ceiling, T bar ceiling or ceiling tile that is hung below the main structural ceiling. They were being used in Japan (1337-1573). Donald Brown September 8, 1958 is credited to be the inventor of dropped ceiling for providing access to any desired location unlike uninstalling the ceiling for repair work and inspection.[8]. The figure 1 below displays dropped ceiling type.

Figure 1: Dropped ceiling, Source: [10]

1.3.2 Acoustic Ceiling tile is seen as a noise inhibitor and increases the intensity of light in the environment.[11]. This will to a large extent reduce external noise effect from the roof and environment. Its effective design will optimize energy usage of the building interior. Figures 2, 3 below show acoustic ceiling type.

Figure 2: Corrugated acoustic ceiling, Source:[12]

Figure 3: Acoustic ceiling, Source: [13]

1.3.3 Stretch Ceiling: used to cover pipe work, wire or existing ceiling. They are usually made of aluminium or plastic PVC. The figures 4 and 5 below are a design of stretch ceiling.

Figure 4: Project of stretched ceiling in Maiduguri, Nigeria, Source:[14]

Figure 5: PVC stretched ceiling ideas, Source: [15]

1.4 Fire Propagation

Fire is an exothermic chemical reaction that emits light and heat in varied intensity which require fuel, an oxidising agent, heat and chemical reaction to ignite [16]. Table 1 reveal responses of matter to temperature increase.

Table 1: Responses of matter to Temperature rise, Source: Ref. [16].

º C	º F	Response
37	98.6	Normal human oral/body temperature
44	111	Human skin begins to feel pain
48	118	Human skin receives a first degree burn injury
55	131	Human skin receives a second degree burn injury
62	140	A phase where burned human tissue becomes numb
72	162	Human skin is instantly destroyed
100	212	Water boils and produces steam
140	284	Glass transition temperature of polycarbonate
230	446	Melting temperature of polycarbonate
250	482	Charring of natural cotton begins

>300	>572	Charring of modern protective clothing fabrics begins
>600	>112	Temperatures inside a post-flashover room fire

The phenomenon of the rate of fire spread per unit area called the heat flux is presented in table 2 below

Table 2: Heat flux Phenomenon, Source: Ref. [16].

Heat Flux (kW/m^2)	Example
1	Sunny day
2.5	Typical firefighter exposure
3-5	Pain to skin within seconds
20	Threshold flux to floor at flashover
84	Thermal Protective Performance Test (NFPA 1971)
60 - 200	Flames over surface

Fire has its advantage of cooking our food but if unchecked according to [17] will cause an unforgettable damage. Fire behaviour of some selected samples of building materials including wood and plastic materials such as PVC and polymethylmethacrylate (PMMA) were assessed. Study was carried on both the thermal aspects and smoke toxicity by testing the sample of wood, PVC and PMMA in a cone calorimeter. It was observed that the PVC material is of low fire risk under 20 kW^{-2} inferring that the material is quite safe under small accidental fire and becomes unsafe when exposed to higher heat fluxes [18]. Cone calorimeter and Thermal Gravimetric Analysis (TGA) are spotted as effective equipment for evaluating fire risk of materials. Their work [19] showed that there is intermediate risk level in the total heat released. The work addressed the issue of heat release reduction for safety in construction engineering. Xu *et al* [18] established that cone calorimeter can be used to acquire useful information on fire behaviour of polymers. Their work considered different model of fire materials. They studied pyrolysis dynamics to understand the thermal behaviour of materials that result in macroscopic fire behaviour. Three different kind of flooring materials which are rubber floor, wool carpet and blended carpet were studied by[20]. Their result showed those fire hazards were in the order of materials presented from high to low. Two kinds of hazards were spotted which are heat hazard and smoke hazard. Associated with heat hazard are heat caused by the three modes of heat transfer; conduction, convection and radiation. Fire growth and heat released hazard are the further division. Smoke hazard on the other hand is subdivided into smoke emission hazard and toxicity hazard. Ignition time is the time between thermal radiation and luminous flame. The shorter the ignition time, the easier will be the ignition, and the greater will be the fire hazard. Yang [20]studied different PVC sheets in Chinese markets using cone calorimeter at different heat fluxes of (25, 35 and 50) kWm^{-2}. The study revealed that the thickness of specimen had effect on their fire behaviour. The work of [21] analyzed the performance in passenger train car materials using cone calorimeter. They maintained that overall safety is assured when fire safety is taken care of. Heat release rate (HRR) is a focal indicator when analyzing fire performance and it is the amount of energy that a material gives during combustion. The relation of HRR given as $\dot{Z}$, to mass burning rate $\underset{\cdot}{m}$ is given as

$$\dot{Z} = \underset{\cdot}{m}\, \Delta H \quad (1)$$

where ΔH is the heat of combustion provided there is complete combustion. Hongqiang et al [22] used cone calorimeter to study thermal degradation of flexible PVC filled with zinc ferrite and $Mg(OH)_2$. PVC was blended with zinc ferrite and $Mg(OH)_2$ which improved flame retardancy and smoke suppressant. Organic polymers decompose by combustion, they are combustible[23]. Model that predict the behaviour of PVC under the influence of sunlight in a photo bioreactor was developed which is a useful tool for simulation, design and optimization[24]. Another model that predict the behaviour of fibre reinforced polymer composite which will investigate the temperature history of structure. Finite element method was employed and the result was compared with experimented heating test on fibre reinforced polymer laminate strips and sandwich panels[25]. The thermophysical and thermomechanical properties of fire reinforced polymer at different heating rates were experimented using thermal gravimetric analysis, differential scanning calorimetry and dynamic mechanical analysis. The authors proposed that they should be experimented at elevated temperatures[26].

1.5 Report of Fire Outbreak of Buildings

Plant based ceiling materials such as plywood, cardboard, thatches; particleboard and seldom wood polymer composites increase the risk of fire and serve as fuel for wildfire in areas close to flammable vegetation and neighbouring buildings. To reduce roof vulnerability to wildfire, it is recommended to fit it with fire resistant materials, apply fire retardant chemicals and install roof watering systems. Consequently, the application of these preventive steps will be short lived due to exposure to heat from the sun and due to leaching [27]. The solution will remain to develop a long-lasting fire-retardant ceiling material. The figure 6 below show the percentages of roof destroyed by wildfire and it revealed that fire resistant roof is less affected than wood originated roofs.

Fire outbreak has been spotted as a man-made kind of disaster which is preventable or at best minimized[28]. The roof is usually the starting point of fire outbreak as shown in figure 7-9. The fire outbreak at Kano market erased properties worth ₦2 trillion. The report showed that there were no preventive measure against the fire and people were hospitalized for inhaling smoke which were noxious[29]. The figure below shows the entrance to Sabo gari market in Kano. Combustible materials from roof, hydrocarbon [30] and ceiling, incomplete combustion leading to inhaling carbon monoxides and exhaling the gas itself [31], poor electrical wiring[32],elemental makeup of the materials and poor electrification are contributory factors to this fire outbreak. The fire outbreak at Lagos airport affected some offices, though the cause of the incidence was not ascertained, [33] however the materials that make the internal finishing contribute to the fire spread.

The failure to adhere to building codes in Nigeria contributes to fire outbreak as spotted by erstwhile Governor of Bayelsa State Mr Timipre Sylva[34].

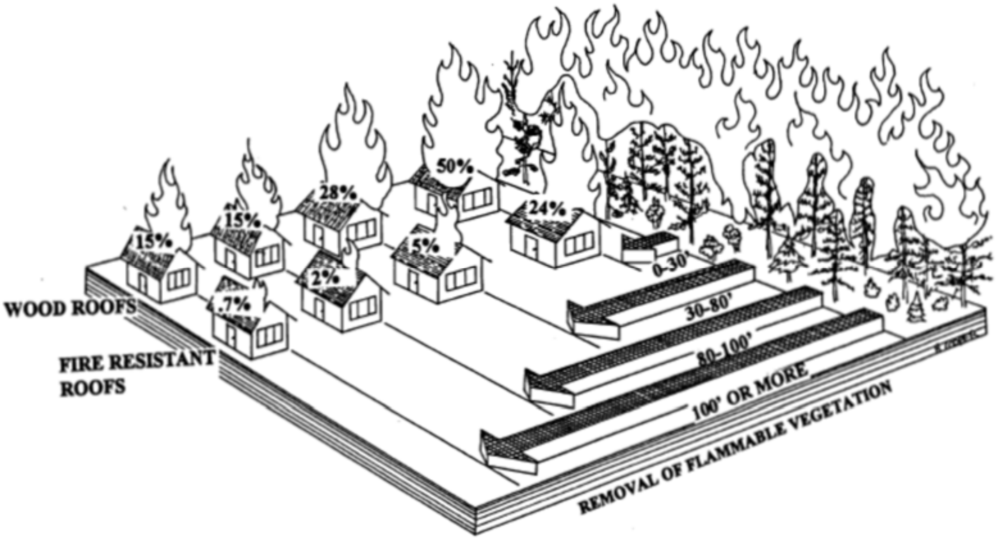

Figure 6: Percentage of homes destroyed by wildfire
Source:[27]

Figure 7: Federal Airports Authority of Nigeria Headquarters gutted by fire in Lagos
Source: [35]

Figure 8: One of the entrances into the Sabon Garri market Kano
Source: [29]

Figure 9: Early morning fire in the University of Lagos Hall of Residence
Source:[36]

Fire was reported to kill entire family in Lagos due to candle light thereby igniting the whole confined apartment [37]. Another news daily reported that about ₦6 trillion were lost due to fire outbreak in the last five years affecting states like Lagos, Kano, Port Harcourt and Abuja[38]. Harmattan was claimed to herald the spread of fire in 40 incidences spotted in Lagos. Poor data on fire incidence makes it difficult to forecast and forestall this fire monster as its economic effect had rendered breadwinners penniless, homeless and psychologically derailed [39]. In a converging report, fire incidence was alleged to be caused by human likely due to corruption and bush burning to a college hostel [40]. Another reason for fire start up is carelessness as triplet were reported dead due to electric spark from water heater[41]. There is complaint of delay in response by fire fighters as experienced in extinguishing fire inferno of Edo shopping mall[42].

2. Heat Transfer and Thermal Analysis

Heat flux is established as a function of the thermal conductivity, area of material, temperature difference and thickness of material. Temperature is the focal factor that dictates heat signatory in the material[43][44]. Its variation in a material predicts its heat conduction ability called thermal conductivity. This is clearly represented in Fourier's law of heat conduction[45].

$$w'' = -X\, dt/dx \qquad (2)$$

$$w'' = W/A_a \qquad (3)$$

where w" is the heat flux (W/m^2), X is the thermal conductivity (W/mK), W is the heat rate (W or in J/s), A_a is the cross-sectional area, dt is the temperature difference (°C or K) and dx is the thickness (m). Related to thermal conductivity is the thermal diffusivity that defines how fast heat accelerates through the interstices of the material. It is a function of both thermal conductivity and heat capacity[46]. The resistance to heat transport of a material is its thermal resistivity or thermal insulation[46]. The work of [44] determined the thermal conductivity of some selected materials among which is PVC varied at 0.04-0.350 $Wm^{-1}K^{-1}$. Polymer combust to emit gaseous products that generate flame.

$$\text{Polymer + Heat} \longrightarrow \text{Thermal Decomposition Products} \qquad (4)$$

$$\text{Decomposition Products + Oxygenated Radicals} \longrightarrow \text{Combustion Products + Heat[47].} \qquad (5)$$

These thermal properties are either desirable or not depending on their area of application. Some materials where recommended as building materials due to their appreciated thermal insulation properties such as Polyvinylchloride[9][48], termite wing[49], plaster of Paris[50], pleko ceiling boards[51],waste paper materials[52][53], saw dust[54], asbestos[55], concrete tiles[56]. The thermal properties of some wood type heat insulating materials were investigated by [57] and were discovered to have higher thermal resistivity which is a desirable property, however the emission characteristics have to be investigated. Wall thermal response at different weather condition is sinusoidal in behaviour. The work of [58]is useful in considering thermal design criteria of wall. El-Agouz [59] worked on the effect of internal heat source and opening locations on environmental natural ventilation. The work sought to optimize indoor air quality by simulating the best position to convect off heat generated by the heat source. Nusselt and Rayleigh numbers were employed to explore the highest heat transferred. The work of [60] on properties of composite materials for thermal analysis involving fires determined the thermal properties for an E-glass, Derakane 510A vinyl ester composite under fire. The apparent specific heat capacity and thermal conductivity were determined and the result imported to a transient heat conduction model which help in predicting temperature profile. Kontoleon [61] presented work on the effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations which will be useful in designing passive buildings in minimizing consumption of conventional energies for cooling and reducing the peak demands of electrical energy. Michels [62]revealed that many manufacturers don't give detailed information on inhibiting radiated heat from the materials but dwell on their thermal conductivity. Sound reflective materials in church auditorium were retrofitted to ceiling in modern church auditorium[63].

3. Emission Characteristics

There are limited articles on emission characterization of building ceilings. However, extract articles were gotten from level of noxious gasses and their effects in the atmosphere. It is reported that several air pollutants contribute to global warming while some inhibit it by impeding solar radiation. There is a national reduction objective for six air pollutants (SO_2, NOx, NMVOCs, NH_3, $PM_{2.5}$ and CH_4) to be met by 2020 and 2030[64]. High exposure to CO at above 7000ppm which may lead to unconsciousness within 4 minutes. Fatality due to fire are usually poison from CO and suffocation from volatile organic compounds[65]. Ceiling emit noxious pollutants such as VOCs, COs, and NO_x [66]; while IC engines emit similar pollutants and unburnt hydrocarbon[67]. These could affect the ozone layer, health of the earth and increase global warming[67]. European Commission National Ceilings Directives aimed at controlling and reducing ammonia emissions so as to protect the environment and human health against pollutants responsible for acidification, eutrophication and ground-level ozone pollution (sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia)[68]. The discontinuity of asbestos induced materials have been widely advised due to the presence of the mineral called asbestos as it is evidenced to propagate health risk to anyone continuously exposed to it[69],[70][71].

4. Conclusion

Ceiling with high thermal insulation properties with negligible noxious gasses is highly desirable as it will inhibit fire spread, aid smoke detection and provide ample decision time to evacuate lives and properties. It is necessary to consider that gasses emitted are environmentally friendly, flame retardants and not hazardous when inhaled. This will be possible if individual material is characterized and investigated on these attributes. These tests have to be prioritized before rolling out mass ceiling production for the public. If these are put in place by manufacturers, assurance is given that an aspect of the entire building structure is reliable in terms of safety.

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