Energy and Buildings 116 (2016) 122–132

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A model for analyzing the thermal performance of roof configurations with flat inclined surfaces

M.P.G. Sirimanna*, R.A. Attalage

Department of Mechanical Engineering, University of Moratuwa, Katubedda, Moratuwa 10400, Sri Lanka

ARTICLE INFO

Article history:
Received 2 January 2015
Received in revised form
27 December 2015
Accepted 28 December 2015
Available online 2 January 2016

Keywords:
Thermal performance
View factor
Inclined surfaces
Roof surface
Ceiling temperature
Finite-volume method
Thermal model
Radiant heat exchange

ABSTRACT

The development of a thermal model, followed by a generalized computational tool that analyses thermal performance of roofs with four inclined surfaces and a ceiling by considering dynamic environmental and operating conditions, changes of roof geometry and materials is presented here. Roof elements are analyzed based on finite-volume method with implicit formulation. View factors of roof enclosures are calculated numerically. Experimental results, obtained for six actual building roofs under tropical climatic conditions of Sri Lanka, indicated that the thermal model is capable of replicating the actual temperature profiles with an average accuracy of 1.1 °C. Ceiling temperature of common roofs were found to be 10 °C above the ambient temperature, which could even rise up to15 °C in hot days. The model was successfully used to compare roofs and quantify the thermal effects of different parameters. For instance, changes in geometrical parameters led ceiling temperature to change by 5 °C, highlighting the importance of roof geometry. Out of the widely used three roofing materials in Sri Lanka, clay tile roofing has showed the best thermal performance. Compared to clay tiles, asbestos and steel roofing can have a maximum ceiling temperature rise of 4 °C and 6 °C, respectively.

1. Introduction

Roof of a building plays a crucial role in the context of building heat gain and thermal comfort. Normally the roof is exposed to a considerable amount of insolation. During clear day conditions this value could be as high as 1 kW/m^2, out of which about 20% to 95% is typically absorbed [1]. This imposes a considerable heat gain to the building and it becomes significant when the roof represents a large portion of outside surface area of the entire building envelope such as in single story and two story buildings. In circumstances where solar irradiance is trivial, radiation heat exchange of the roof with the sky might become dominant making the indoor environment cooler. This becomes an undesirable effect in a cold climate. Studies have indicated that roofs contribute to 12% heat loss out of total heat loss and 14% out of total heat gains for residential buildings in U.S. [2]. The study was based on both single and two story residential buildings and in the case of single story buildings these figures gets even higher. Therefore, although people tend to select a roof type for a building only based upon its cost and esthetic aspects and without paying enough attention to its thermal performance, it is observed that disregarding the thermal performance of a roof finally ends up with causing thermal discomfort or using active techniques such as fans and air conditioning to achieve thermal comfort.

There are various parameters which affect the thermal performance of a roof such as covering material, orientation, slope, ceiling type and surface properties of the roof. It is necessary to assess these parameters and perform accurate thermal analysis of the building roof. However, this task has become extremely complex due to facts such as dynamic nature, non-linearity and complex interplay of the parameters. Several researches have been performed regarding various types of building roofs and their components' thermal behaviors. Faghih and Bahadori [3] studied thermal performance of domed roofs, in order to determine their usage to reduce the maximum air temperature inside the buildings. They evaluated deviations of indoor air temperature using energy balance and empirical correlations. They limited the representation of roof to two nodes across its thickness in thermal network analysis and constant convection coefficients for inner surfaces were assumed. Domed roof was considered as a pyramid for radiation analysis, where view factors can be easily estimated. Results of a previous study made by same authors were used to estimate solar irradiance absorbed by domed roofs [4]. They made a

* Corresponding author. Tel.: +94 779024024; fax: +94 112650622.
E-mail addresses: gayanmrt@gmail.com, gayan@mech.mrt.ac.lk (M.P.G. Sirimanna).

http://dx.doi.org/10.1016/j.enbuild.2015.12.052
0378-7788/

Nomenclature

A	surface area (m^2)
B	amplitude of periodic temperature variation (K)
C	specific heat capacity (J/kg K)
C_p	specific heat at constant pressure (J/kg K)
$F_{dA_k \to dA_j}$	view factor between two differential areas, from kth surface to jth surface
F_{kj}	view factor from kth surface to jth surface
g	gravitational acceleration (m/s^2)
h	convection coefficient (W/m^2 K)
I_{bh}	beam component of solar irradiance on the horizontal surface (W/m^2)
I_{dh}	global diffuse horizontal solar irradiance (W/m^2)
I_h	global horizontal solar irradiance (W/m^2)
I_T	solar irradiance on the tilted roof surface (W/m^2)
J	radiosity (W/m^2)
k	thermal conductivity (W/m K)
L_c	characteristic length (m)
m_a	attic air mass (kg)
$\mathbf{n}_j$	unit normal vector of jth surface element
$\mathbf{n}_k$	unit normal vector of kth surface element
Pr	Prandtl number
Q	heat exchange (W/m^2)
r	ground reflectance
Ra_L	Rayleigh number
T	temperature (K)
t	time (s)
T_{sky}	effective sky temperature (K)
v	kinematic viscosity (m^2/s)

Greek letters

α	solar absorptivity
β	slope angle (rad)
γ	coefficient of volume expansion (1/K)
Δt	time span (s)
Δx	element thickness (m)
$\in$	emissivity of the surface
θ	incident angle (rad)
θ_z	zenith angle (rad)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($W/m^2 K^4$)
τ	mesh Fourier number
φ	phase shift angle (rad)
ω	frequency (rad/s)

Subscripts

at	attic
c	by convection
en	ambient
g	ground
in	inner surface of roof element
j	jth surface
k	kth surface
ou	outer surface of roof element
p	constant pressure
r	by radiation
rm	room
T	tilted surface
0,1,2,. . .m,. . . N	node number
∞	away from surface

Superscripts

i	ith time instant

thorough analysis in their study on solar radiation on domed roofs and used isotropic diffuse model to estimate incident solar radiation. Hadavand, Yaghoubi and Emdad [5] analyzed flow patterns around typical vaulted roofs and identified the contributions of different parameters in related to thermal exchange of vaulted roofs with ambient air. They have considered transient heat conduction through the roof and validated the developed numerical code by simple flow problems. A detailed finite element model to investigate the thermal performance of non air-conditioned buildings with vaulted roofs has been presented by Tang, Meir and Wu [6]. They have considered unsteady two dimensional heat transfer of vaulted roofs and integrated heat transfer of entire building to their model. Purpose of this research was to compare vaulted roofs with flat roofs in terms of indoor temperature and due to that reason they did not validate the developed model. Elseragy and Gadi [7] studied about variations of total hourly clear sky irradiance received by a vaulted roof and a flat roof for different orientations. They used a previously developed computer algorithm to estimate clear sky radiation. To study the effects of a passive cooling system on heat transfer through flat concrete roofs, Alvarado and Martínez [8] developed two experimental models and numerical models. However, developed analytical models were based on experimental models and they observed that simplified boundary conditions applied for analytical models have caused considerable deviations between experimental and numerical results. Al-Sanea [9] evaluated thermal performance of building roofs using a numerical model based on an implicit finite volume method. Considered configuration was a flat horizontal roof, which does not form a shape of an enclosure. He used ASHRAE clear sky model to estimate solar irradiance on horizontal surface. Convection coefficients of outer surface were estimated considering wind speed and constant values were selected as combined heat transfer coefficients for the inner roof surface depending on the direction of the heat flow. Accuracy of his numerical model was validated by comparing with an exact analytical solution for a simplified problem. Studies [3–9] are based on domed, curved or horizontal flat roofs, where the number of surfaces which resembles the shape of the roof is less. For instance, a flat roof can be represented by a planner horizontal surface and a domed roof by a hemispherical surface. Thermal model developed for a triangular shaped roof with inclined surfaces is found in a study conducted by Fitzgerald et al. [10]. They developed a computer based thermal simulation for the roof by treating entire roof as a single two dimensional surface with constant temperature. Despite the fact that different roof surfaces have different temperatures, this assumption which they made particularly considering New Zealand houses greatly simplified the thermal analysis of the roof. Apart from the studies which discuss thermal performance of specific roof types of simple configurations, some research have been conducted on different roof types and their elements in various perspectives, such as modeling of forced convective heat transfer [11], influence of ceiling [12], effects of solar reflectance [1,13] and roof insulation [14].

When the roof geometry become complex with inclined surfaces, it is observed that researches have been focused on experimental analysis, case studies and individual roof elements [11–14], rather than addressing the entire roof in a generic approach as in the case of domed, vaulted and flat roofs [3–9]. Therefore, in this study, a thermal model is developed to analyze thermal performance of building roofs with inclined surfaces. The model is generalized in such a way that it can analyze a roof under various environmental conditions, roofing materials and roof geometries. A computational tool that can analyze a roof with four inclined surfaces and a ceiling, a basic popular roof type, is developed following the thermal model. As found in many other studies, the model is developed based on the energy balance of the roof enclosure. Transient heat conduction of roofing materials is considered in order to get