Numerical Simulation of Heat Transfer Process in Inclined Roofs with Radiant Barrier System

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Submitted: 15/06/2019
Revised: 21/12/2019
Accepted: 23/12/2019

ABSTRACT

In this study, the performance of using radiant barrier in inclined roof was numerically investigated by using the COMSOL Multiphysics software package. A roof was simulated as two parallel plates with an air gap in between for enhancing ventilation through convection heat transfer. The simulated results were validated using a published experimental work. Results suggest that a maximum of 89% reduction in the heat gain through the roof for a heated channel with a uniform heat flux of 650 W/m^2 was possible. Moreover, the roof inclination angle reduces the heat-gain through the roof up to 41.5% for an inclined angle of 75 degrees. Variable heat variation effect was considered in a case study to account for ambient temperature and solar heat flux intensity variation from hour to hour throughout the day. This effect will have a direct impact on the heat transfer through the roof. Using radiant barrier helps reduce the amount of heat transfer through the roof up to 28.2% when 75-degree inclined roof is used.

Keywords: Radiant Barrier (RB), Natural Convection, Inclined Roof, Simulation.

INTRODUCTION

The role of free convection has been recognized in a myriad of engineering applications and naturally occurring processes (Sheikholeslami et al., 2006). Many researches were accomplished experimentally and numerically (Wang et al., 2012; Corvaro et al., 2016; Sojoudi et al., 2016; Bhowmick et al., 2018; Zhai et al., 2018; Dutta et al., 2018; Skullong et al., 2016; Rahman et al., 2016; Kent, 2009; Saha et al., 2010; Saha, 2011) to analyze heat transfer in an attic under laminar conditions. Few studies were investigated under turbulent flow conditions (Wang et al., 2012; Spalding, 2015). Shimin et al. studied the turbulent airflow and heat transfer in both sealed attic and vented attic through developing a computational fluid dynamic (CFD) model using Reynolds-averaged Navier–Stokes (RANS) model (Wang et al., 2012). More attention was received to natural ventilation of buildings as a new alternative source of energy saving (Sheikholeslami et al., 2006). Recently, Radiant Barrier Systems have seen a widespread utilization for reducing the cooling load in buildings. This system mainly consists of a thin layer, covered by low emissive coating that provides the reflective phenomena. A suitable example may present in the form of aluminium foil (Sheikholeslami et al., 2006). Several studies were carried out to recognize the performance of RB in the roofs experimentally (Michels et al., 2008; Roels and Deurinck, 2011; Lee and Lim, 2016). Likewise, Roels and Deurinck (2011) reported that low emissivity decreases the heat gain in the indoor environment. A reflective foil may help in re-emitting the heat in the bottom part of the roof (Roels and Deurinck, 2011). Furthermore, studies evaluated the thermal characteristics of RB through the use of analytical and experimental methods (Escudero et al., 2013). Wang et al. (2006) conducted a study in which the numerical simulation of buoyancy-driven turbulence ventilation in attic space under winter conditions was discussed. The results of the study showed that the airflow in sealed attics was found to be asymmetric; however, the airflow in vented attics was found to be symmetric. Moreover, the study reported that the sealed attic consumed less energy in cold days as compared to the vented attic. Furthermore, the results of the study showed that ventilation airflow rate increases in the cold days and by increasing the size of the vent, higher ventilation could be achieved. Another study conducted by Sojoudi et al. (2016) discussed the natural convection subject to sinusoidal thermal forcing on inclined walls and heat source that was located on bottom wall of an attic-shaped space. The findings of the study were demonstrated in terms of isotherms and streamlines. Moreover, Nusselt number was used to demonstrate the heat transfer. The study used finite volume numerical methods to solve the governing equations. The results suggested that, during the day time, the flow in the attic space is stratified due to the heating stage. However, the results also predicted that the flow becomes unstable during the night-time, i.e., the cooling stage. Furthermore, the study conducted by Skullong et al. (2016) discussed the experimental and numerical heat transfer investigation in turbulent square-duct flow through oblique horseshoe baffles. The results of the study showed that the horseshoe-baffle vortex generator (HB) can be significantly used for enhancing the heat transfer. Moreover, the HB results predicted that they were far more significant than the smooth duct. Moreover, CFD numerical HB results also showed great relevance to the measurements. Also, the optimum HB parameters were also recorded for both numerical and experimental experiments. The numerical results of the study conducted by Saha et al. (2010) also suggested stratified flow in the attic space during the daytime. Moreover, the results predicted that the flow becomes unstable during the night time. Furthermore, the study results showed that a transition in the critical value of Ra is recorded as Ra gradually increases. The heat-transfer as calculated for the night-time cooling stage v/s the daytime heating stage predicted a higher heat-transfer rate for night-time. In the current study, the effect of implementing RB at the lower plate inside roof channel will be invistegated. Also the effects of varying roof inclination angle and the level of emissivity used in RB material will be studied numerically. In addition to that, the variable heat variable heat flux coming to the inclined roof due to change in solar radiation throughout the day will be studied.

PROBLEM DEFINITION

In this study, the effect of implementing RB at the lower plate of the channel was investigated as shown in Figure 1. The effects of varying the inclination angle and the emissivity of the lower plate were studied numerically.

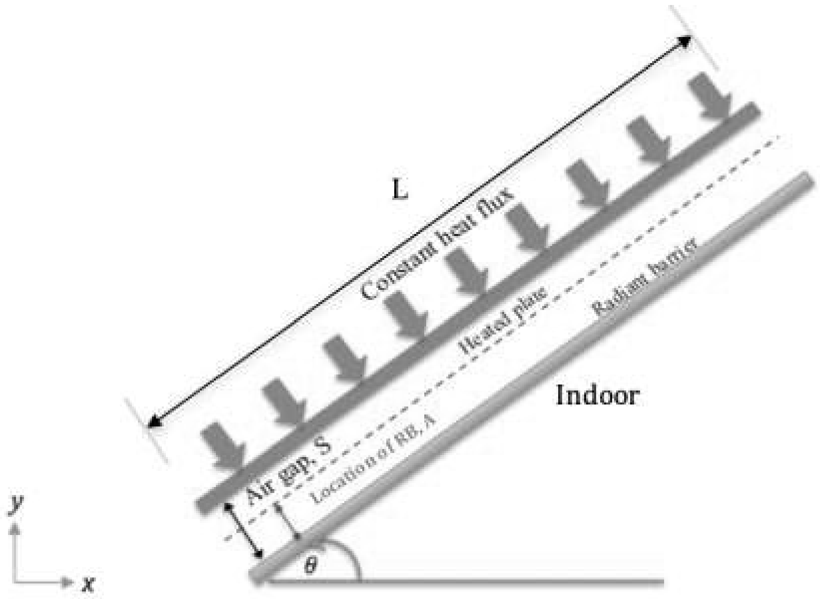

Figure 1. Schematic diagram of inclined roof with heated plate and RB.

In addition to the fluid flow in the channel, the simulated model combines the three modes of heat transfer: conduction, convection, and radiation. The heat is conducted through the upper and lower plates of the channel. Convection occurs when the heat is transferred from the lower surface of the upper plate to the channel air. The flowing air carries part of this heat, while the rest reaches the lower plate, where the RB is located. RB reflects most of the heat back up into the channel/air and transmits part of it through the lower plate. The aim of this study is to identify a system to minimize the net heat transfer to the indoor area. The inlet and exit of the channel are open to the atmosphere, where the temperature is Ta and the pressure is Pa. For the fluid part, the air density decreases along the channel due to the rise in the temperature as a result of the reflected heat from the RB. The air naturally flows upward due to this temperature difference combined with the gravity force, so the buoyancy force is introduced into the model to act as the driving force for the flow.

GOVERNING EQUATIONS

Some assumptions were considered in the simulation to derive the governing equations. For instance, conditions of 2D, steady state, and laminar flow were applied. Additionally, incompressible flow was taken into consideration and plates with constant properties were also studied. Moreover, the inlet temperature was retained at 26 °C. It is also important to note that Boussinesq approximation was applied and that the heat was transferred from the lower plate to the room by radiation solely. Lastly, the emissivity of radiant barrier is 0.02 and the emissivity of the upper plate is 0.903. Then, the steady two-dimensional natural convection flow along an open channel is governed by the continuity, momentum, and energy equations (1, 2, and 3).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

where u is x-velocity component (m/s) and v is y-velocity component (m/s).

The Boussinesq approximation for the gravity term is used, so the momentum equation is simplified to

$$\rho_a\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)= -\frac{dP}{dx}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\rho_a g\beta(T-T_a) \qquad (2)$$

where ρ_a is the density of the air (kg/m^3) , P is the pressure (Pa), μ is the dynamic viscosity of the air (Pa.s), g is gravity acceleration constant (m/s^2) , β is coefficient of thermal expansion (1/K), and T is temperature (K). Energy equation in natural convection assuming that viscous dissipation is negligible is

$$\rho_a c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2} \qquad (3)$$

where c_p is the specific heat capacity at constant pressure (J/(kg.K)), and k is air thermal conductivity (W/m.K).

Boundary Conditions

For the heat flux applied to the upper plate, the inward heat flux option is specified. For the internal walls of the upper and lower plates, the no-slip boundary condition is specified. At the exit of the channel, the outflow option is specified. For surface-to-surface radiation between the internal walls of the upper and lower plates, the following equation is used:

$$-k\frac{\partial T}{\partial x}= \varepsilon(G-\sigma T^4) \qquad (4)$$

where the solid surfaces are considered to be opaque surfaces, ε is surface emissivity, G is incident radiation heat flux (W/m^2), and σ is Stefan-Boltzmann constant (W/(m^2.K^4)).

For surface-to-ambient radiation between the surface of the lower plate and the indoor area, the following equation is used:

$$-k\frac{\partial T}{\partial x} = \varepsilon\sigma(T_i^4 - T^4) \quad (5)$$

An open boundary condition is used where the normal stresses are assumed to be zero at the inlet and exit of the channel. Thus, air temperature and pressure at the inlet and exit of the channel are specified as the ambient temperature and pressure.

Non-Dimensional Parameters

Some non-dimensional parameters were used in defining the physics of heat transfer. Nusselt number was defined as the ratio of convective to conductive heat transfer and it is calculated as follows:

$$Nu = \frac{hL}{k} \quad (6)$$

where h is heat transfer confident (W/m^2.K), L is length of channel (m), and k is fluid thermal conductivity (W/m.K). Heat transfer coefficient is calculated according to this equation (Puangsombut et al., 2007):

$$h = \frac{1}{T_1 - T_{bm}}\left[q_s - \left(\frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_2} - 1}\right)\right] \quad (7)$$

where T_1 is mean surface temperature at heated plate (K), T_{bm} is air bulk mean temperature (K), T_2 is mean surface temperature at radiant barrier (K), q_s is sun radiative heat flux (W/m^2), σ is Stefan-Boltzmann constant (W/(m^2.K^4)), ε_1 is emissivity of heated plate (gypsum board), ε2 and ε_2 is emissivity of radiant barrier.

The other non-dimensional parameter is Rayleigh number that is related to buoyancy driven flow (free convection). It is defined as follows:

$$Ra = \frac{g\beta q_s S^4}{k\nu\alpha} \quad (8)$$

Based on the Boussinesq approximation, the volumetric thermal expansion coefficient is calculated as follows:

$$\beta = \frac{1}{T_{bm}} \quad (9)$$

where S is air gap length (m), ν is air kinematic viscosity (m^2/s), and α is thermal diffusivity of the air (m^2/s).

METHODOLOGY

The simulations of the problem were carried out using the COMSOL Multiphysics software package. A roof was simulated as two parallel plates with an air gap in between to enhance ventilation through convection heat transfer. Basically, a gypsum board roof is built to evaluate the amount of heat flux through the roof. Then, a radiation model is added to evaluate the amount of heat flux through the roof when adding an RB layer to the lower plate.

Non-isothermal fluid flow laminar flow is chosen in the program. The three modes of heat transfer are included in the problem. Therefore, surface-to-surface radiation option is used to involve the radiation in the model. The upper plate is exposed to a constant uniform heat fluxes. The heat is transferred from the lower surface of the upper plate to the channel by convection and radiation. RB helps reflect most of the received heat and transmit less heat through the plate. The transmitted heat through the roof is discharged to the ambient by radiation (surface-to-ambient radiation). The “open boundary” condition is applied to the inlet and exit of the channel since they are exposed to the atmospheric air. The density of the air varies inside the channel so volume force option is applied to express the effect of body force.

As a first step, the model is validated based on a selected 0.05 m air gap roof with those obtained experimentally by Puangsombut et al. (2007). This study discussed the free convection in an inclined rectangular channel that is open-ended at several aspect ratios. The width and the length of the channel were taken to be 0.7 m and 1.5 m, respectively. However, the tilt angle chosen for the study was taken to be 15 degrees. The study was aimed at discussing the airflow rate and the heat transfer coefficient. The heat transfer coefficient was also evaluated through the correlation between the Reynolds and Nusselt numbers as a function of Rayleigh number. The selected study for the validation of current study also evaluated the enhancement in the heat transfer, which was due to the radiant barrier and was evaluated with the help of a comparison carried out to a channel consisting of gypsum board. Validation is based on the value of the heat flux through the roof, and on the Nusselt number. Simulated and experimental heat flux through the roof and Nusselt number are compared under several uniform heat fluxes applied to the upper plate: 190.5, 285.7, 380.9, and 472.6 W/m^2. The experimental data were taken when the flow is in steady state.

The roof has a length of 1.5 m, and a thickness of 0.05 m (air gap), as shown in Figure 1. The thicknesses of RB layer and the parallel plates are assumed to be 0.001 m and 0.01 m, respectively. Only half of the channel is modeled to save computational time so the symmetry boundary condition was used. The ratio of the thermal conductivity of the solid to the air ks/ka = 390. The roof inclination angle is 15 degrees. The inlet and exit of the channel are open to an ambient temperature of 26 ^{o}C. The emissivity of radiant barrier is 0.02, while the upper plate’s emissivity is 0.9. Heat is transferred from the lower plate to the indoor area by radiation only. The results in Figures 2 and 3 fulfill the correlation obtained experimentally as shown in the equation below:

$$Nu = 0.5887(Ra\, sin15)^{0.2079}\left(\frac{S}{L}\right)^{0.0231} \qquad (15)$$

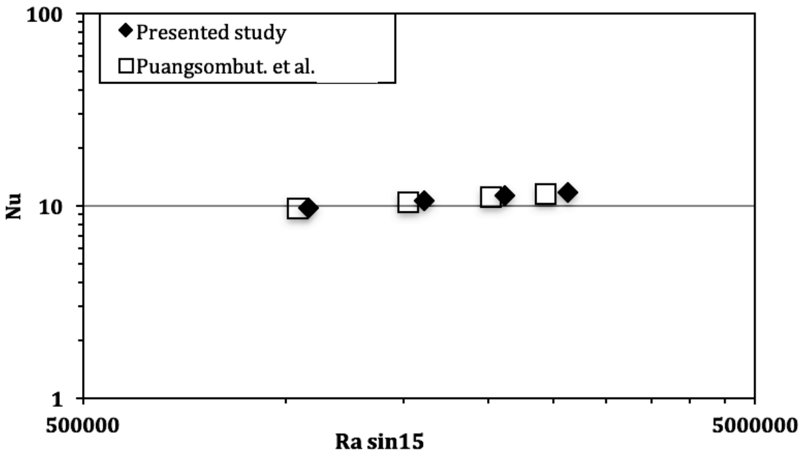

Figure 2. Validation of Nu versus Ra sin 15 under various applied heat fluxes.

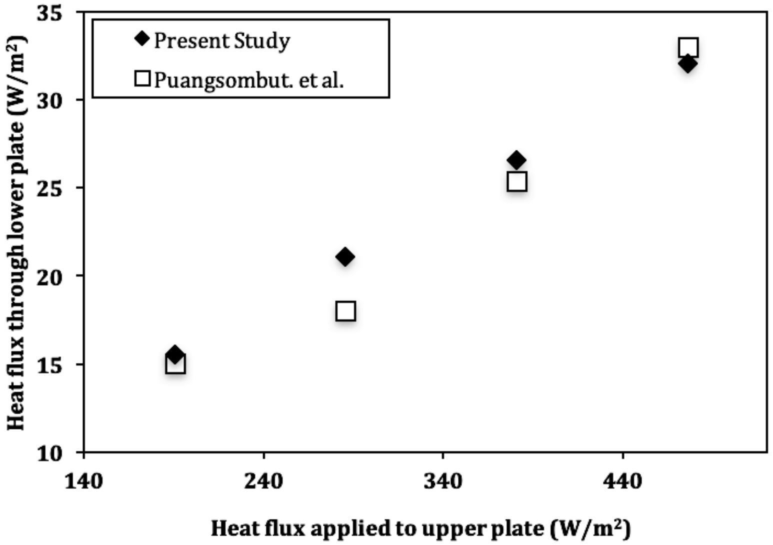

Figure 3. Validation of heat flux through lower plate under various applied heat fluxes.

RESULTS

This section includes the comparison between a channel with and without RB at the lower plate, the effect of varying lower plate emissivity, and the effects of varying the roof inclination angle. Discussions pertaining to roof inclination angles were incorporated in previous studies (Ayadi et al., 2017; Shukla et al., 2016). Furthermore, the significance of emissivity with regard to designing roofs had been highlighted in the literature (Qin et al., 2017). Therefore, this study had aimed to contribute to the existing literature by investigating the effectiveness of RB technology in this regard.

Performance of Radiant Barrier

The purpose of this part is to observe the effects of RB in blocking heat flux through lower plate compared to a basic gypsum board roof. The effectiveness of RB technology in the thermal insulation systems within buildings had been highlighted in previous studies (Lee and Lim, 2016; Kosny et al., 2018). In this study, the applied heat fluxes at the upper plate are 250, 350, 450, 550, and 660 W/m^2 for a 15-degree roof inclination angle.

Figure 4 shows a comparison between the exit velocity and the heat flux passing through the roof as functions of the heat flux applied to the outside of the roof. The velocity magnitude is measured at S/4 from the upper plate, and the heat flux values are measured along the surface of the lower plate in contact with the indoor space. This is obvious since the heat flux is applied to the upper plate in both cases. The velocity magnitude is increased by 0.08 to 0.12 m/s when installing RB because it reflects more of the heat and thus raises the temperature of the air flowing in the channel. As a result, the air moves with a higher velocity because of the enhanced density gradient, thereby enhancing natural convection.

It was additionally observed that increasing the heat flux applied to the upper plate corresponded to an increase in the flowing heat flux in both cases. Furthermore, installing RB to the roof reduces the heat gain through the roof up to 89% when the applied heat flux is 650 W/m^2. It was noticed that heat flux passing through the lower plate increases slightly with the applied heat flux when the RB is fixed to the roof. This can also be seen in the temperature profile, as shown in Figure 5.

Temperature values at the upper and lower plates plate at various channel lengths (L = 10, 40, 75, 110, and 140 cm) as shown in Figure 5. This figure represents the upper and lower temperature distributions for an applied heat flux of 250 W/m^2. For a gypsum board roof, the upper plate temperature has almost the same values; meanwhile, the lower plate temperature is increasing along the roof length because of the heat accumulation due to high emissivity. When RB is fixed to the roof, most of the radiant heat is reflected from the lower plate. Therefore, its temperature remains almost constant. The air carries most of the reflected heat; however, part of this air reaches the upper plate, thereby causing a rise in the temperature. The temperature difference between the upper and lower plates for a roof with RB is between 42.4 and 80.4 ^{o}C, while it is between 17.7 and 24.8 ^{o}C in the case of a roof without RB.

When conducting a comparison of the temperature values of the upper plate, it was noticed that placing RB increases the temperature of the upper plate by 16.4 ^{o}C to 41 ^{o}C and reduces the temperature of the lower plate by 8 ^{o}C to 17 ^{o}C. This is a by-product of the enhancement in natural convection. Therefore, the RB not only seals the lower surface of the channel against a good chunk of the radiant heat, but also reflects it back to the upper place, increasing its temperature and providing the means to advent the heat away with the enhanced natural convection.

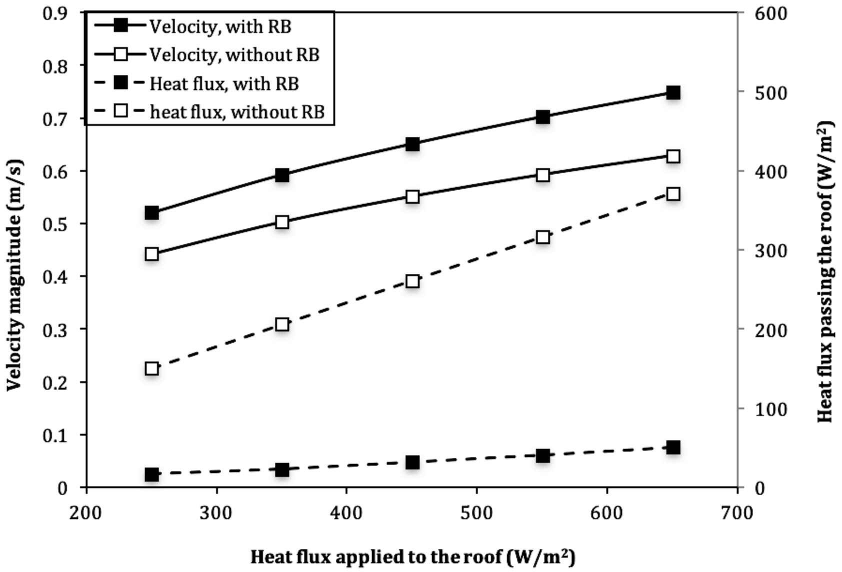

Figure 4. Exit velocity magnitude and heat flux passing the roof, with and without RB.

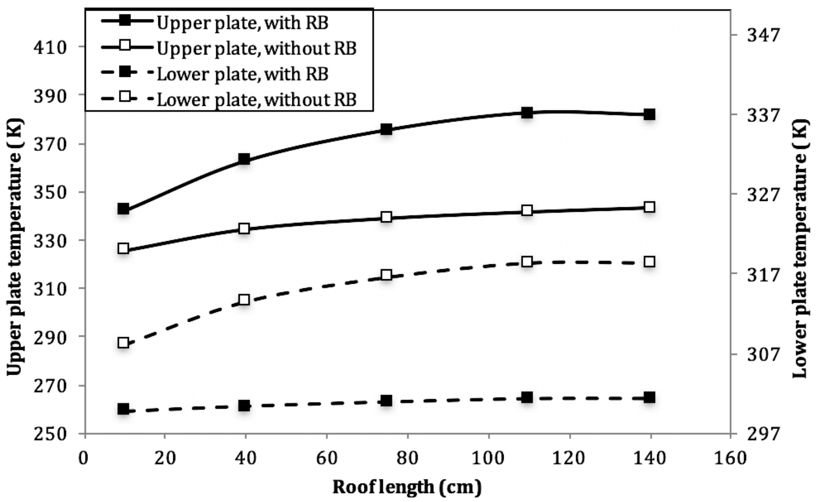

Figure 5. Upper and lower plate temperatures for a roof, with and without RB.

Figure 6 shows that, in both cases, Nu increases as the heat flux applied to the upper plate increases. Additionally, Nu increases when the RB is fixed to the roof since the natural convection is enhanced as explained above.

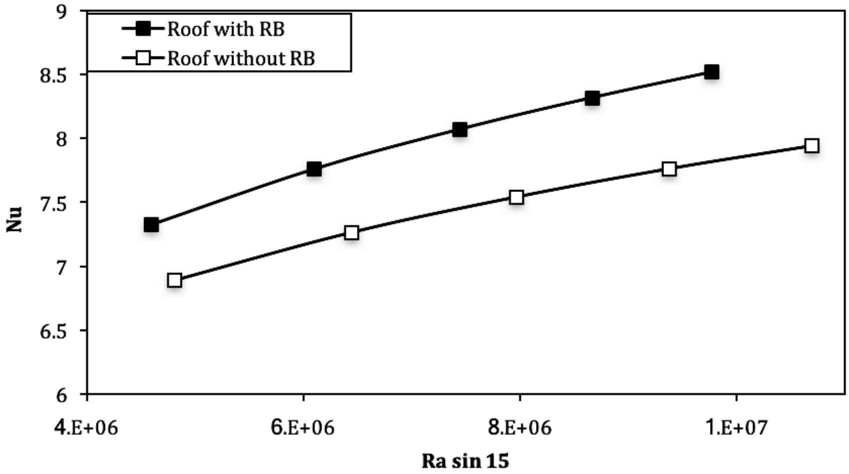

Figure 6. Nusselt number for a roof, with and without RB.

Lower Plate Emissivity Effects

The effect of varying the lower plate emissivity is studied with the effect of many parameters such as exit velocity, heat flux through lower plate, upper and lower plate temperatures, and Nusselt number. The relationship between plate emissivity and heat flux was earlier explored (Dai et al., 2015), and the association between plate emissivity and the Nusselt number was also studied previously (Bahrehmand et al., 2015). In this study, the base case is for an emissivity of 0.02 and it is varied between 0.01 and 0.5.

Figure 7 shows the velocity magnitude and the heat flux passing through the lower plate for various emissivity, as functions of the heat flux were applied at the top. It is observed that as the emissivity of lower plate decreases, the velocity of the air in the channel increases since the radiant heat is reflected mostly by the low-emissivity surface. The maximum velocity, 0.75 m/s, occurs when the lower surface emissivity is 0.01, while it reaches a maximum of 0.62 m/s for an emissivity of 0.5.

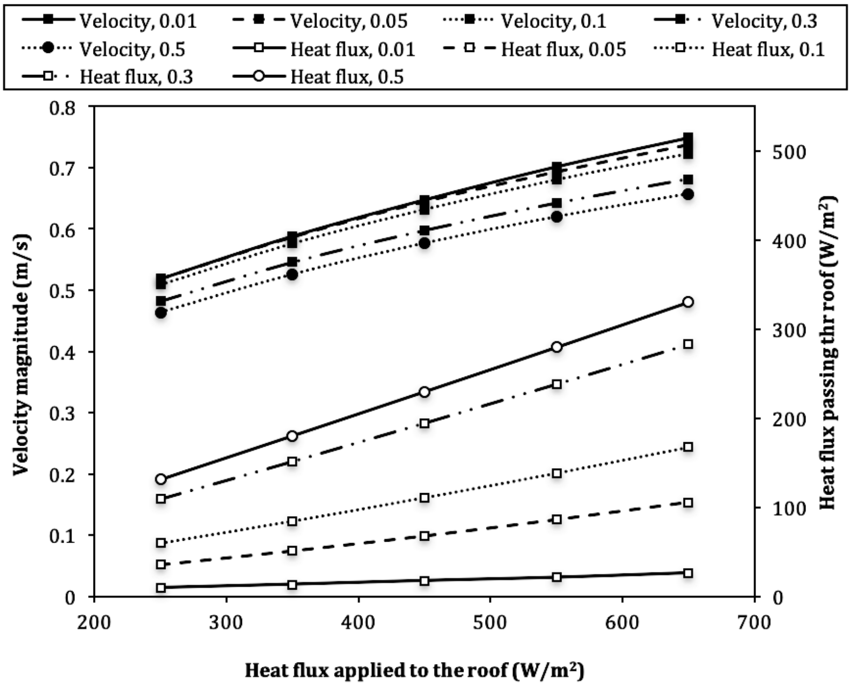

Figure 7. Vlocity magnitude and heat flux passing the roof for various emissivity in terms of the heat flux was applied at the top.

The same figure shows that the heat flux passing through the roof increases as the emissivity increases. The surface with the lowest emissivity allows almost the same amount of heat to pass (with the same air velocity) for almost the entire range of upper plate heat flux tested. At higher emissivity, the amount of heat passing the roof increases linearly as the applied heat flux to the upper plate increases. The maximum reduction of 92% in heat flux occurs when a surface with emissivity 0.01 is used. Therefore, to maintain the performance of such RB, dust accumulations, which reduce its performance, should be guarded against. This depends indirectly on the resulting temperature profile, which is shown in Figure 8. Namely, the amount of energy exchanged between two plates depends on the temperatures of their surfaces and the emissivity of the used material. Energy exchange is greatest when the temperature difference is high. Decreases in emissivity correspond to increases in the temperature difference, in addition to improvements in velocity magnitude and natural convection. The association between emissivity and temperature difference had been highlighted in previous studies (Pivovarnik et al., 2017).

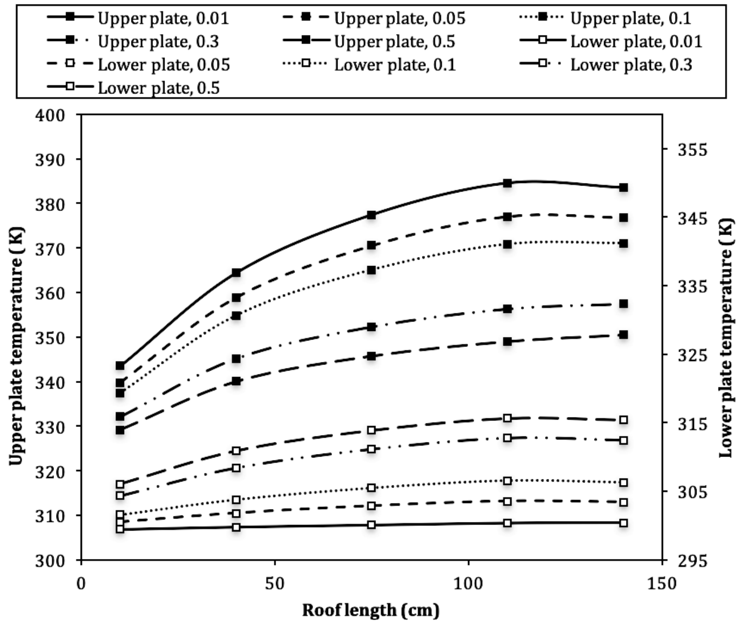

Figure 8. Upper and lower plate temperatures along the length of the channel for various RB locations.

In general, Nu increases with the increase of Ra. This directly proportional relationship was discussed in recent studies pertaining to this context (Sheikholeslami et al., 2017). Also, at any given Ra value, Nu increases with decreasing lower plate emissivity. This indicates that lower emissivities enhance the natural convection of the air between the plates, as reasoned above. And as a result of enhanced natural convection, the velocity of the flow increases. Nu correlation with Rayleigh number and lower plate emissivity is proposed as follows:

$$Nu = 0.38\, Ra^{0.19}(\varepsilon)^{-0.017} \quad (16)$$

The correlation is valid in the range:

$$1.2 \text{ x } 106 < Ra < 2.6 \text{ x} 106$$

$$0.01 < \varepsilon < 0.9$$

Inclination Angle Effects

This section of the study aimed to establish a Nu correlation with inclination angles. The relationship between Nu and inclination angles has previously been highlighted (Williamson et al., 2016). Upper and lower temperatures, velocity magnitude, heat flux through lower plate, and Nu are also considered. Figure 9 shows the exit average velocity magnitude and the heat flux passing through the roof. The velocity magnitude increases as the heat flux applied to the upper plate increases. Moreover, the exit velocity increases to 0.4 m/s for an inclined angle of 75 degrees, compared to the 15 degrees case. This is a due to the reduced friction between the flow and the plates as the roof inclination angle is increased. The velocity magnitude values are close for inclined angles of 45, 60, and 75 degrees.

Figure 9 additionally depicts the heat flux passing through the lower plate. Basically, as the heat flux applied to the upper plate increases, the heat flux increases in all cases. Moreover, increasing the roof inclination angle reduces the heat gain through the roof by up to 41.5% for an inclination angle of 75 degrees, compared to the 15-degree case.

Figure 10 shows a gypsum board roof and a roof with RB at a specified inclination angle. An inclination angle of 45 degrees is selected for comparison. RB implementation reduces the heat flux passing the roof by 90% compared to a gypsum board roof. For a gypsum board roof, the maximum reduction in heat is 22% when the 45-degree inclination angle is compared to the 15-degree one. So, implementing RB enhances the natural convection and reduces the heat flux passing through the roof up to 68% in the cases of increasing the roof inclination angle.

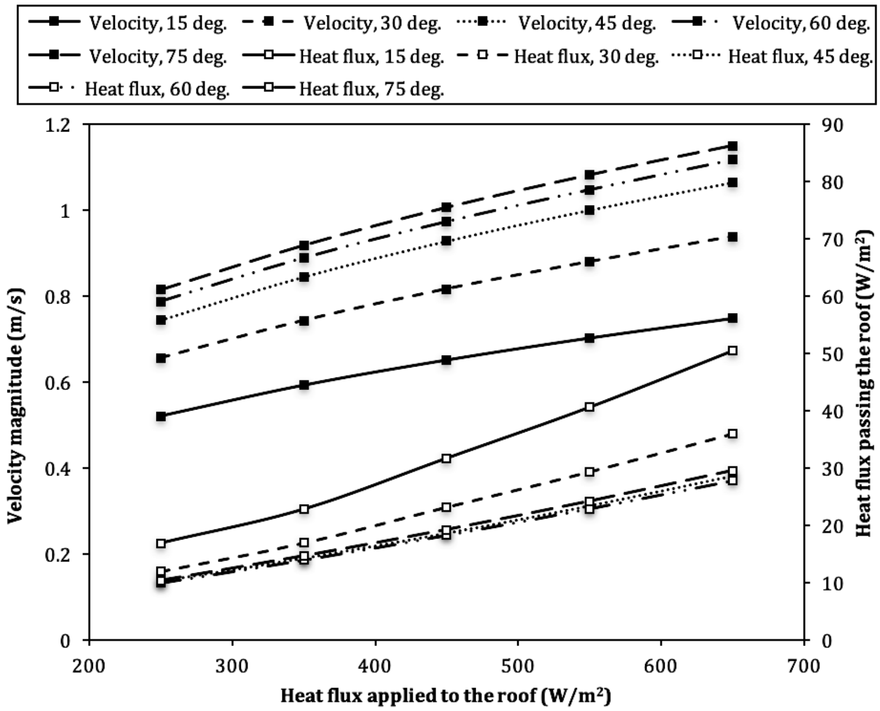

Figure 9. Velocity magnitude and heat flux passing the roof for various roof inclination angles.

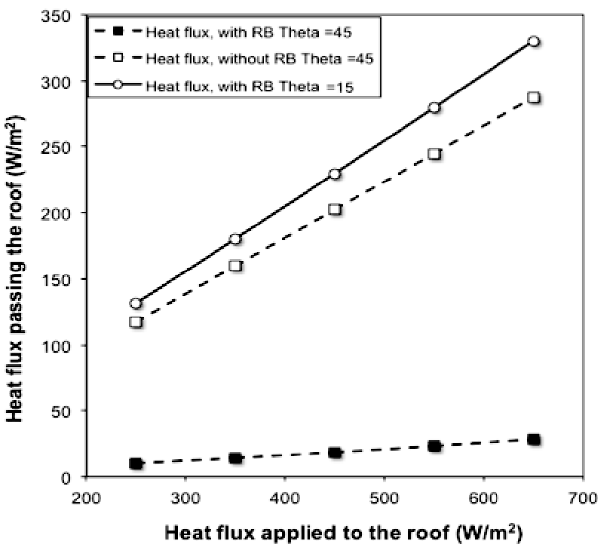

Figure 10. Heat flux passing a 45-degree inclined roof.

Figure 11 shows the upper and lower plate temperatures for various inclination angles. The upper and lower plate temperatures decrease with the inclination angle. This is a result of the higher velocity magnitude for greater inclination angles; the flow carries more heat so the temperature of the upper plate is decreased. Moreover, the RB reflects more heat as the inclination angle increases so the lower plate temperature is also reduced. The differences between the upper and lower plate temperatures increase with the length of the plates, so the average velocity magnitude increases; therefore, the natural convection increases. The percentage increase in velocity magnitude at 140 cm compared to 110 cm is double compared to the percentage increase in the velocity magnitude at 110 cm compared to 75 cm because of the velocity boundary layer in the channel. Thus, the upper plate temperature at 140 cm is slightly less compared to the temperature at 110 cm.

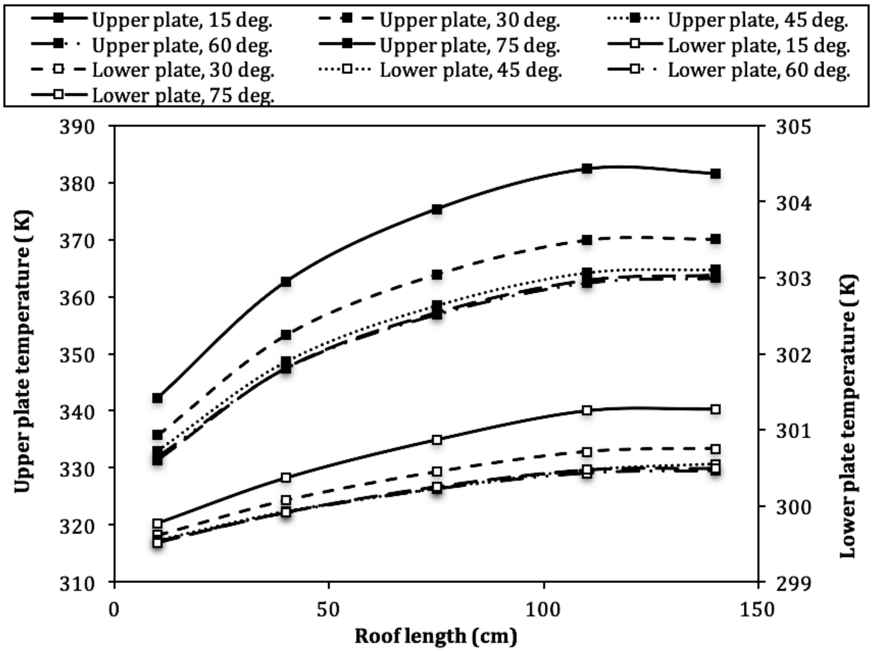

Figure 11. Upper and lower plate temperatures along the length of the channel for various roof inclination angles.

A proposed correlation for Nu for different Ra values and inclination angles is defined as

$$Nu = 0.46\, Ra^{0.2}(sin\,\theta)^{0.2} \quad (17)$$

The correlation is valid in the range

4.5 x 106 < Ra < 1 x107

15 < θ < 75

The results of the present study suggested that the roof inclination angle was found to reduce the heat-gain through the roof up to 41.5% for an inclined angle of 75 degrees. To this end, several other studies have also been conducted to discuss different parameters and conditions regarding the heat transfer process in inclined roofs. The results of the study conducted by Sheikholeslami et al. (2015) showed that the Lattice Boltzmann approach followed in this study was found to be a powerful approach for the simulation of natural convection heat transfer among nanofluids with curved boundaries. Moreover, the results of the study predicted a direct relationship between

Rayleigh number and Nusselt number; however, an inverse relation between the Hartmann number and Nusselt number exists.

A study conducted by Corvaro et al. (2012) discussed the natural convectin in an enclosure filled with air and with opposite cooled and heated walls. The experiment was conducted on four samples of different tilts such as θ = 0, $\frac{\pi}{6}$, $\frac{\pi}{3}$ and $\frac{\pi}{2}$. Moreover, the results of the study showed that a good agreement was found between the experimental and numerical analysis. The study also highlighted the PIV aspect and also reported the obtained Nusselt number. PIV was used as a nonintrusic technique in the following study.

Another study conducted by Tong and Li (2014) evaluated the heat transfer phenomenon in naturally inclined roofs. CFD analyses were carried out in the study to determine the convective resistance in the naturally ventilated inclined cavities. To validate the results obtained from the CFD model, several laboratory experiments were also carried out. The results of the study suggest only satisfactory agreement between the numerically simulated and experimentally measured temperature in the cavity and airflow velocity. A model was developed for the current study along with a full CFD model. The results of the study predicted good agreement between the two proposed models.

Variable Heat Flux

In the previous steady simulations, the main focus was to test the performance of RB with the roof angle in reducing heat transfer passing through the roof. This section of the study aimed to include the variable heat variation effect in the simulation. Since the ambient temperature and the solar heat flux intensity will vary from hour to hour throughout the day depending on the location, this effect will have a direct impact on the heat transfer through the roof. To show this effect, A case study with actual Kuwait City weather data in mid-July was considered taking into account the variable weather temperature and solar radiation intensity variation throughout the day as shown in Figure 12.

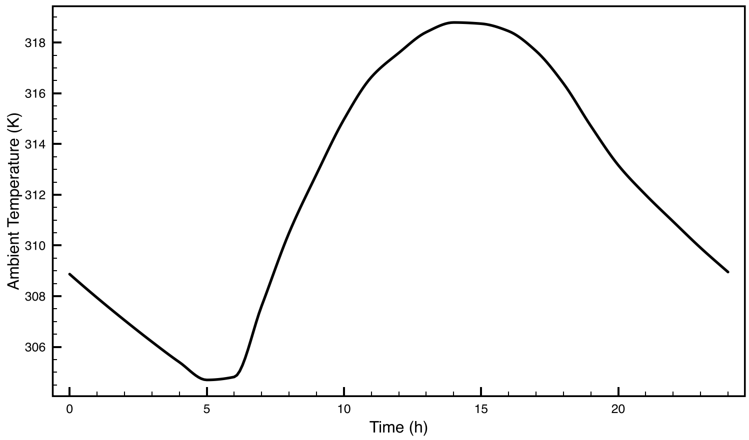

Figure 12. Ambient temperature varitation along day in Kuwait City in mid-July.

Based on the recommendation we reached in previous sections for roof angle and emissivity for RB, in this study we considered a roof angle of 45 degrees with 0.02 lower plate emissivity. Figure 13 shows the actual amount of heat flux received by 45-degree inclined roof with RB and the amount of heat passing through the roof along that day. This figure indicates that the heat flux passing through the roof is not constant as indicated in the steady simulation shown in Figure 10 and depends on the variable weather temperature and solar radiation intensity variations. At the maximum heat received point, 11.264 W/m^2, the RB reduced about 18.5% off the heat received by the roof, while the maximum amount of heat reduction increases to 28.2% when a 75-degree inclined roof is used as suggested by results in Figure 14. This figure shows the heat flux passing through different roof angles with RB as a result of applying variable weather temperature and solar radiation intensity.

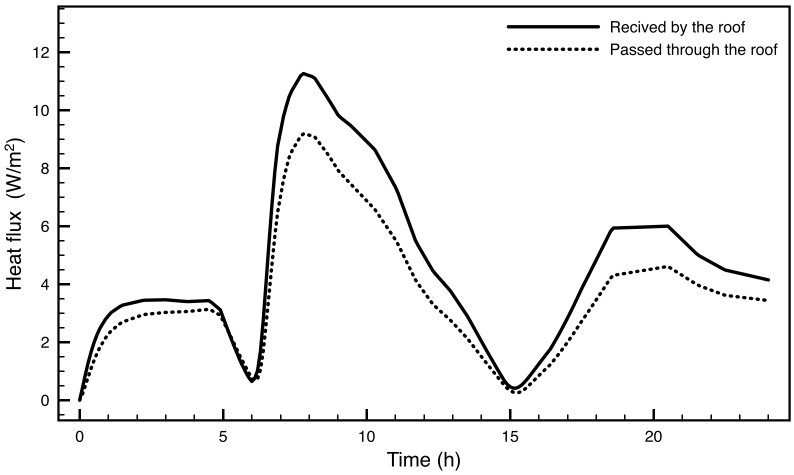

Figure 13. Effect of RB in reducing heat transfer passing through 45-degree inclined roof.

Figure 15 shows the exit average velocity magnitude at different roof angles with RB as a result of applying variable weather temperature and solar radiation intensity. The velocity magnitude increases as the heat flux applied to the upper plate increases similar to the behavior we observe with steady simulations. Moreover, the exit velocity increases by 245% on average for an inclined angle of 75 degrees, compared to the 15 degrees case. This is due to the reduced friction between the flow and the plates as the roof inclination angle increases.

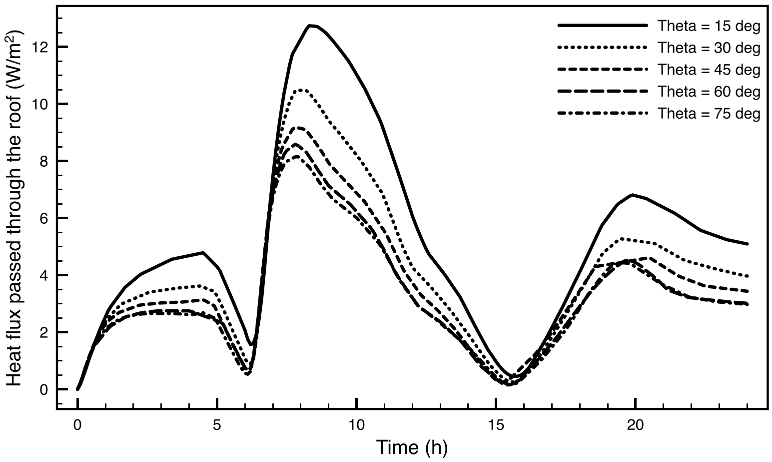

Figure 14. Variation of heat transfer passing through the roofs for diffenet roof angles.

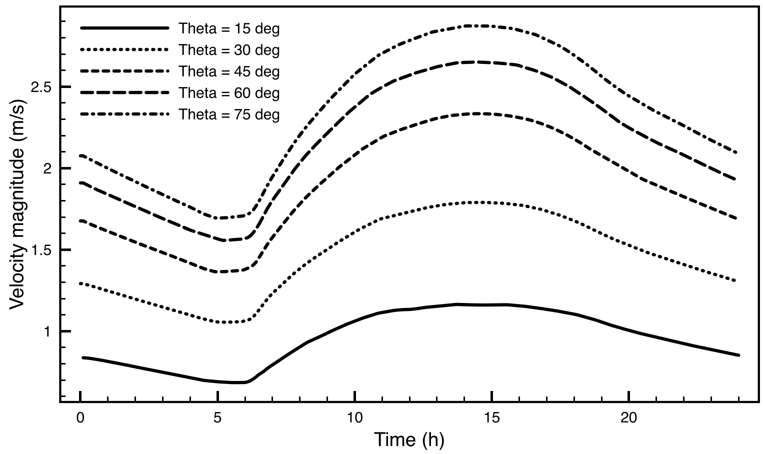

Figure 15. Variation of velocity magnitude passing through the roofs for diffenet roof angles.

CONCLUSION

The free convection in an inclined channel of two parallel plates was modeled using the COMSOL Multi-physics software to evaluate the heat flux passing through the roof. The main objective was to investigate the utility of using a Radiant Barrier (RB) assembly within the composite roof, and to find an optimum setup. Nu correlations were proposed for three different cases based on the height of the RB in the channel, the roof inclination angle, and emissivity, as well as Rayleigh number, which encompasses geometry/fluid characteristics. Nu values for a typical case were validated using a previously published experimental work. The heat flux through the lower plate was initially examined for a roof fixed with RB as well as a gypsum board roof. The results showed that a maximum of 89% reduction in the heat gain through the roof for a heated channel with a uniform heat flux of 650 W/m^2 was possible. RB reflects most of the radiant heat back to the channel air, thereby allowing for a faster flow inside the channel due to the enhanced natural convection.

The corresponding increase in Nusselt number was also observed. In the case of varying the emissivity of lower plate, a maximum reduction of 92% in heat flux occurs, when a surface with an emissivity of 0.01 is placed compared to a surface with an emissivity of 0.5. Therefore, it should be kept clear of dust accumulations to maintain the performance of RB, which negatively affects RB performance. It was found that increasing the roof inclination angle reduces the heat-gain through the roof up to 41.5% for an inclined angle of 75 degrees, compared to a 15-degree inclination angle. For a gypsum board roof, changing the inclination angle by itself from 15 to 45 degrees results in a 22% reduction in heat. RB implementation greatly enhances the natural convection and provides further reduction in heat flux up to 68%. Nu correlations equations (16 and 17) were proposed for various ranges of Ra and geometry characteristics. These correlations can be used to calculate Nu at many RB location, roof inclination angle, and lower plate emissivity values. Furthermore, these correlations are useful for building designers and engineers working in the energy conservation and energy efficiency areas, as they allow them to compare small alternatives to proposed designs that could yield considerable savings in energy consumption. Moreover, the current study proves to be encouraging for the designers and constructors to implement RB systems in house models. The RB model will help in reflecting more than half of the radiant heat in the attic resulting in reduced electricity bills. The temperature functions of houses can also be controlled through this system. The system is noncarcinogenic, durable, and nontoxic and is useful for commercial applications.

Unsteady simulations were conducted to study the effect of variable ambient temperature and solar heat flux intensity effects in the heat transfer through the roof. Results showed that the maximum amount of heat reduction increases to 28.2% when 75 degrees inclined roof is used with RB. And the exit velocity increases by 245% on average for an inclined angle of 75 degrees, compared to the 15 degrees case. Using RB and inclined roof helps in reducing heat transfer through the roof specially during the peak temperature hours as indicated by the time dependent simulations.

The current study could be expanded/augmented in a number of ways that would improve its utility. For example, a particle-tracking model can be used to estimate the dust accumulation on the reflective surface. The aim was to find the correlation for heat-gain through the roof as dust accumulates in particular climates. Forced convection can also be applied at the inlet of the air gap in order to study the reduction in heat transfer when both natural and forced convections are present.

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