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Selection of Optimum Radiant Barrier System (RBS) Location in Double Skin Ventilated Roofs

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Abstract

Double skin ventilated roof is one of the important passive cooling techniques that aims to reduce solar heat gain through roofs by reducing both the conduction and convection heat transfer from the roof to the ceiling of buildings. On the other hand, radiant barrier system (RBS) is very powerful in blocking the radiation heat transfer between the two skins. In this research, the effect of placing a thin layer of aluminium foil at different locations on the thermal insulation performance of a double skin ventilated roof model is investigated experimentally and the optimum location that transmits less heat flux from the lower skin is specified. The model is made of two parallel inclined galvanized steel plates. Galvanized steel has been used in the roof construction of industrial buildings and storehouses in Iraq. The radiant barrier is applied alternately, on the outer surface of the upper skin, on the inner surface of the upper skin, suspended in the airgap between the skins, and on the inner surface of the lower skin. These cases are considered as Model A, Model B, Model C, and Model D, respectively. It is found that the radiant barrier can block up to 78% of the heat in Model A, 71% in Model B, 94% in Model C, and 91% in Model D as compared with the Basic Model. Since the radiant barrier in both Model C and Model D blocks almost the same amount of heat, the location of the radiant barrier in Model D is chosen as the optimum radiant barrier location because this model is more practical.

Keywords: *Passive cooling, double skin roof, ventilated roof, radiant barrier system.*

1. Introduction

Roofs of buildings during summer are highly susceptible to the solar radiation and therefore cause a serious challenge of overheating. It was found that approximately 49% of the site's electricity consumption has been used in air conditioning system [1]. Double skin roof is a high-performance passive cooling system. It consists of two solid parallel layers; one at the top and the other at the bottom separated by airgap. The upper layer shields the lower one from direct solar radiation, and the airgap works as an insulation layer. The accumulated heat transferred from the upper layer can be removed by ventilating the airgap either naturally or by forced convection using mechanical fans. The ventilation of the gap by natural means needs a tilt angle of 10° to 30° in order to induce an upward flow of air due to buoyancy effect. Air flow takes away the accumulated heat between the roofs skins and hence reduces the heat gain into the indoor environment. When the solar radiation falls on the upper roof plate, part of the radiation is absorbed due to the absorptivity of the surface and the other part is reflected. Since the material of the plate is opaque, no radiation is transmitted through the roof. The absorbed heat is transferred by conduction through the solid plate and its temperature rises up then heat is transferred by both convection with the surrounding air and radiation with the surrounding surfaces as illustrated in Fig.1. Both the conduction and convection heat transfer are reduced in this type of roofs. The radiation heat transfer can be reduced by using Radian barrier systems (RBS). A radiant barrier as defined by the American Society for Testing and Materials (ASTM) [2] is a thermal insulation material that consists of one or more reflective/low-emittance surfaces, such as metallic foil or metallic deposits, unmounted or mounted on substrates where the emittance is 0.10 or less, installed on or near a building component, facing enclosed air spaces. RBS intercepts the flow of radiant energy to and from the building component. One of the most common cheap RBS is the aluminium foil. A literature review shows that many investigations had been performed to study the effectiveness of RBS in blocking the radiation heat transfer through double skin ventilated roofs. In 2006, Dimoudi et al. [3] tested a full-scale double skin horizontal roof component ventilated by a solar chimney under real climatic conditions by placing a RB immediately under upper roof skin. They found that the RB improves the performance of the roof remarkably since it keeps the lower skin at a temperature 5 K lower as compared to the one without RB. Next year, W. Puangsombut et al. [4] made an experimental investigation on free convection between two parallel plates heated from above and inclined at 15°. They examined two lower plates, namely radiant barrier and gypsum board. They found that the induced airflow rate through the channel is higher in the case of RB than the gypsum board while it could decrease the heat gain passing through the lower plate. In 2008, P.-C. Chang et al. [5] studied the thermal insulation of a double skin roof prototype incorporating RBS in different locations. They concluded that the RBS attached to the interior surface of either roof plate or hung inside the duct, can enhance the thermal insulation of the basic prototype. In the same year, C.-m. Lai et al. [6] made a similar study with different roof model and stated that installing a RBS on top of the bottom plate is very effective in preventing the roof heat from passing into the building. In 2011, S. Roels and M. Deurinck [7] investigated the effect of the emissivity of a roof underlay on the overall thermal behaviour of double skin inclined roofs by carrying out field testing, laboratory experiments, and a numerical investigation. They concluded that a low emissivity of the underlay reduces the heat gain to the indoor. In 2014, S. Tong and H. Li [8] built up a computational fluid dynamics (CFD) model to investigate the effect of the emissivity of the upper heated surface on the transferred heat flux from the lower skin. They found that the transferred heat flux reduces with the decrease of the thermal emittance. Next year, D. Li et al. [9] investigated numerically the effect of the absorption coefficient of the external surface on the thermal performance of double skin ventilated roofs. They found that increasing the absorption coefficient increases the average temperature of the lower skin. In 2018, M. Ferreira et al. [10] presented a brief analysis on a radiant barrier applied on a single skin roof of a house. They concluded that the use of RBs is advantageous in attenuating the flow of heat through roofs. Although many researches have been made on the effect of using radiant barriers on the insulation performance of double skin roofs, only P.-C. Chang et al [5] have studied its performance on different locations. The aim of this research is to select the best radiant barrier location in a double skin roof model that is made of two parallel galvanized steel plates. Galvanized steel has been used in the roof construction of industrial buildings and storehouses in Iraq. The experimental rig as well as the measuring devices are presented in section 2. While the theoretical approach is explained in section 3. Then our results will be discussed in section 4.

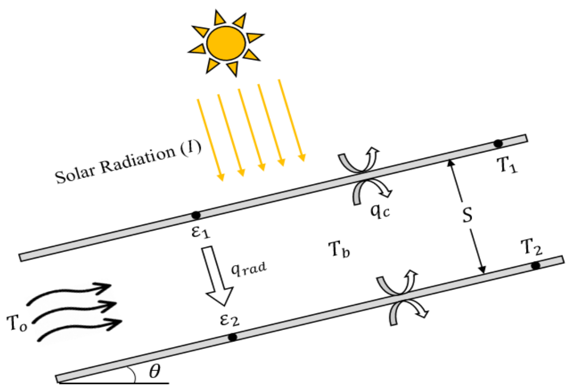


Fig. 1. Heat transfer mechanism across a double skin ventilated roof.

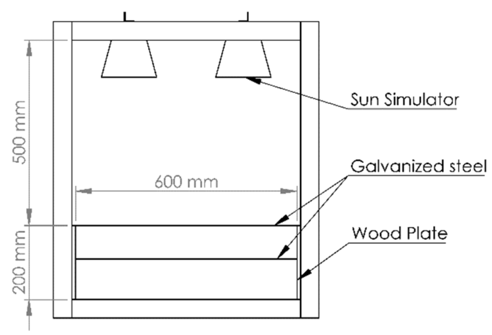
2. The Experimental Setup

The experimental rig is well designed and constructed for the purpose of the study. As illustrated in Fig. 2, it consists mainly of four major parts, the stand, the roof model, the sun simulator, and the control panel. The upper part of the stand is movable to adjust the inclination angle of the roof. However, the angle in this study is fixed at 30°. The roof model includes two identical parallel galvanized steel sheets of 1.5 m long, 0.6 m wide and 1 mm thickness, as shown in Fig. 3, and two side wood plates of 1 cm thickness followed by a layer of 5 cm extruded polystyrene (XPS) insulation board in order to neglect the flow of heat in the third direction. The airgap thickness is fixed at 0.04 m. The experiments are performed indoor to exclude the effect of wind and to avoid testing in variant sunlight conditions and standardize the testing environment. Therefore, a sun simulator has to be used to simulate solar radiation. It is consisted of a set of eight 500W/2A/220V tungsten halogen lighting bulbs. Tungsten halogen lamps have been used in the construction of commercial solar simulators [11]. They have also been used before by many researchers for the same purpose [6], [5], [12]. The electromagnetic wavelengths of these bulbs fall between 0.4 and 2.4 μm [5], [6], which are almost the same wavelengths of the solar radiation received on the ground. They are distributed in such a way that ensures almost uniform heat flux over the upper plate. A solid-state relay is connected to the lightings with a variable resistor for making the study at different radiation intensities. The electrical power is fed to the system from a stabilizer to provide a stable voltage and secure power supply and to avoid the variation in the radiation intensity. All the electrical accessories are fixed on a wood board and attached to the rig body, as shown in Fig. 2a. A thin layer of aluminium foil is used as a radiant barrier due to its very low emissivity and low cost. The two plates are coated with RUST-OLEUM matt black paint to maximize and standardize the emissivity of the surfaces and to simulate high emissivity slab materials such as wood, concrete, gypsum boa oxidised galvanized steel …etc. The aluminium foil is applied alternately on four different locations as illustrated in Table 1. To reduce the contact resistance between the foil and the plate, toothpaste is used to stick the foil on the plate without air voids.

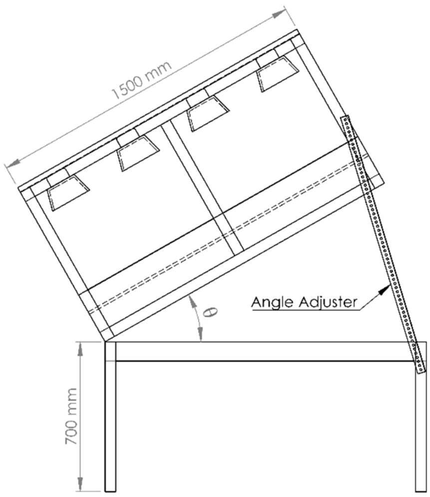
(a)

(b)

Fig. 2. The experimental rig. (a) Photographic image. (b) Isometric view.



(a)



(b)

Fig. 3. Schematics of the experimental rig. (a) Side view. (b) Front view.

2.1 Measurements

All the measurements made are in terms of temperature, radiation intensity and heat flux. Type-K calibrated thermocouples with an accuracy of 1°C are used to measure the temperature in twenty different places, four on each plate to estimate the average temperature of them and twelve thermocouples are distributed in the airgap along three imaginary planes (four thermocouples in each plane) to study the temperature distribution between the two plates, as shown in Fig. 4. All thermocouples are connected to a digital thermometer type (TM-903A) from LUTRON ELECTRONIC through a COMARK selector switch (20 channel). The radiation intensity fallen on the roof model is measured via a solar power meter model SPM-1116SD with an error of ±10 W/m^2. Regarding the heat flux transferred through the upper and lower plates, it is measured using two items of PHFS-01 heat flux sensor and its FluxDAQ reader from FluxTeq. All readings are taken when the system reaches a steady state condition (Appendix A). The emissivity of the coated plates and the aluminium foil are measured at the Iraqi Ministry of Science and Technology by a TIR100-2 Emissometer and they found to be 0.792 and 0.006 respectively.

3. Theory

The rate of heat transfer per unit area (q_u) measured from the upper plate is equal to the rate of heat transfer by convection to the air in the cavity and the rate of heat exchange by radiation with the lower plate as follows [13]:

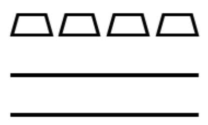
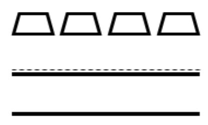
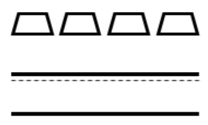
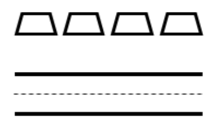
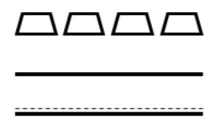
$$q_u = q_c + \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \text{... (1)}$$

Where T_1 and T_2 are the average temperature of the upper and lower plate respectively in K, σ is the Stefan–Boltzmann constant and it is equal to 5.67 × 10^{-8} W/m^2K^4, and ε_1 and ε_2 are the inner surface emissivity of the upper and lower plate respectively. In the case of suspended RB (Model C), equation (1) becomes [13]:

$$q_u = q_c + \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + \frac{1-\varepsilon_{3.1}}{\varepsilon_{3.1}} + \frac{1-\varepsilon_{3.2}}{\varepsilon_{3.2}}} \qquad \text{... (2)}$$

Where $\varepsilon_{3.1}$ and $\varepsilon_{3.2}$ are the upper and lower surface emissivity of the RB respectivily. Since the two plates are parallel, large, too close to each other, and facing each other, the view factor is assumed to be unity. T_1 and T_2 are calculated by the appropriate numerical integration methods [14] (Appendix B).

Table 1,
The roof models based on the RB location.

Basic Model	Model A	Model B	Model C	Model D
				
Without RB	RB on the outer surface of the upper plate	RB on the inner surface of the upper plate	RB suspended in the air gap between the plates	RB on the inner surface of the lower plate

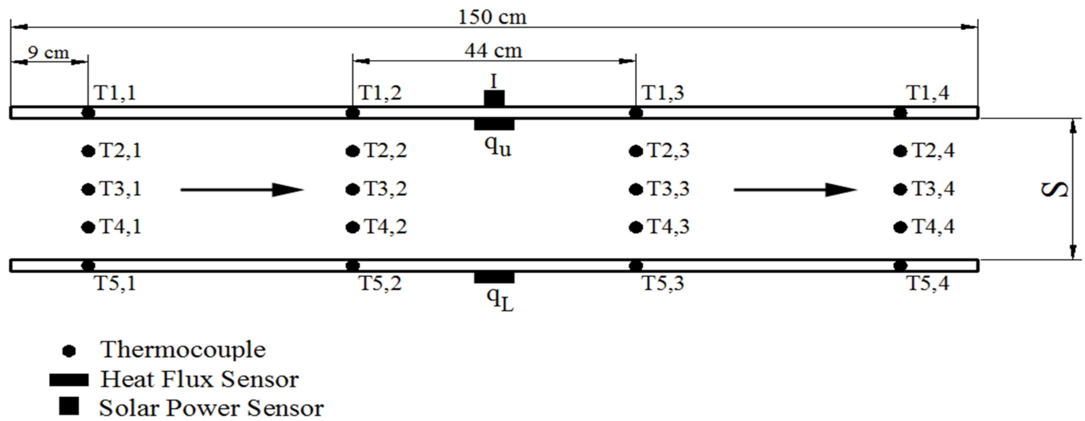


Fig. 4. Schematic of sensors distribution in the roof model.

4. Results and Discussion

The effect of placing a thin layer of aluminium foil at different locations on the thermal insulation performance of a double skin ventilated roof model is investigated at 30° inclination angle, 4 cm airgap thickness for different radiation intensities (550, 700, 850, and 1000 W/m^2), and the best location is determined. Four locations are examined, namely, on the external surface of the upper plate, on the interior surface of the upper plate, suspended in the air gap between the plates, and on the internal surface of the lower plate. Considering the roof model without RB as the basic model, these cases are termed as Model A, Model B, Model C, and Model D respectively. Note that the emissivity of surfaces is assumed to be constant. The thermal behaviour of each model is discussed below:

4.1 The Basic Model

It can be observed from Fig. 5 that the temperature of the lower plate is higher than the temperature of the air in the channel which indicates that large amount of heat is exchanged by radiation between the high emissivity inner surfaces of the upper and lower plate. As a result, the heat flux transferred from the lower plate is too high due to the high temperature difference between the lower plate and the air under the plate, see Fig. 6. Therefore, the heat flux transferred from the upper plate is mainly transferred by radiation as illustrated in Fig. 7.

4.2 Model A

As for Model A in which the RB is attached to the outer surface of the upper plate, all temperatures are decreased considerably due to the high reflectivity of the aluminium foil. However, the temperature of the lower plate is still higher than the temperature of the air in the channel (Fig. 5) which means that heat exchange by radiation between the two plates is still high and hence the heat flux is also high. The heat transferred from the upper plate by radiation is dominating as compared to the convection because the temperature difference between the plate and the air in the channel is low, as shown in Fig. 7. Placing the Aluminium foil in this position blocked 78% of the heat transferred through the roof model as compared with the basic model (Fig. 6).

4.3 Model B

Attaching the RB to the inner surface of the upper plate increases the temperature of the plate to the highest degree as the RB prevents the heat exchange by radiation with the lower plate, and hence the heat is accumulated in the material. Therefore, the temperature of air layer adjacent to the foil is rapidly increased due to the high temperature difference between the air and the upper plate, as shown in Fig. 5. The RB in this model blocked 71% of the heat transferred through the roof model (Fig. 6).

4.4 Model C

When the RB is suspended in the airgap between the two plates (Model C), the temperature of the upper plate is also high because its heat is only transferred by convection. The heat flux from the lower plate is the least in this case since the RB blocked 94% of the heat transferred through the roof model, as shown in Fig. 6. The RB split the air gap into two separated regions blocking both the convection and radiation heat transfer from the upper plate to the lower plate. It works as a radiation shield [15] because two additional low emissivity surfaces is added, hence radiation has to be exchanged first between the inner surface of the upper plate and the upper surface of the RB, then between the lower surface of the RB and the inner surface of the lower plate. However, placing the RB in this location is hard to be fulfilled practically.

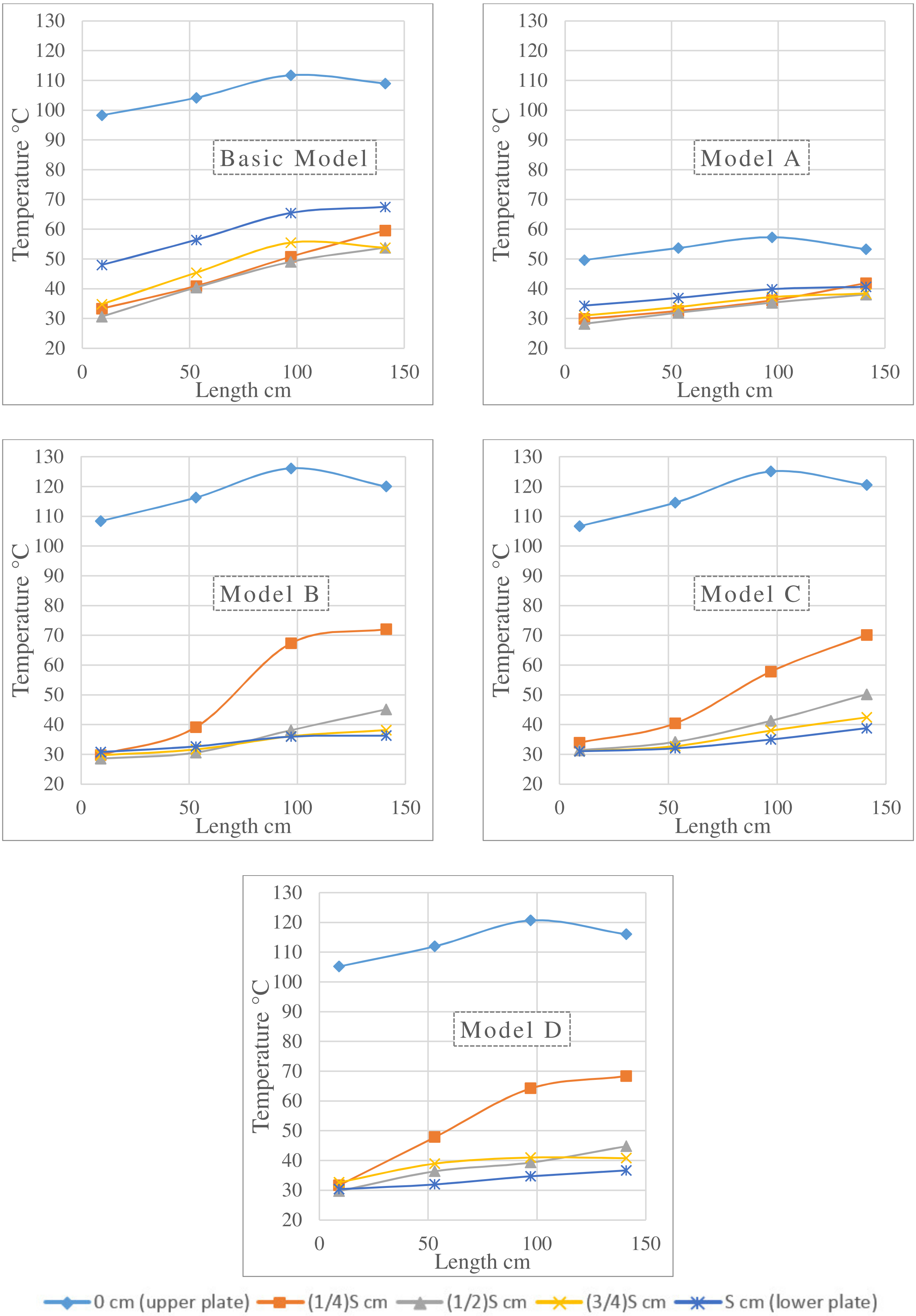


Fig. 5. Temperature profiles along the length of the channel at 1000 W/m^2 radiation intensity.

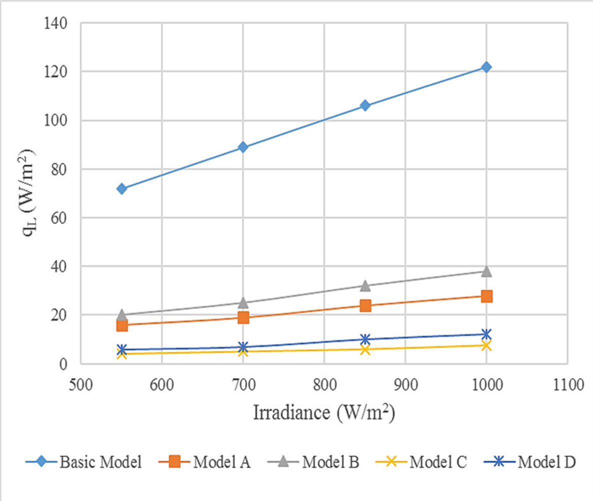


Fig. 6. The transferred heat flux through the lower plate.

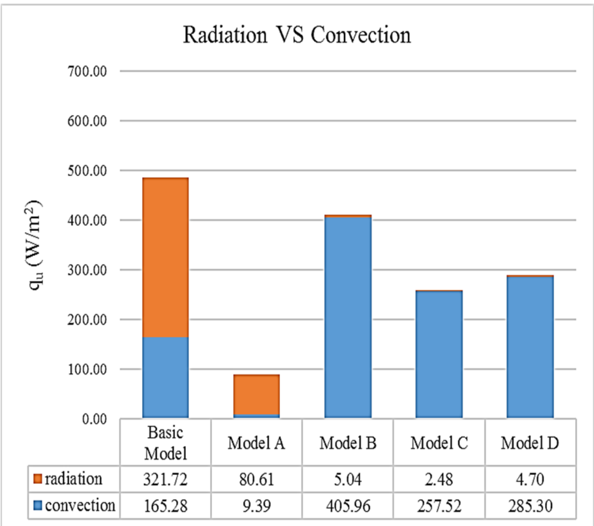


Fig. 7. The transferred heat flux through the upper plate.

4.5 Model D

Theoretically, this model is the same as Model B. However, it transmitted less heat than Model B. One of the reasons could be due to the variation of the surface emissivity with temperature. 91% of the heat has been blocked in this model which is almost the same as the heat blocked in model C, as shown in Fig. 6. Furthermore, the RB in this case can be applied practically by applying a thin layer of a reflective underlay or by applying reflective paints on the inner surface of the lower skin. Therefore, this model is the most appropriate one. The only disadvantage of this model as well as Model A is the accumulation of dust over a period of time which could decrease the performance of the RBS by increasing its emissivity.

These results are in agreement with P.-C. Chang et al. [5], who have examined the thermal insulation performance of a different double skin roof model that is consisted of a steel wave plate as the upper skin and reinforced concrete slab as the lower skin incorporating RBS at different locations.

5. Conclusion

An experimental investigation is performed to study the effect of placing a thin layer of aluminium foil at different locations on the thermal insulation performance of double skin ventilated roof model at different radiation intensities. It is found that the RB can block up to 78% of the heat in Model A, 71% in Model B, 94% in Model C, and 91% in Model D as compared to the Basic Model. It can be concluded that placing the RB in the airgap between the plates which is the case in Model C blocks the most radiation heat exchange between the plates. However, this model is hard to be applied practically. Since Model D in which the RB is applied on the inner surface of the lower plate blocks almost the same amount of heat as Model C, the location of the RB can be chosen as the best RB location. The only disadvantage of this model (as well as Model A) is the accumulation of dust over a period of time which could decrease the performance of the RBS by increasing its emissivity. This research highly recommends applying a thin layer of a reflective underlay or reflective paints on the inner surface of the lower roof skin which can enhance the thermal insulation performance of the roof.

Appendix A
Estimation of Steady State Condition

Three different criteria are considered to estimate the steady state condition, these are the average temperature of the upper and lower plate, as well as the bulk temperature of the air cavity (Appendix B). As depicted in Fig. A.1, less than an hour is sufficient for the system to be at steady-state condition. Any increase in temperature after that time is due to the increasing temperature of the environment. Therefore, all readings are taken after one hour from the application of heat.

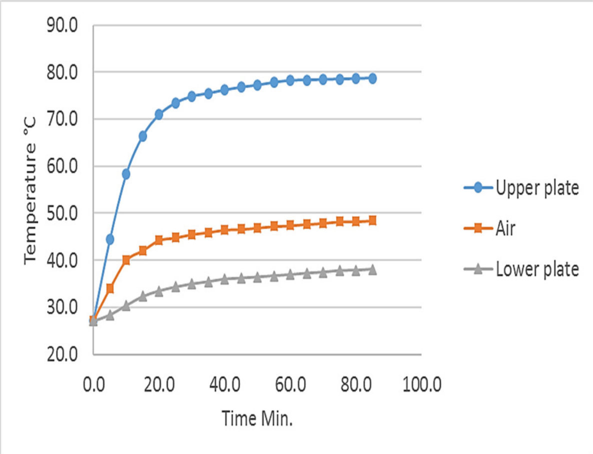


Fig. A.1: The mean temperatures of the upper and lower plates and the bulk temperature of air as a function of time.

Appendix B
Numerical Integration

The appropriate integration method for estimating the average temperature of the upper and lower plates is Simpson's 3/8 rule as follows [14]:

$$T_1 = \frac{T_{1.1} + 3T_{1.2} + 3T_{1.3} + T_{1.4}}{8} \quad (B.1)$$

$$T_2 = \frac{T_{5.1} + 3T_{5.2} + 3T_{5.3} + T_{5.4}}{8} \quad (B.2)$$

As for the bulk temperature of air, it is estimated by first integrating the vertical five points of each section using Boole's rule, then integrating the resulting points by Simpson's 3/8 rule as follows [14]:

$$T_{b1} = \frac{7T_{1.1} + 32T_{2.1} + 12T_{3.1} + 32T_{4.1} + 7T_{5.1}}{90} \quad (B.3)$$

$$T_{b2} = \frac{7T_{1.2} + 32T_{2.2} + 12T_{3.2} + 32T_{4.2} + 7T_{5.2}}{90} \quad (B.4)$$

$$T_{b3} = \frac{7T_{1.3} + 32T_{2.3} + 12T_{3.3} + 32T_{4.3} + 7T_{5.3}}{90} \quad (B.5)$$

$$T_{b4} = \frac{7T_{1.4} + 32T_{2.4} + 12T_{3.4} + 32T_{4.4} + 7T_{5.4}}{90} \quad (B.6)$$

$$T_b = \frac{T_{b1} + 3T_{b2} + 3T_{b3} + T_{b4}}{8} \quad (B.7)$$

Notation

I	Radiation intensity
L	The channel length
q_L	The heat flux from the lower plate
q_c	The heat flux transferred by convection
q_{rad}	The rate of heat exchange by radiation
q_u	The heat flux from the upper plate
S	The spacing between the upper and lower plates
T_1	The temperature of the upper plate
T_2	The temperature of the lower plate
T_b	The bulk temperature of air
T_o	The external temperature of air

Greek Letters

σ	Stefan–Boltzmann constant
ε_1	The inner surface emissivity of the upper plate
ε_2	The inner surface emissivity of the lower plate
$\varepsilon_{3.1}$	The upper surface emissivity of the RB
$\varepsilon_{3.2}$	The lower surface emissivity of the RB
θ	The inclination angle of the roof model from the horizontal

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اختيار افضل موقع لنظام الحاجز الاشعاعي في السقوف المهواة مزدوجة الطبقة

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الخلاصة

السقوف المهواة مزدوجة الطبقة هي احد اهم تقنيات التبريد المستتر المستخدمة لتقليل الحمل الحراري الشمسي من السقوف من خلال تقليل عملية انتقال الحرارة بواسطة كلاً من التوصيل والحمل. من ناحية اخرى، حواجز الاشعاع تعتبر من الوسائل الفعالة في منع انتقال الحرارة بالاشعاع بين طبقتي هذا النوع من السقوف. في هذا البحث، تم دراسة تاثير وضع طبقة من رقائق الالمنيوم في مواقع مختلفة على فعالية العزل الحراري لنموذج سقف مهوى مزدوج الطبقة وتم تحديد افضل موقع لها. النموذج مصنوع من طبقتين متوازيتين ومائلتين من صفائح الحديد المغلون. الحديد المغلون كان ولا يزال يستخدم في تسقيف البنايات الصناعية والمخازن في العراق. تم الاختبار بوضع الحاجز الاشعاعي بالتبادل على السطح الخارجي للطبقة العلوية، على السطح الداخلي للطبقة العلوية، معلق في الهواء بين طبقتي السقف، وعلى السطح الداخلي للطبقة السفلية. تم اعتماد تسمية هذه الحالات بالنموذج A، النموذج B، النموذج C، والنموذج D، على التوالي. حيث وجد ان الجدار الاشعاعي بامكانه حجب ٧٨% في النموذج A، ٧١% في النموذج B، ٩٤% في النموذج C، ٩١% في النموذج D اذا ما تم مقارنتها مع النموذج الاساسي. بما ان كلا من النموذج C و النموذج D بامكانهما حجب نفس المقدار من الحرارة تقريباً، تم اختيار موقع الحاجز الاشعاعي في النموذج D كافضل موقع له وذلك كونه عملياً اكثر.