Energy saving analysis of double roofs incorporating a radiant barrier system

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Abstract

A double roof is known as a very effective way to reduce both the conduction and convection heat transfer from a roof to the ceiling of a building; on the other hand, RBS (Radiant Barrier System) is very effective in blocking the radiation heat transfer between a roof and a ceiling. In this study, prototypical double roofs inspired by the concepts of both double-skin structure and the RBS technique were specifically designed to cut down the solar heat gain from the roof. The effect of energy saving was experimentally measured.
Keywords: double roof, RBS (Radiant Barrier System), heat gain.

1 Introduction

In Taiwan, electricity consumption by buildings or related properties takes 27% of the total national electricity consumption, and is the most important energy consumption besides industrial electricity consumption. It is a primary task of the national energy-saving program to decrease building energy consumption under the premier of not influencing the lifeline of Taiwan industry and the economy. Building electricity consumption can divide into three sectors: lighting, conditioning and dynamic power. As the changes of the seasons, energy demand, and building scale, there will be some difference in the proportion of those three sectors. In summer, energy consumption of the building conditioning sector may reach up to 28%. According to the statistics offered by Taiwan Power, conditioning energy consumption has increased from 4293MW in 1990 to 7518MW in 2000, with an average increase of 323MW annually, that is to say, with an increasing rate of 7.5% annually. Therefore, the

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electricity-saving strategy should emphasize more on reducing electricity consumption by conditioning and lighting. Passive cooling technology is a way to reduce solar heat-gain by incorporating natural resources, so as to reduce cooling load. Double-skin design for building exterior walls and roofs is one kind of passive cooling technology and is a rather available and accessible method for architects to make energy-saving designs.

The double skin structure can make an air layer in the mezzanine, which can reduce the heat transported into the room in summer, and keep out the cold while preventing heat loss in the room during winter. As for a double roof, after the roof receives solar radiation heat, it heats up the air within the channel, creates naturally convective flows, and allows the induced airflow to remove part of the heat transported into the interior, thus reducing the cooling load.

A double roof structure can only reduce the solar heat gain (which is the amount of heat that needs to be removed to maintain indoor comfort) of buildings by reducing overall thermal conduction and convection [1–9]. Such a structure, however, fails to block the thermal radiation. Therefore, this research explores another method, which focuses on blocking solar radiation upon the roof. This technique is called a Radiant Barrier System (RBS). Combining these two design philosophies (double roof and RBS) may enhance the overall thermal insulation performance of the roof structure. RBS is a glossy surface sheet (film) with low emissivity (often lower than 0.1) and high reflectivity (often higher than 0.9). Compared with other building materials, RBS releases less and reflects more thermal radiation. Therefore, it reduces the radiant heat transferred into a building, and the energy required for air conditioning. Most of the relevant researches focused on the influence of the amount and method of attic ventilation, RBS location, moisture and fallen dust on energy benefits.

In this study, prototypical double roofs inspired by the concepts of both double-skin structure and RBS technique will be specifically designed to cut down the building heat gain from a roof. The effect of energy saving will be experimentally measured.

2 Experimental setup

2.1 Test prototype

To facilitate the experiment's operation and reduce costs, we considered reasonable thermal and flow boundary conditions, and made judgments to arrive at simplified physical models of the prototypes. Fig. 1 displays the duct in cross-section with the parallel plates at inclination angle θ. The openings on the two sides are exposed to the outside static fluid (T_∞).

This prototype employs a steel wave plate as the top layer, and a steel reinforced concrete slab on the bottom. The arrangement will enable the experimental results of the prototype to reflect the double roof structure of school buildings and factory buildings. The dimensions of this prototype are as follows: the length of duct direction (Z axle in Fig. 1) is 100 cm; lateral direction length (perpendicular to X and Z axles in Fig. 1) is 60 cm; the widths of the duct

(S) are 5, 10, 15 and 20 cm respectively. Therefore, duct's aspect ratio in the flow direction is 5-20; the duct's side direction aspect ratio is 3-12. Those will make the thermal and fluid field 2-dimensional (X-Z). The inclination angle of the prototype (θ) is 0^o (horizontal) ~90^o (vertical). In order to avoid testing in variant sunlight conditions, and standardize the testing environment, six 500W/2A/220V infrared ray-less reflection film tungsten halogen light bulbs were used to mimic solar radiation. The largest electromagnetic wave lengths for beam split radiation are between 0.4 μm and 2.4μm when the tungsten halogen light bulb has no infrared ray film. This corresponds to electromagnetic wave lengths between 0.38 to 3μm of vertical incidence, approximately the radiation strength of sunshine. In our tests, the distance between light bulbs and the prototype roof were adjusted to bring the average incidence of sunshine close to 600w/m^2.

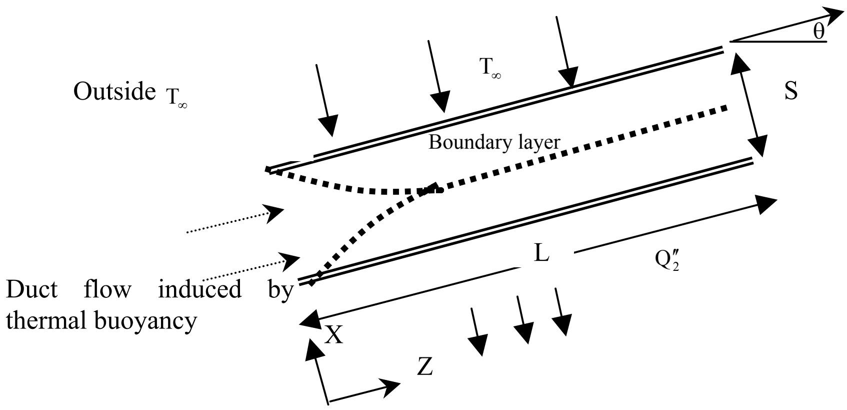

Figure 1: Physical model of the prototype.

The prototypes can be further divided into four structures:

(1) Basic prototype (roof plate: steel wave plate; bottom plate: steel reinforced concrete slab) (as illustrated in Table 1(a))
(2) Basic prototype with RBS applied on the inner side of steel wave plate: Model 1 (as illustrated in Table 1(b))
(3) Basic prototype with RBS suspended on the duct: Model 2 (as illustrated in Table 1(c))
(4) Basic prototype with RBS applied on the steel reinforced concrete slab: Model 3 (as illustrated in Table 1(d)).

2.2 Measurement apparatus

Outdoor air velocity, temperature and solar radiation are measured via a weather station. For determining the amount of ventilation rate, wind velocity at the mezzanine of the experimental prototype is measured and flow-field structure observation is made via a tracer gas technique. For temperature measurement, we place thermocouples at the outside of the roof plate, sides of duct, inner part of RC and RC bottom surface. T-type thermocouples (model number Omega T-type (PR-T-24)) are used in this experiment to measure and monitor the temperature distribution along the heat flow path. NTC thermograph measures the air temperature within the duct. The heat flow meters are attached to the outside of the roof plate and RC bottom surface to determine the heat flow into the roof plate and into the interior.

Temperature data collection is conducted with data loggers (YOKOGAWA MX100) and PCs. TESTO 445 Multi-functional ventilation/air-conditioning detectors equipped with two sensing connectors are used to detect various environmental factors, such as wind velocity, temperature and humidity. The data are analyzed with an RS 232 transmitting line and the professional analyzing software ComSoft 3 (Testo 0554 0830) on the Windows platform. Two weather stations (Jauntering EE-04 Sensors+HL10 Data acquisition system, and DAVIS Instruments), a multi-channel heat flow meter (HFM-215) and an anemometer (ALNOR CF8585M) are also used.

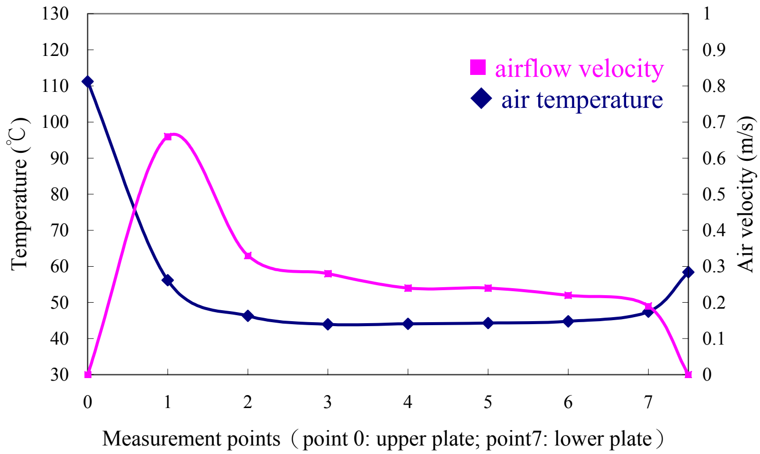

Figure 2: Temperature and velocity profile on the exit of flow channel when $\theta = 60°$, S=7.5cm.

3 Preliminary investigation

We waited until the upper plate was heated to a steady state at a fixed temperature, then the measurement was carried out. We took the mode of $\theta = 60°$, S=7.5cm for illustration purposes. The temperature profiles measured are in Fig. 2. The temperature profile of each point along the flowing direction underneath the upper plate obtained in the experiment approaches equi-temperature lines. It is very uniform across the plate except for points nearing the entrance and exit of the channels where the measurement is easily affected by edge effect, making the measured temperatures lower than the actual value. In order to simplify the calculations, we took the upper plate and lower plate as the nearly constant temperature distribution.

4 Results and discussion

4.1 Thermal insulation performance of the basic prototype

From the results of the experiment, regardless of the widths of duct, heat flows into the interior basically change in correspondence with the inclination angles of the basic prototype. Provided that the inclination angle increases (i.e., from horizontal status to vertical wall), the heat flow into the interior will also diminishes. In the range of common roof structure inclination angles (0^o [horizontal roof] to 30^o), there is a minute difference of thermal flow rate (rates are around 40~53W/m^2) into the interior in the basic prototypes with duct widths 10, 15 and 20 cm. In the basic prototype of duct width of 5 cm, the heat flow rate into the interior is larger. The reason, as explained earlier, might be that when the duct width (also the distance between the roof plate and RC) is less than 5 cm, the flow boundary layers of the two sides tend to interfere with each other and make the turbulence in the duct occur earlier, increasing heat transfer benefits and bringing more heat flow into the interior.

To apply the energy consumption index specified in the Building Codes of Taiwan in the evaluation of energy saving benefits of the prototype, when the heat flow inside the prototype is in a steady state, the average thermal transmittances (U-values) are calculated with temperature distribution and relevant thermal property of the construction materials.

Later, this study attempted to understand the relation among U values, duct width/height ratio (S/L), the angle ϕ between the prototype and gravity ($\phi = 90^o - \theta$), solar radiation (represented by modified Ra) with dimensionless parameters. Definitions of each dimensionless parameter are as follows:

$$Nu^* = \text{conductivity resistance /overall thermal resistanc} \quad (1)$$

$$Ra = \frac{g\beta(T_e - T_i)}{\nu\alpha} \quad (2)$$

With the results shown in Fig. 3, the following formula can be obtained:

$$Nu^* = 0.8\left[\left(\frac{S}{L}\right) Ra \cos\phi\right]^{0.173} \quad (3)$$

Therfore, to understand the U value characteristics of the basic prototype at a certain inclination angle and duct width, one can place the outdoor temperature (To), solar radiation, Sol-Air temperature Te (coming from To and solar radiation), duct width/height ratio (S/L), included angle θ between the duct and the horizontal (or the angle ϕ between the prototype and gravity, $\phi = 90^o - \theta$), interior temperature (Ti), roof plate, and conductivity resistance of top plate/air layer/RC slab, into formula (3) to obtain the U values. The dimensionless description, formula (3), will enhance the application of this project in practical construction.

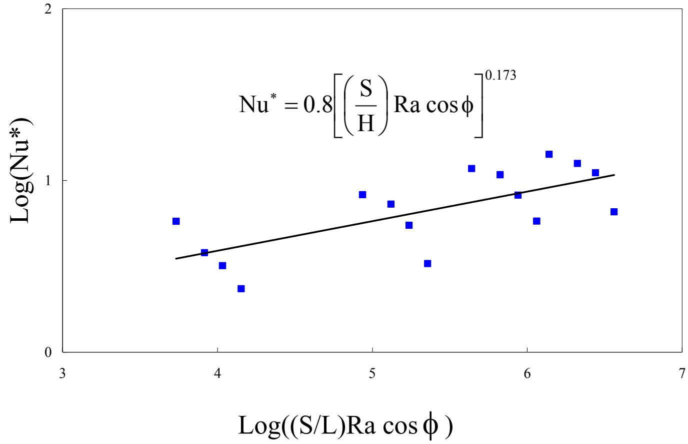

Figure 3: Relationship between dimensionless parameters.

4.2 Thermal insulation of the basic prototype incorporating RBS

From the above, it is clear that the double roof structure from steel wave plate and RC (basic prototype) has quite good heat insulation benefits under some situations. However, it fails to meet regulation requirements. Therefore, this study adds RBS at the basic prototype of duct width 5 cm and inclination angle of 30 degrees. The thermal insulation performances are illustrated in Table 1. It is found that RBS, attached onto the roof plate or hung inside the duct, will both make the basic prototype meet thermal insulation requirements of Building Codes of Taiwan. The U value of the prototype with RBS on an RC slab is close to the requirements. Table 1 illustrates the case of duct width 5 cm and inclination angle of 30 degrees. In the case with 10 cm duct width in the structure of RBS attached onto the roof plate or hung inside the duct or applied on RC slab, U values all conform to the regulation requirements.

Table 1: Comparisons of thermal insulation performance of the prototype with and without RBS.

Remark	(a) Basic prototype	(b) Model 1	(c) Model 2	(d) Model 3
Roof structure (S=0.05, θ=30)	roof plate: steel wave plate; bottom plate: steel reinforced concrete slab	Basic prototype with RBS applied on the inner side of steel wave plate	Basic prototype with RBS suspended on the duct	Basic prototype with RBS applied on the steel reinforced concrete slab
Illustration: (as RBS) (as RC)				
Convective heat transfer rate within the duct (W)	204	331	216	201
Conductive heat transfer rate in RC (W/m^2)	64.6	53.3	22.1	35.4
U-value	3.0	2.5	1.0	1.7

5 Results and discussion

This study proposes a novel domestic building roof structure with good thermal insulation that uses a combination of double roof and RBS technology. The energy-saving benefits and installation technology of the prototype are explored using various installations and operation tests in actual climate conditions, particularly for hot and humid regions. The conclusions are as follows:

1 Thermal insulation performance of the basic prototype. When the inclination angle (i.e., from horizontal to vertical wall body) of the basic prototype (steel wave roof plate and steel reinforced concrete bottom slab) increases, the heat flow into the interior and U values diminish and the thermal insulation performance improves.

2 Thermal insulation performance of the basic prototype incorporating RBS. RBS, attached onto the roof plate or hung inside the duct, will both make the basic prototype meet thermal insulation requirements of Building Codes of Taiwan. The U value of the prototype with RBS on an RC slab is close to the requirements.

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