ENERGY ANALYSIS OF VENTILATED ROOF WITH EXTENDED TOP IN HOT REGIONS

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ABSTRACT

An extended top of the roof can induce the upflowing wind which flows close to the wall and in this way it increases the intake airflow rate in the air gap. A model was set up to save energy with the consideration of a suitable thickness of the air gap and a suitable length of the extended top. The Computational Fluid Dynamics (CFD) was employed to simulate the wind field in the ventilated roofs with extended top and the cases were carried out according to Changsha's climate parameters in China. The results show that the extended ventilated roof works very well in summer. The air velocity inside air gap and airflow rate increases with the increasing thickness of the air gap, but for the length of the extended top, it almost changes nothing when its length reaches a certain value. With the same extended top, the thicker the air gap is, the more energy it can save. In other hot summer regions an optimized ventilated flat roof can also be gotten in the similar way mentioned in this paper.

KEYWORDS

Ventilated roof, Extended roof top, Model, Energy saving, Hot regions

INTRODUTION

Due to the shortage of non-renewable energy sources and serious environment pollution problems, it's hard for the whole society to avoid making efforts to reduce energy consuming. The energy required for building heating and cooling is approximately 6.7% of the total world energy and most of the systems for cooling applied air conditions are enormous energy consumers (J.Khedari 2000). Utilization of the passive cooling systems can save 2.35% of the world energy requirement (Agrawal 1989). Therefore, architectures are all try their best to make good use of passive cooling. Above all, the passive cooling for roof is of the greatest interest for the reason that for the buildings, roof covers the 36.7% of the total solar radiation falling on the single storied building having all four sides exposed to sun in summer and the heat from solar radiation is the main heat gain in summer (Nahar et al. 2003). Some literature shows that 50% of the heat load in the building is from the roof (Nahar et al. 1999). Therefore, a lot of passive cooling techniques are used to improve the roof thermal performance. For example, the use of high albedo materials on the surface of the roof (Simpson and Mcpherson 1997), evaporative roof (Nahar et al. 2003), roof pond with movable insulation (Runsheng and Etzion 2005), planted roof (Niachou et al. 2001), ventilated roof and evapo-reflective roof (Hamida and Ammar 2004) and so on. Among these roofs, little research is committed to ventilated flat roof with an extended top which functions well in hot regions. The ventilated flat roof, with an air gap on top of the bare roof, can be naturally ventilated by winds. Ventilation provides cooling by using moving air to carry away heat from the roof when the roof temperature is above the outdoor temperature. In this way, it reduces the heat accumulation in the structure and at the meantime reduces the heat conducting into building from the roof. Compared to other passive cooling roofs, the advantage of the ventilated roof is that it has a simple structure, it merely has an air gap on the top of the tradition flat roof, therefore it's quite light and it won't add much weight to the whole building structure which will be caused by planted roofs. Moreover, it won't act like pool roof which causes a large water loss.

In cities such as Changsha which located in subtropics areas, flat roof is quite popular and it gradually takes the place of tilt roof in the countryside in this area, for the reason that flat roof has other functions in countryside. The unventilated roof, with the air layer as its insulation, it works better than tradition bare flat roof. Furthermore, the ventilated roof reduces more energy consumption than unventilated one (Dimoudi et al. 2006). A tilt ventilated roof was theoretically investigated and it's shown that an energy saving of higher than 30% can be achieved in summer compared to an unventilated structure (Ciampiet al. 2005).

In literature, an application of a ventilated roof was always proposed for a sloping roof and the natural ventilation caused by stack effect was intensely investigated (Niachou et al. 2001). But in this paper, the natural ventilated flat roof was discussed. In hot summer it is believed this kind of roof has an excellent thermal performance for it can block the outside heat from conducting into the room in the daytime, at the same time the heat obtained during day was quickly dissipated to outside environment during night. For its simple structure, it is very convenient to use for the renovation of existing buildings by adding a ventilated part on top of the roof to improve the building's energy efficiency. An extended top of the roof can catch the upflowing wind which flows close to the wall and in this way it increases the intake air mass rate in the air gap so it is more energy efficiency than the one without the extended top. A numerical model was set up to get the energy efficiency of various ventilated roofs, and the CFD was used to simulate these roofs to get a proper thickness of the air gap and the length of the extended top according to Changsha's climate parameter.

MATHMATICAL MODEL

The traditional ventilated flat roof in Changsha is composed of concrete slab with its outside surface painted by white cement, air gap, cement layer, waterproof, insulation material, vapor barrier, cement layer, and reinforced concrete hollow slab with inside stucco, which are arranged from top to bottom of the roof. To paint the top concrete white seems indispensable as it greatly decreases the absorbability of solar radiation which causes most of the cooling load. For the position of the insulation material in the roof, it was worked out by Ciampi (Ciampi et al. 2003) that its location above the air gap is more efficient than under it. The same components without the air gap make up of the common bare roof. In the simulation, the top concrete slab is supposed to be slab A and others are supposed to be slab B. The basic configuration of the roof considered here is shown in Fig.1. The sketch of ventilated roofs with and without extended top is shown in Fig.2 and Fig.3 respectively.

Compared to the solar radiation, the radiative transfer of the roof to the sky and other objects is so little that it can be ignored. So considering the solar radiation which was absorbed by the roof, the solar-air temperature T_r is simplified as follows.

$$T_r = T_0 + \alpha r_{ou} I \qquad (1)$$

Where T_0 is the outdoor temperature in shade, α is the outside surface solar radiation absorbability and I is the solar radiation intensity.

The total thermal resistances, R_{t1} and R_{t2}, respectively means the total thermal resistance of the unventilated roof and ventilated roof, are shown as follows:

$$R_{t1} = r_{ou} + R_A + R_{air} + R_B + r_{in} \qquad (2)$$

$$\begin{aligned} R_{t2} &= R_{A1} + R_{B1} \\ &= R_A + r_{ou} + r_1 + R_B + r_{in} + r_2 \end{aligned} \qquad (3)$$

Where R_A and R_B are the thermal resistance of the upper and lower slab of the roof respectively, R_{air} is the thermal resistance of the ventilated air gap, r_{in} and r_{ou} are the inner and outer surface of the roof, r_1 and r_2 are thermal resistance of the upper and lower surface of the air gap. r_1, r_2 and Φ are defined in (Ciampi et al. 2003) as follows:

$$r_1 = r_A * \Gamma / \Phi,\ r_2 = r_B * \Gamma / \Phi,$$
$$\Phi = r_A + r_B + \Gamma \qquad (4)$$

Γ is the radiative thermal resistance between two slabs and it can be calculate as follows: $\Gamma = (1/\varepsilon_1 + 1/\varepsilon_2 - 1)/4\sigma \bar{T}^3$, where ε_1 and ε_2 are the emissivity of the gap's inner faces and respectively of the slabs A and B; σ is the Stefan-Boltzman constant and $\overline{T} = (T_1 + T_2)/2$ is the mean temperature of T_1 and T_2. T_1 and T_2 are the temperature of the air gap's inner faces, respectively of the slab A and slab B. r_A and r_B are convection resistance inside the air gap.

The mean heat flux coming into the room through the three different roofs is discussed as follows.

(1) Unventilated roof:

$$Q_1 = \frac{T_r - T_{in}}{R_{t1}} \tag{5}$$

(2) Ventilated roof:

The outlet air temperature of the air gap can be written as follows (Ciampi et al. 2003):

$$T_{ol} = T_m + (T_0 - T_m) * e^{-\upsilon} \tag{6}$$

Where T_{ol} is the air temperature at the outlet of the air gap, $T_m = zT_{in} + (1-z)T_r$ and $\mu = \dfrac{1}{CR_{t1}\left[H + z(1-z)\right]}$, $z = R_{A1}/R_{t1}$, $C = M * C_P/A$, z is a dimensionless parameter, M is the air mass flow rate, C_P is the air specific heat capacity rate, A is the roof area. H is the relative correction with the equation $H = r_A\, r_B/(\Phi * R_{t2})$. H is the radiative factor and it's due to the fact that the introduction of the surface thermal resistance heat transfer coefficients (instead of the convective ones) is not sufficient for quantifying entirely the radiative heat transfer inside the air gap (Ciampi et al. 2003).

So for the mean heat flux from the ventilated roof was calculated as follows (Ciampi et al. 2003):

$$Q_2 = \frac{T_r - T_{in}}{R_{t2}} - zC(T_{ol} - T_0) \tag{7}$$

Compared to Q_1 and Q_2, it is obvious that Q_2 is much less than Q_1 as it minus $zC(T_{ol}-T_0)$, which stands for the heat moved away by the air flowing through the air gap. For a natural ventilated roof, the air flow rate is determined by the following factors: air velocity outside, the inlet area of the air gap and the length of the extended roof top, the direction of the air velocity and the air gap, the length of the roof. The velocity used here is the mean outside air velocity in Changsha. It is known that when the direction of the outside air velocity is parallel to the air gap the air flow rate is maximal compared to other directions. In the paper the air gap and air velocity are assumed in the same direction. It is also proposed that the length and the breadth of the roof are fitted. The relation of the length of extended top and the thickness of the air gap to the air mass flow rate and air velocity in the air gap is simulated by CFD.

The energy saving between unventilated roof and ventilated roof is defined by (Ciampi et al. 2003) as follows:

$$S_1 = \frac{Q_1 - Q_2}{Q_1} \tag{8}$$

The energy saving between unventilated roof and ventilated roof with extended roof top:

$$S_2 = \frac{Q_1 - Q_a}{Q_1} \tag{9}$$

The energy saving between ventilated roof with and without extended top:

$$S_3 = \frac{Q_2 - Q_a}{Q_2} \tag{10}$$

Q_a is the mean heat flux coming into the room through ventilated roof whose extended top is a m long.

SIMULATION AND CALCULATION

If the height and breadth of the wall is more than ten times to its thickness, then it is supposed the heat conduction of the wall is one-dimension. It is obvious that the breadth and length of the roof model used here is long enough compared to its thickness. So there is a one-dimension heat flow through the roof, including the roof surface, the air gap, and the insulation and so on. All the values of the parameters used in above equations are from the norms and manuals of buildings in China and the weather parameters are chosen according to the weather in Changsha (The Design Manual for Heating and

Ventilation and The Design Norm for Envelope Thermal Characteristic in Civilian Building, in Chinese).

The model used in simulation is 10 meters long, 10 meters wide and 4 meters tall. It is reported that for an efficient ventilated roof, its length should be 10 meters long (Ciampi et al. 2003). And a space which is 8 times of the model was set up to get a quite accurate wind field. The thickness of the air gap is range from 0.15m to 0.30m, and the length of the extended top is range from 0.10m to 0.50m. In the simulation the air gap was considered to be a huge whole gap but not separated into numerous gaps as shown in figure 1.

FLUENT is the most widely used software for modelling engineering fluid flows due to its robustness, accuracy and user-friendliness. Air flow in the air gap would be turbulent. Therefore, the standard k– ε turbulence model (Launder BE, Spalding DB. 1974) was used to simulatethe effect of turbulence of air flow. The model for predicting air flow consisted of the conservation equations for mass, momentum, enthalpy, turbulent kinetic energy and its dissipation. A nonuniform computational grid was used for the prediction of two-dimensional flow in the air gap, with dense grid cells distributed in the air gap and near the walls of the building. Convergence of the numerical solution was considered to have been achieved when the sum of normalised residuals for each flow equation was less than 10^{-3}.

DISCUSSION AND RESULT ANALYSIS

The ventilated roof is well performed in summer days. But in Winter or other times when the outdoor solar temperature T_r is lower than the indoor temperature T_{in}, then the air gap should be shut, for the reason that in equation (5) when $T_r < T_{in}$, Q_1 will be a minus value which means heat flows from indoor to outdoor. At that time, the ventilated air gap will increase the cooling load so it should be shut. What’s more, good efforts should be made to prevent the air gap from water condense in rainy season as most of the winter days in Changsha are rainy days, or its thermal performance will be worse than the bare roof.

The energy saving between unventilated roof and ventilated roof gradually increases along with the increasing thickness of the air gap as shown in Fig.4. That’s because both the air velocity inside the air gap and the inlet area increases at the same time. When the roof was set with extended roof top, the energy saving increases fantastically, that is to say, S_2 is much larger than S_1 and this can be seem from Fig.4 too. It is obvious that the extended roof top is very useful in catching upflowing wind which flows close to the wall. However, S_2 hardly increases when a is longer than 0.2m as shown in Fig.5. Fig.5 shows the air velocity inside the air gap with different a value when the thickness of the air gap d=0.15m, 0.20m, 0.25m, 0.30m. The velocity v markedly increases at first, then keeps invariable when a is larger than 0.2m. For example, when d=0.15m, the velocity increases from 0.36m/s (a=0) to 1.26m/s (a=0.1m) and then to 1.30m/s (a=0.2m), but after that, when a keeps increasing, it almost keeps fixed. So it can be concluded that for all the ventilated roofs, the optimized length of the extended roof top is about 0.2m.

The velocity inside the air gap increases with d increases when a=0, but when a is longer than 0.1m, v changes little when d increases as shown in Fig.6, meanwhile, S_2 keeps rising all the time. That’s to say, when the roof was set with extended top, the area of the inlet has a larger influence on the airflow rate than v. From Fig.7, it can be seen that S_3 also increases according to the increasing d. It may because that with a larger d the extended top can catch more upflowing wind which flows close to the wall.

It is traditional to have extended roof tops both at the inlet side and outlet side just as shown in Fig.3. The results of the simulation showed the extended top at the outlet side is not necessary as it changes nothing of the air mass flow rate M inside the air gap as indicated in Fig.8. Fig.8 shows an example when d=0.2m.

Also notice that, referring to the building overall heat losses, the wider the roof area is, compared to the building envelope one, the more remarkable will be the energy saving achievable using ventilated structures: ventilated roofs seem to be, therefore, particularly convenient in moderate-height and wide-area buildings (Ciampi et al. 2005).

CONCLUSION

The analysis shows that the ventilated roof with extended top has an excellent function in reducing energy consuming. The results can be concluded as follows:

① To the ventilated roof, it is obvious that energy saving and air velocity inside air gap increases along with the increasing thickness of the air gap. When the roof is set up with an extended top, the air velocity changes little while the energy saving is still in rising as the thickness of the air gap increases.

② The air velocity inside air gap increases substantially when the roof top is extended, that means much more energy is saved when the ventilated roof is built with extended top. The simulation also indicates that a length of 0.2m for the extended top is enough.

③ The extended top at the outlet side is not necessary and the same extended roof top works better for thicker air gaps.

The model together with CFD can be also adapted in other areas where also needs a ventilated roof and it is useful for design of natural ventilated flat roof and the renovation of old buildings' roofs.

Results by simulation indicate that ventilated roof with extended top performed substantially better than ventilated roof without extended top. It saves so much energy as shown in the figures are all because it is operated in perfectly conditions. The affection of the outside air velocity direction and the length of the roof to the energy saving will be researched in future studies. A further field examination on the cooling performance of ventilated roof with extended top is needed before putting the results into practice.

NOMENCLATURE

a	length of the extended top (m)
A	roof area (m^2)
C_P	air specific heat capacity rate (JKg^{-1}K^{-1})
d	thickness of the air gap (m)
H	radiative factor
I	solar radiation intensity (Wm^{-2})
M	the air mass flow rate (Kgs^{-1})
r_{in}, r_{ou}	the inner and outer surface of the roof (m^{2}KW^{-1})
r_1, r_2	thermal resistance of the upper and lower surface of the air gap (m^{2}KW^{-1})
r_A, r_B	convection resistance inside the air gap
R_{t1}, R_{t2}	total thermal resistance of the unventilated roof and ventilated roof respectively (m^{2}KW^{-1})
R_A, R_B	thermal resistance of the upper and lower slab of the roof(m^{2}KW^{-1})
R_{air}	thermal resistance of the ventilated air gap(m^{2}KW^{-1})
S_1, S_2, S_3	energy saving between unventilated roof and ventilated roof, energy saving between unventilated roof and ventilated roof with extended roof top, energy saving between ventilated roof with and without extended top(%)
T_r	solar-air temperature (K)
T_0	outdoor temperature in shade (K)
T_{in}	indoor temperature (K)
T_m	mean temperature of T_{in} and T_r (K)
T_{ol}	outlet air temperature of the air gap (K)
T_1, T_2	temperature of air duct's inner faces, respectively of the slabs A and B (K)
$\bar{T} = (T_1 + T_2)/2$	mean temperature of T_1 and T_2 (K)
Q_a	mean heat flux coming into the room through ventilated roof whose extended top is a cm long (Wm^{-2})
Q_1, Q_2	mean heat flux coming into the room through Unventilated roof and Ventilated roof respectively (Wm^{-2})
v	outside air velocity(ms^{-1})
z	dimensionless parameter
σ	the Stefan-Boltzman constant(Wm^{-2}K^{-4})
α	the out surface solar radiation absorbability
ε_1, ε_2	emissivity of the gap's inner faces and respectively of the slabs A and B
μ	dimensionless quantity

Γ radiative thermal resistance between two slabs (m^2KW^{-1})

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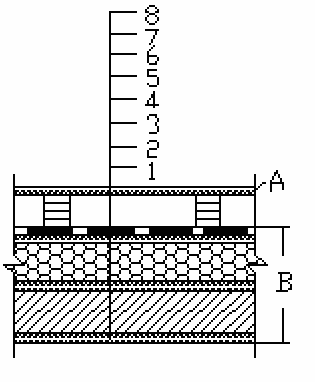

Fig.1 the configunation of basic ventilated roof in Changsha (1. reinforced concrete hollow slab with inside stucco 2. cement layer 3. vapor barrier 4. insulation material 5.cement layer 6. waterproof 7. air gap 8.concrete slab with its outside surface painted by white cement)

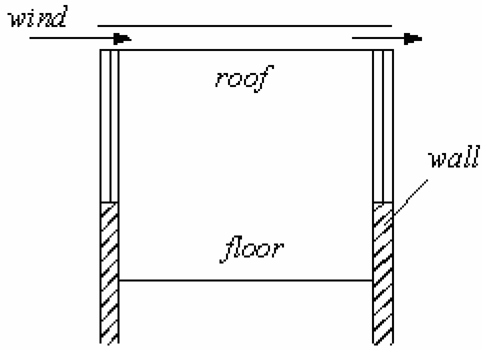

Fig.2 ventilated roof without extended top

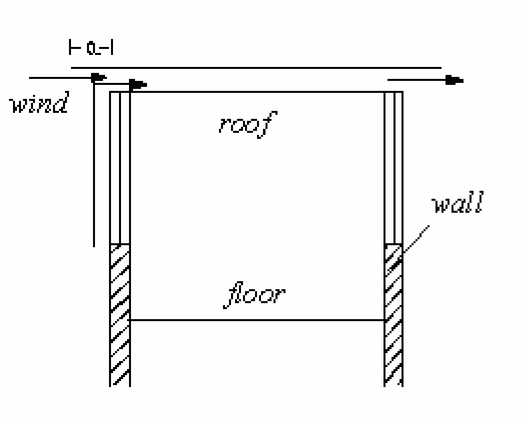

Fig.3 ventilated roof with extended top

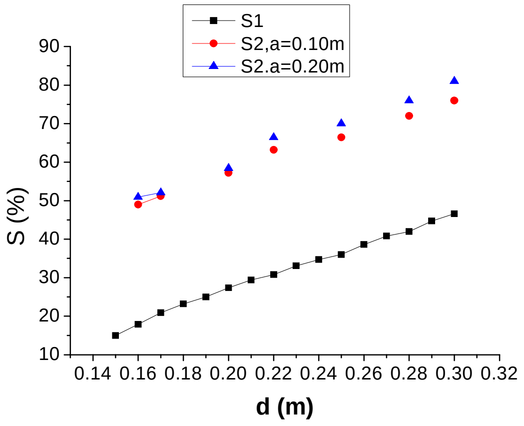

Fig.4 the energy saving of the ventilated roof

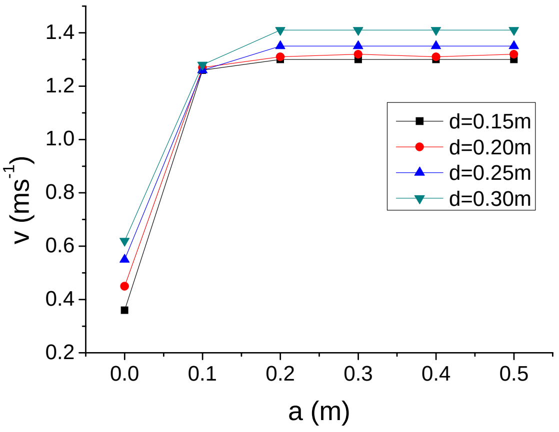

Fig.5 the air velocity inside the air gap

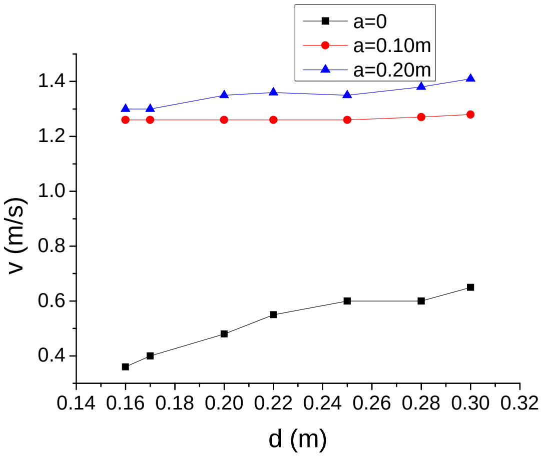

Fig.6 the air velocity inside the air gap

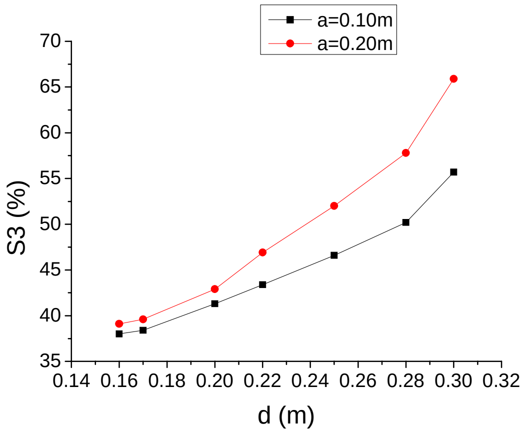

Fig.7 the energy saving between roofs with and without extended roof top

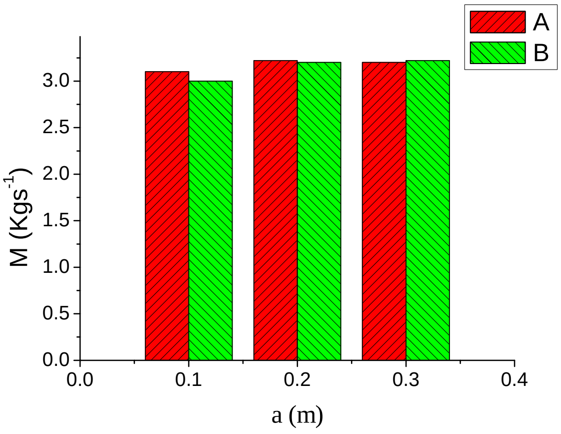

Fig.8 air mass rate when d=0.2m

A both outlet side and inlet side with extended tops

B only inlet side with extended top