Ventilated Cathedral Attics in Summer Conditions—Testing Method

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ABSTRACT

Latest building regulations – like the French document RT2005 elaborated by CSTB (Centre Scientifique et Technique du Bâtiment, Paris) - are asking to perform thermal comfort or cooling load calculations under summer climate conditions (for newly designed buildings). The methods indicated for both of these calculations require as an input parameter the solar factor (symbolized S) of building elements (both opaque and transparent). But for some of them, like ventilated cathedral roofs, the S assessment via testing must be done in large scale facilities, under artificial climate and is quite fastidious.

This paper describes a testing facility where such tests were conducted. It was developed by Saint-Gobain Isover with the assistance of CSTB (French Scientific and Technical Centre for Buildings). The testing procedure and calibration method are described. Then, the first testing results and solar factor values obtained are shown.

INTRODUCTION

The insulation performance of the building elements during summer season has become a more and more important issue since the last decades. Designing highly performing roofs, walls and windows helps to ensure better thermal comfort inside the buildings that are not air-conditioned or to consume less energy (electricity, gas) in the air-conditioned buildings.

The assessment of these indicators (thermal comfort and air-conditioning energy consumption) started to be included in building codes like RT2005 in France. It supposes:

- to realize a calculation for at least a room, or a building, and for conventional climate conditions;
- to perform a transient study for a given period (at least one day cycle);
- to include in the analysis other factors than the building elements (ventilation, building usage, air-conditioning system performances if present etc.)

The above mentioned indicators may be assessed via various calculations methods – see CEN ISO (2004a), CEN ISO (2004b), CSTB (2000). The method described in CEN ISO (2004a) is very precise, but difficult to use – some special software must be designed in order to do it.

The French building regulation (CSTB 2006) has adopted a simpler method (very close to the one showed in (CEN ISO 2004b)) that was implemented in various pieces of software – see www.cstb.fr. It should be applied to all new building designs.

The influence of the opaque building elements (walls, roofs etc.) is taken into account via 3 parameters: the *U*-coefficient; the solar factor, *S;* the daily heat capacity, *Cj*. The first and the last of them may be assessed by using standardized methods ((CEN ISO 1996), (CEN ISO 2005)).

A rough, but easy to understand definition of S is that it represents the average heat flow density transmitted through the insulation system to the indoor environment of the building element for each W/m^2 of solar radiation intensity that is incident to its outdoor surface.

The solar factor – *S* (named “solar energy transmittance” and symbolized “*g*” in (CEN ISO 2004b)) is easy to calculate

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for opaque building elements that do not include ventilated air spaces – in such cases a simple equation may be used:

$$S = \frac{\alpha_{ext} U}{h_{ext}} \tag{1}$$

where α_{ext} is the solar absorptance of the wall outdoor surface; U is the U-coefficient of the building element (in $W \cdot m^{-2} \cdot K^{-1}$) and h_{ext} is the convection coefficient from the wall outdoor surface to the air (in $W \cdot m^{-2} \cdot K^{-1}$).

For ventilated building elements (roofs, walls), that are very frequently encountered in practice, a more complicated equation is given both in (CEN ISO 2004b) and in (CSTB 2000). But it presents the problem that the mass air flow through all the ventilated air spaces must be known from the start. Also it is completely inappropriate for cases where natural convection is significant and is not able to take into account 2D and 3D phenomena. To conclude, the application of this equation leads to less accurate results in most cases.

The application of Equation 1 to a ventilated opaque building element leads to very important errors, as shown further, in paragraph "Comments". We definitely do not recommend the usage of this equation for these elements. This is because the ventilation air flow (and the corresponding heat flow removed from the tiles and the wind barrier, by this air flow) is completely ignored by the heat transfer model that was used to obtain Equation 1. Or, these parameters are considerably influencing the heat flow that goes through the building element (in present study, a roof system).

The sun induced heat flow density entering through the opaque part of a roof system is less important than the similar value entering through the windows—10 to 100 times lower, depending on windows g-value (the equivalent of the solar factor, but for windows) and on the S-value of the opaque part. But, it must be taken into account that, in an attic, the area of the opaque part is much higher than the area of the windows—typically, according to ratios close to previous ones (10 to 100 times higher, according to building practice in France). Therefore, the heat flow through the opaque part is as important as the heat flow through the transparent part and it is very important to assess it accurately, or to find ways to minimize it. It must also be taken into account that the influence of the heat flow gains through the opaque part of the roof becomes even more important when high-effective windows are used—as the trend is in building practice, today.

The topic of reducing the S-value of ventilated roofs is considered important in France, where a dedicated study is currently performed under ADEME (The French Agency for Environment and Energy Conservation) coordination (see Duforestel 2006). There are also manufacturers promoting on the market wind barriers and insulation products claiming high performances in this area, which were not checked experimentally. Unfortunately, there are no studies available, addressing precisely this topic, which explains the shortness of the reference list.

Previous study (Ciucasu 2006) describes a method to calculate more accurately the value of the solar factor for ventilated opaque building elements. It is based on computational fluid dynamics simulations that need first to be validated against experimental data.

A method is described in this paper based exclusively on testing results that allow to assess the solar factor for ventilated roofs without needing additional simulations. The experimental data is obtained in a facility situated in Rantigny, France. The S-values can be used in further thermal comfort calculations or in air-conditioning consumption calculations as those described in (CEN ISO 2004a), (CEN ISO 2004b), and (CSTB 2000).

It is underlined that this study deals only with the assessment of the solar factor for the ventilated roofs. The heat flow values that are shown in further paragraphs are valid only for steady state conditions generated under laboratory conditions. They do not represent the heat flow that would pass through the same roof when submitted to natural climate conditions, which are time-variable during a day time. This is because these heat flow values would also be influenced by the thermal inertia of the roof system—a factor that is not taken into account, by definition, in our steady state tests dedicated to the assessment of the S-value.

It is also underlined that we do not look for "an average response of the roof" to "an average sun radiation intensity in a day time", but want only to determine the solar factor.

THE TESTING FACILITY

The testing facility includes a roof module, a set of metal halide lamps and sensors. A photo of the testing module is shown in Figure 1. Its sizes are representative for a real roof: 4 m width and 4 m length along the slope—that is 45°.

The roof module is located in a hall having a big air volume and is currently covered with ceramic tiles. Different insulation products and systems may be installed on the wooden studs like in an actual cathedral attic.

A set of 42 metal halide lamps is installed on a mobile metallic support located in front of the roof module as shown in Figure 2. They are ranked on 6 horizontal lines, each includ-

Figure 1 *The roof module of the testing facility.*

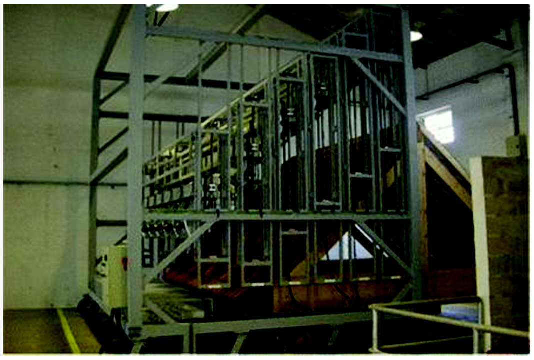

Figure 2 *The support with the lamps in front of the roof module.*

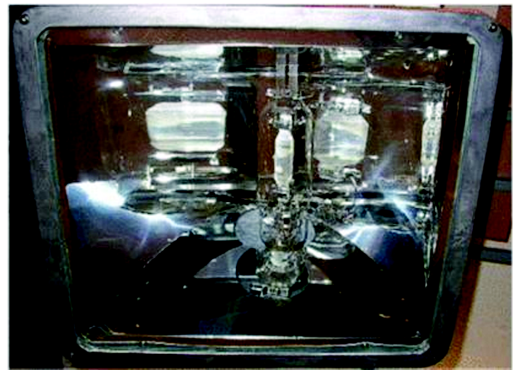

Figure 3 *A lamp installed in a projector.*

ing 7 lamps. One lamp has an electrical power of 1 kW and is installed inside an aluminum projector, as may be seen in Figure 3. The spectral distribution of the radiation emitted by a lamp is very similar to that of the sun – the color temperature is 6000 K.

The intensity of the radiation incident to the external face of the tiles installed on the roof module may be modified by varying the distance between the projectors and the roof, the height of each line of lamps and the number of lamps turned on. It was found that the value of the incident radiation (symbolized I_{sr}) may be tuned, in this way, in the range of 0 and 1000 W/m^2—this is representative to the solar radiation that may be recorded during the summer season.

A pyranometer was used to measure the radiation intensity on the surface of the tiles. It was calibrated by the manufacturer and gives the hemispheric radiation corresponding to the range of 0.285 to 2.5 µm.

Many heat flow meters are used to measure the heat flow density going through the insulation system to be tested. They are 1 mm thick, have a metering area of 0.305 x 0.305 m^2 and were calibrated in an accurate guarded hot plate apparatus for the temperature and heat flow density ranges where they are expected to be used. The mean value of the heat flow density passing through the insulation system is denoted q_i.

A large number of thermocouples would also be installed in different points of the roof, insulation system and, also in the air. The mean temperature of the air volume above the tiles is symbolized t_e and of the air volume beneath the insulation system is denoted t_i.

THE TESTING METHOD

The testing method to assess the S-value was developed by Saint-Gobain R&D (CRIR and SGR) and is currently under agreement of French institute CSTB (Scientific and Technical Centre for Buildings).

The method includes two steps:

- realizing a set of tests for the system analyzed (typical 4 to 6);
- processing the results obtained from simulations in order to calculate the *S*-value

One typical test consists of:

- subjecting the roof system to a level of I_{sr} and identical values of t_e and t_i;
- measuring the mean value of I_{sr} on the tiles surface;
- waiting for the steady-state conditions to occur;
- measuring the value of q_i

In this way, by using numerical values, we generate the following function:

$$q_i = func(I_{sr}) \tag{2}$$

In many cases this function would be found to be:

- quasi-linear in the range of I_{sr} from 100 to 1000 W/m^2;
- almost independent on t_e and t_i values, when they are in the range 25 to 35°C.

The slope of this variation is the solar factor S. If the solar factor varies with $t_e = t_i$, then a range of values of *S* will be specified and not a single one.

The analysis of function (2) is more complex if it is found to be far from a linear variation. In such cases it is not possible to calculate an *S*-value and the performance of the building element would be represented by Equation 2.

The mean value of I_{sr} is calculated from many local values (typical 150 to 200) measured by pyranometer on the surface of the tiles. The local values were measured on different locations uniformly distributed (at 0.2 m distance one to another) on the entire roof surface. The I_{sr} distribution was not even, the rate of maximum to minimum local values was typically equal to three. In order to assess the influence of this unevenness on the accuracy of testing results, a study based on CFD simulations will be carried on. The simulations will be performed for various roof configurations and typical testing conditions and will assess the q_i values (and, subsequently, the *S*-values) for even and uneven (actual) distributions of I_{sr}. These results will be processed in order to be taken into account in the uncertainty assessment. It was assumed that this unevenness did not affect significantly the accuracy of experimental results for the tested systems since some preliminary tests (see paragraph "Preliminary test for validation") showed reduced bias with respect to known R-values.

The mean value of q_i is calculated from many local values (typical 6 to 8) measured by heat flow meters and uniformly applied to the measuring surface of the roof. This measuring surface is considered in the middle (1 m away from the central axis, on both sides) of the half of the roof exposed to the lamps' radiation. This enables us to reduce the error induced by lateral heat losses through the edges of the insulation system. In Figure 4 is shown a case where 8 heat flow meters are installed on the internal surface of the plasterboard surrounding an insulation system.

The thermocouples would allow one to assess the following mean surface temperatures: on the tiles, on the internal surface of the system, on different depths inside the insulation system. They will also be used to measure the mean air volume temperatures t_e and t_i above the tiles and beneath the roof.

The steady state conditions are considered to be achieved when all the above-mentioned mean temperatures are not changing more than 1°C, and the q_i value does not change of more than 7%, for at least a 3-hour period.

These criteria were arbitrarily chosen and they will be included in the uncertainty analysis of the testing result.

PRELIMINARY TEST FOR VALIDATION

A preliminary test was conducted in order to have a first validation of the method. It was realized for a very simple unventilated insulation system, consisting in a layer of glass wool having a known R-value, previously determined by testing in a heat flow meter apparatus (according to (CEN, EN 12667) and (ISO 8301)). The tiles were removed, in order to eliminate the air space between them and the insulation product.

Mean surface temperatures were measured on both sides of the product as was the mean heat flow density through it. The aim was to check if the R-value obtained by using these experimental values was close enough to the value already known. This was done for 2 levels of radiation intensity.

During the steady-state regimes, the bias between the experimental and known R-values was less than 4%.

TESTS TO ASSESS SOLAR FACTOR

Two series of tests were conducted in order to asses the solar factor values for ventilated roof insulation systems.

First Series of Tests

This series was conducted on a ventilated cathedral roof system including, from indoor side to outdoor: a gypsum plasterboard; a glass wool layer under the rafters ($\rho = 11$ kg/m^3, λ at 10°C = 0.040 W/m·K; thickness 200 mm); an unventilated air space between rafters; a wind barrier highly permeable to water vapor installed on the rafters; an assembly of battens and

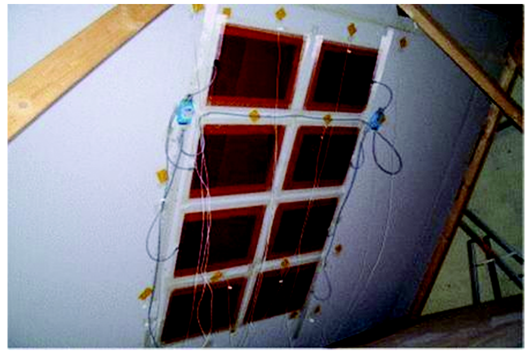

Figure 4 *Heat flow meters installed on the internal surface of an insulation system.*

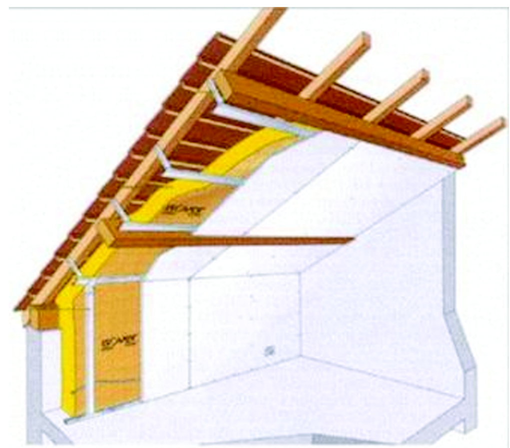

Figure 5 *Roof insulation system tested in the first series.*

counter-battens creating a ventilated air space between the wind barrier and the tiles and the ceramic roofing tiles.

The system is depicted in Figure 5 and the main dimensions are shown in Figure 6.

Many thermocouples (16 at each level) were installed in the central measurement area: on the gypsum plaster board, on the glass wool and on the tiles. Other thermocouples were used to record the air temperatures.

The testing method described in the previous section was then applied.

Five similar tests were performed for 5 values of the distance between the projectors and the tile surface: 0.6; 0.9; 1.2; 1.5 and 1.75 m. The duration of one test was between 12 and 60 hours.

The data process had two aims:

- checking the test accuracy by calculating from experimental data the R-value of the glass wool layer and comparing it to its known value;
- checking the linearity of the variation q_i = func (I_{sr}) and calculating the solar factor S.

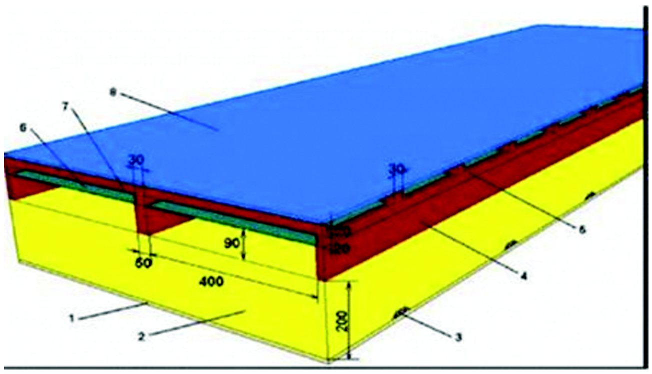

Figure 6 *Scheme and main dimensions of the roof insulation system tested in the first series. Legend: 1—gypsum plasterboard; 2—glass wool; 3—steel profile; 4—wooden rafter; 5—wooden counter-batten; 6—wind barrier; 7—wooden batten; 8—ceramic tiles.*

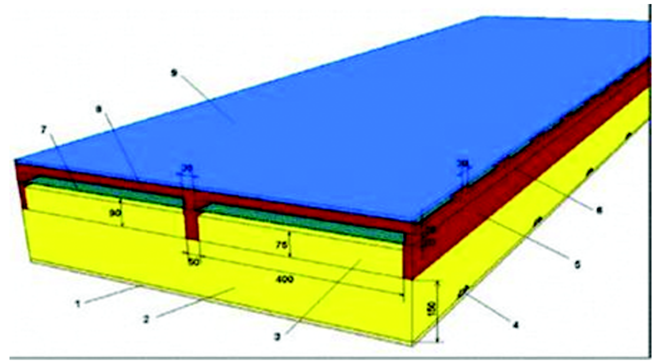

Figure 8 *Scheme and main dimensions of the roof insulation system tested in the second series. Legend: 1—gypsum plasterboard; 2—glass wool (first layer); 3—glass wool (second layer); 4—steel profile; 5—wooden rafter; 6—wooden counter-batten; 7—wind barrier; 8—wooden batten; 9—ceramic tiles.*

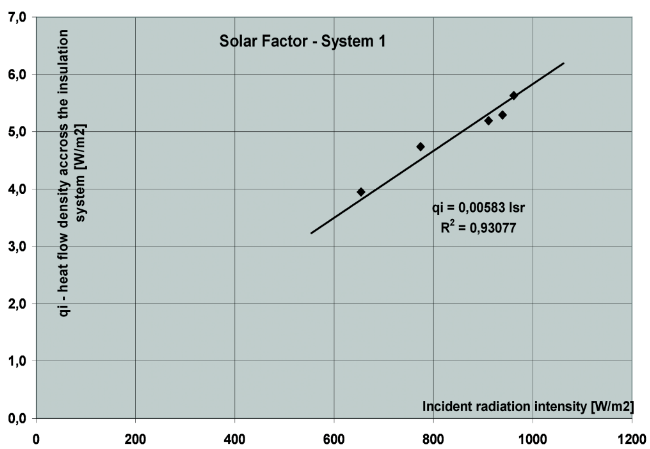

Figure 7 *Variation of* q_i *against* I_{sr} *for the first series of tests.*

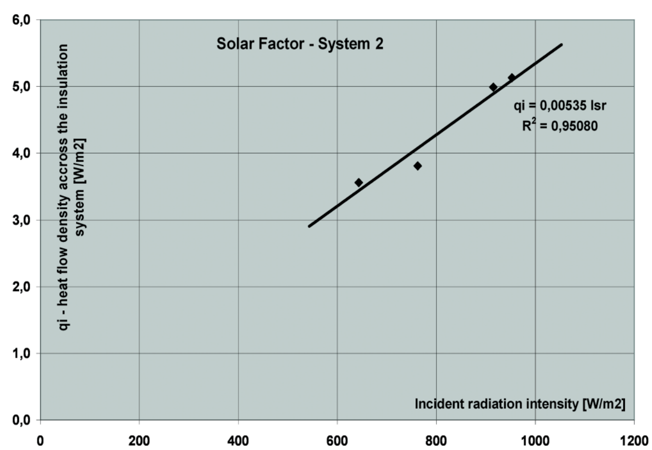

Figure 9 *Variation of* q_i *against* I_{sr} *for the second series of tests.*

During the steady-state regime, the R-value of the glass wool layer, assessed from experimental data, showed a bias of less than 2.9% from the known value.

Figure 7 shows the variation of q_i against I_{sr} for the 5 tests.

It may be seen that the spread of the individual points around the regression line passing through the axis origin is very low – the correlation coefficient R^2 is 0.966. Therefore the calculation of S as the slope of this variation is physically meaningful—a value of 0.0058, or 0.58% is found.

Second Series of Tests

The tests were conducted on a ventilated cathedral roof system including, from indoor side to outdoor: a gypsum plasterboard; a first glass wool layer under the rafters (ρ = 14.7 kg/m^3, λ at 10°C = 0.0354 W/m·K; thickness 150 mm); a second glass wool layer between the rafters (ρ = 16.4 kg/m^3, λ at 10°C = 0.0347 W/m·K; thickness 75 mm); a wind barrier highly permeable to water vapor installed on the rafters; an assembly of battens and counter-battens creating a ventilated air space between the wind barrier and the tiles and the ceramic roofing tiles.

The main dimensions are shown in Figure 8. The testing method described in previous paragraph was then applied. 4 similar tests were performed for 4 values of the distance between the projectors and the tiles surface: 0.6; 0.9; 1.2; and 1.8 m.

Figure 9 shows the variation of q_i against I_{sr} for all the testing points.

It may be seen that the spread of the individual points around the regression line passing through the axis origin is very low – the correlation coefficient R^2 is 0.951. Therefore the calculation of S as the slope of this variation is physically meaningful—a value of 0.0054, or 0.54% was found.

Comments

It may be seen that the solar factor values are very close for the two roof systems: 0.0058 and 0.0054. They are very small compared to the usual solar factor values for windows, for unventilated or bad insulated walls. At the same time the French building code RT2005 indicates a default value for all types of walls of 0.02, that is more than 3 times higher than these measured values. Therefore, it is unrealistic to use such a value for these roof insulation systems having a high R-value.

This statement is endorsed by the fact that the real summer conditions are less severe than the testing conditions and will normally lead to even lower S-values than those issued from tests. This is because the outdoor air speed near the tiles for real roofs is higher than the values recorded during tests (inferior to 0.5 m/s, as was measured by hot wire anemometer) – this leads to an increased amount of heat lost by convection, therefore to smaller values of q_i and S.

Another consequence is that the air flow in the ventilated space under the tiles should be higher in real conditions than during tests, which also shows that the S-value would be lower under these circumstances.

It is also underlined that the thickness of this air space for the tested systems was as low as admitted by the French building regulations (20 mm). In real life, this thickness is higher, which leads to smaller hydraulic resistance in the path of the air flow under the tiles, thus to higher air flow rates. The amount of heat removed by the air from the tiles would be higher and the solar factor smaller.

There is no practical way to perform tests under real climatic conditions in order to validate the solar factor values. The main reason is that such tests must be carried on under stable state conditions, which can not be ensured under real climate – the sun may not be stopped in the same position and the weather conditions can not be kept constant.

For the analyzed systems, the ventilation is an important factor. If ventilation is neglected, then the Equation 1 could be used to compute the S-value.

For the system tested in the first series: α_{ext} is the solar absorptance of tiles outdoor face, which was measured in spectrometer and has the value of 0.68; U coefficient of the roof was computed and found equal to 0.21 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

The coefficient h_{ext} may be computed by using following equation:

$$h_{ext} = h_{rad} + h_{conv} \tag{3}$$

where

h_{rad} = surface heat transfer coefficient taking into account the long wave radiation exchanges between tiles surface and the environment of the testing room

h_{conv} = surface heat transfer coefficient taking into account the convection between tiles surface and the air

All coefficients mentioned in the above paragraph are expressed in $W{\cdot}m^{-2}{\cdot}K^{-1}$.

According to (CSTB 1962) the coefficient h_{rad} may be computed by the following equation:

$$h_{rad} = 1.8 \cdot 10^{-7}\left(\frac{T_{air} + T_{tiles}}{2}\right)^3 \tag{4}$$

where T_{air} and T_{tiles} are the absolute temperatures (in K) of the air and respectively, of the tiles. The maximum value of t_{tiles} recorded during the tests was 80°C and the air temperature was about 20°C. These lead to h_{rad} of maximum 6.1 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

The convection heat transfer coefficient may be calculated by adding the natural and forced convection effects:

$$h_{conv} = h_{conv,nat} + h_{conv,for} \tag{5}$$

The natural convection heat transfer coefficient can be calculated (Ozisik 1985) by using the following equation:

$$\mathrm{Nu} = 0.145\mathrm{Pr}^{1/3}(\mathrm{Gr}_L^{1/3} - \mathrm{Gr}_c^{1/3})(\cos(\psi))^{1/3} + (\mathrm{Gr}_c\mathrm{Pr}\cos(\psi))^{1/4} \tag{6}$$

where:

Nu = Nusselt number

Pr = Prandtl number for the air, at the average temperature between the tiles and the bulk air

Gr_L = Grasshoff number, in which the characteristic length is the roof module height

Gr_c = critical Grasshoff number, assessed function of the roof slope

Ψ = slope of the roof module (ψ = 45°)

Equation 6 is valid for ascending heat flows from a sloped surface to a fluid. Applying it for the same values of t_{tiles} and t_{air} as those used previously for h_{rad} calculation let us obtain a maximum $h_{conv,\,nat}$ value of 5.8 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

The forced convection heat transfer coefficient can be assessed (CSTB 1962) by using the following equation:

$$h_{conv,for} = 3.5w_{air} \tag{7}$$

where w_{air} is the average air speed near the tiles, in m/s. This speed was measured during the tests with hot wire anemometer and found about 0.5 m/s. This gives a $h_{conv,\,for}$ value of 1.8 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

Going back to Equation 5 it may be seen that a maximum value of 7.6 $W{\cdot}m^{-2}{\cdot}K^{-1}$ was achieved for h_{conv} coefficient during the tests. If this value is input in Equation 3, it shows that a maximum value of 13.7 $W{\cdot}m^{-2}{\cdot}K^{-1}$ was obtained in the tests. This is consistent to the conventional value (13.5 $W{\cdot}m^{-2}{\cdot}K^{-1}$) indicated in standards (CEN, ISO 2004b) and (CSTB 2006) for actual outdoor conditions.

When these values are input in Equation 2, an S-value of 0.010 or 1.0% is obtained. This value is 80% higher than the solar factor obtained from testing, for the same system (0.0058, or 0.58%, see paragraph “First series of tests”). Our interpretation is that a major part of the difference between these two values is due to the effect of ventilation in the air space under the tiles. This 80% difference is underestimated, because for some testing conditions t_{tiles} was about 40 °C, and for this value h_{ext} is about 11 $W \cdot m^{-2} \cdot K^{-1}$, which leads to an S-value of 1.0% and a bias of 100%.

CONCLUSIONS AND FURTHER WORK

A method to assess the solar factor value for ventilated roofs was developed in the R&D Center of Saint-Gobain Isover. It is based exclusively on experimental data. The facility and the testing method were submitted to the analysis and validation of French Scientific and Technical Center for Buildings (CSTB).

A preliminary series of tests showed that the main measured parameter – the mean heat flow density going across the tested insulation system - may be determined with less than 4% bias, for a roof system having a known R-value (see paragraph “Preliminary test for validation”). In the future, a study based on CFD simulations would be performed in order to assess the error due to the limited area on which the heat flow meters meter the heat flow going through the roof. Should this error be found too high, the area metered by the heat flow meters will be increased.

Subsequent series of tests determined the solar factor for two roof systems. They are situated in the range 0.0050 to 0.0060, which is much less than the value indicated by default in the French building regulation (RT 2005).

Some additional work will be carried on in order:

- to assess the uncertainty of the S-values issued from the testing facility;
- to find the influence of factors like the thermal resistance, solar absorptance of the tiles, internal ventilation and wind barrier emissivity on the S-value of the roof insulation system.

This last point would be performed as a sensitivity study based on CFD simulations. These simulations should first be validated (for the most significant cases of each category) against experimental data issued from the facility described in this paper.

It would also be interesting to evaluate the impact of the roof S-value on the thermal comfort or on the cooling load of different buildings located in different climate areas. These studies should additionally take into account the thermal inertia of the entire building and should be customized to each particular building in which the analyzed roof system may be installed and to various sets of climate conditions.

REFERENCES

CEN, EN 12667:1996, Building materials - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance.

CEN, ISO 1996. EN ISO 6946 - Building components and building elements — Thermal resistance and thermal transmittance — Calculation method.

CEN, ISO 2004a. prEN ISO 13791 – Final draft. Thermal Performance of Buildings – Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling – General criteria and validation procedures.

CEN, ISO 2004b. prEN ISO 13792 – Final draft. Thermal Performance of Buildings – Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling – Simplified Methods.

CEN, ISO 2005. EN ISO 13786 – Thermal performance of building components – Dynamic thermal characteristics – Calculation methods.

Ciucasu, C., Gilles, J., Ober, D., Petrie, T., - Solar factor for ventilated roofs, Research in Buiding Physics and Building Engineering, Proceedings of 3rd International Building Physics Conference, Montreal, 2006, pp. 479-487.

CSTB (Centre Scietifique et Technique du Batiment) – Cahiers du CSTB, 1962, no. 58, cahier 467, pp. 5-6.

CSTB, 2006. Règles Th-E, Réglementation Thermique 2005.

Duforestel, T, De Cacqueray, D., Peniguel, C., Ciucasu, C., Rieunier, J. B., Pompeo, C., Kherrouf, S., Confort d’été des locaux sous toiture, IBPSA Seminary, France, 2006.

ISO 8301:1991, Thermal insulation – Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus.

Medina, M. On the performance of radiant barriers in combination with different attic insulation levels, Energy and buildings 33 (2000), pp. 31-40.

Ozisik, N., – Heat Transfer. A basic approach, Mc Graw Hill, 1985.

Petrie, T.W., Wilkes, K.E., Childs, P.W., Christian, J.E., - Effects of radiant barriers and attic ventilation on residential attics and attic duct systems, Internal Report, Oak Ridge National Laboratory, 1998.