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A methodology for experimental evaluations of low-e barriers thermal properties: Field tests and comparison with theoretical models

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1. Introduction

Thermal insulation properties of low emittance surfaces have been known for a long time: it was one hundred years ago that Sir James Edwards used low-e materials to minimize heat loss from his vacuum flask. Despite the maturity of the technique, the issue of performance evaluation still remains open, especially when these materials find their application in building envelopes, where the cooling load calculations necessitate the investigation of dynamic behavior with the same accuracy dedicated to steady-state conditions.

With the aim of reducing the solar irradiation that enters inside buildings, coatings or paintings are often used to cover the exterior side of walls (roofs in most cases), imposing high reflection coefficients on wavelengths where the solar spectral emission is maximum (from 0.3 to 2.5 μm) [1,2].

Once the heat has entered the structure, the decrease of radiative fraction could be obtained only by interposing an air gap with at least one face made of a low-e material (radiant barrier): in this case, the reflection properties have to be optimized in an upper range of wavelengths (from 4.0 to 35.0 μm, since the temperature of each irradiating surface stands around 300 K); at the same time, to fulfill fire safety protection requirements, high reflection coefficients are needed in the 1.0–10.0 μm range [3]. The combination of inner low-e surfaces and air gaps allows a bidirectional insulation, effective in vertical walls as well as in horizontal structures, and during both heating and cooling seasons, even if it must be remembered that in cold climates the radiant barrier also stops winter solar heat gains [4]. The barrier also constitutes a vapor retarder, since the low-e material is often made of aluminum foil, with very low permeability [5].

The performance of radiant barriers is linked to the presence of an air space, therefore, the definition of the system thermal behavior is case sensitive, depending on the thermal field, the spectral properties of all surfaces and the gap thickness and orientation, since natural (or forced) convection could take place [6].

Different methods are proposed to give an intrinsic characterization of radiant barriers, but a specific International Standard is still lacking, testifying to the difficulty of giving a simple and shared approach.

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An outdoor experimental apparatus (a structure) was built combining in situ environmental conditions with common laboratory setups; the purpose is that of evaluating the “in situ” thermophysical properties (stationary and dynamic) of the radiant barrier-air gap system alone in vertical walls. Measurements were done in central Italy, during the summer, on the hottest days of July and August, thus exposing surfaces to strongly variable outdoor conditions.

Results constitute a possible frame of a Standard Protocol for the evaluation of low-e materials thermophysical properties, as well as a basis for the comparison with theoretical models now available.

A Computational Fluid Dynamics analysis completes the investigation, giving a stronger validation to the results obtained.

2. Review of methods proposed for the evaluation of the thermal properties of low-e materials

The majority of plane radiant barriers are made of a lightweight insulating material core (whose characteristics depend on the manufacturer’s choice) and one or both sides covered with a low emittance outer layer.

2.1. Static properties

The first step in the definition of low-e thermal insulator properties consists of defining the thermal conductivity of the panel alone, leaving for further evaluations the effect of low emission surfaces placed on vertical walls. The different layers joined together make up the panel often consist of incompact shapes such as bubbles or foams; therefore, it is necessary to consider and measure an equivalent thermal conductivity, rather than evaluating the thermal resistance starting from intrinsic properties of each layer. The guarded hot plate and heat flow meter methods [7] accomplish this task, positioning the hot and cold plates in direct contact with the survey; it has to be taken into account that with multi-foil solutions, the external surface is not flat, therefore, it is possible that further thermal resistances are introduced, where air pockets form between the product surface and the hot or cold plates [8]. The same considerations must be applied to the specific heat of the panel alone, but the light weight of the materials suggests that a rough method such as the weighted average (by mass) of all specific heats will not give considerable errors in the wall’s overall performance. A sensitivity analysis was developed to support this assumption, showing that an error of ±50% on the evaluation of the panel specific heat, leads to a variation lower than 1% for all the thermophysical properties of the entire wall.

2.1.1. Theoretical approach

Once the apparent thermal conductivity of the panel is known, the effect of the low-e surface has to be estimated, coupling the barrier with an air space. The International Standard ISO 6946 [9] defines a theoretical path to evaluate the thermal resistance of unventilated air gaps:

\[ R_\text{g} = \frac{1}{h_a + h_r} \]

where \( h_a \) is the conduction/convection coefficient; \( h_r \) is the radiation coefficient.

The conduction/convection coefficient for closed vertical cavities is calculated in a simplified manner: \( h_a \) is the maximum between 1.250 W/m²K and the quantity 0.025/d, where d is the air space depth. It is demonstrated that the optimal thermal resistance is obtained with a gap thickness of about 0.020 m: wider gaps enhance the overall wall size without reducing the heat exchange. A more detailed calculation for heat transfer in closed vertical cavities is suggested by another Standard [10] where \( h_a \) is evaluated as a function of the Rayleigh number, which contains the air thermophysical properties (density, dynamic viscosity, thermal conductivity, thermal expansion coefficient and specific heat at constant pressure) and the temperature difference between vertical faces. Using this method, the resulting optimal depth becomes dependent on boundary conditions: the higher the temperature difference between the faces, the lower the air space depth that minimizes the heat transfer. As for the radiation coefficient, since in building applications the horizontal dimension of the air volume is limited (a few centimeters) compared to the width and the length of the wall (meters), the view factor between...
the vertical faces could be considered equal to 1; therefore, \( h_c \) could be written as follows [9,10]:

\[
h_c = \frac{1}{1 + \frac{1}{E_1} + \frac{1}{E_2} - 1} \cdot 4\sigma\theta_m^2
\]

(2)

where \( E_1 \) and \( E_2 \) stand for the hemispherical emissivities of the surfaces bounding the air gap, \( \sigma \) is the Stefan–Boltzmann constant and \( \theta_m \) is the average thermodynamic temperature of the surfaces participating in radiation heat exchange. The weakness of this method lies in the difficulty of defining accurately the spectral properties of the materials: few laboratories are involved in making these kind of measurements and emissivity measurements have to be made with particular attention since small errors have a strong effect on final results [6]. In fact, typical emissivities for building materials such as brick or concrete normally range from 0.70 to 0.95 [11], while from the low-e material side, values below 0.10 are expected: in a gap with one face of brick and the other of aluminum, an error of 0.03 on the brick thermal emissivity (0.87 instead of 0.90) leads to a total thermal resistance variation lower than 0.1%; on the other hand, considering a thermal emissivity of 0.09 instead of 0.06 for the low-e material brings about a variation close to 10%.

Once the radiation contribution is determined, it is possible to compare the two Standards for the evaluation of the overall thermal resistance \( R_g \); setting the gap depth at 0.020 m, it follows that:

- differences increase with wall temperature differences; ISO 15099 hypothesizes that the natural convection increases with boundary temperature differences, while ISO 6946 leaves the value unchanged;
- when the emissivity of the low-e surface rises, differences are less evident since the radiation contribution, which gives the same result for the two Standards, becomes more significant;
- both Standards show a reduction of \( R_g \) with the increase of the average thermodynamic temperature, but the variation of ISO 15099 is more accentuated, since \( \theta_m \) appears also in the coefficient \( h_a \).

In any event, considering a 0.06 emissivity for the low-e surface, if the temperature differences do not exceed 5 K and \( \theta_m \) variation is limited to the 273–313 K range, the two methods produce differences less than 6% in the evaluation of \( R_g \). Therefore, the more simplified modeling of ISO 6946 could be used, provided that a check is done on the thermal field with the aim of verifying that the above-mentioned conditions are followed.

2.1.2. Guarded hot plate and heat flow meter method

The thermal resistance of the whole system (air gap + panel) could be also measured using the guarded hot plate and heat flow meter method, and placing an air gap of the desired thickness between the plate and the survey. These results must be interpreted with particular attention: firstly, the emissivity of the plate must be known, since if it were similar to that of the low-e surface (aluminum plates), the thermal resistance assessed would be different from its real application, where building materials have higher emissivity values. Moreover, the usual dimensions of the test plates in the vertical direction are too low (around 0.300 m) to reproduce the air motions that could occur in real applications, therefore, the convective heat transfer inside the gap is practically negligible.

2.1.3. Hot box methods

An improvement of experimental techniques for the evaluation of \( R_g \) consists of the use of a hot box apparatus, where a large wall could be tested. Two methods are available: the calibrated hot box and the guarded hot box [12]; the low-e material has to be connected to another panel with an air gap of the desired thickness between the two walls, becoming a part of the surface separation between a cold and a hot chamber. The main advantages of these methods are the bypassing of the necessity of measuring the emissivity of the low-e surface and the possibility of taking convection into account, at least in steady-state conditions if the box is large enough to host a full height specimen [13].

2.2. Dynamic properties

If the analysis of low-e materials has to be extended to dynamic conditions, both the theoretical model and experimental methods could be used. Hypothesizing parallel and homogeneous layers, if the boundary conditions are represented as periodic functions, harmonic methods such as the one described in ISO 13786 [14] could be adopted, or response factor methods and conduction transfer functions, which make it possible to overcome the hypothesis of boundary conditions being periodic and linear [15]. The analysis could be also developed through a Computational Fluid Dynamics code, extending the investigation to two or three dimensions and to any boundary conditions, at the same time taking into account the convective and radiative heat transfer.

2.2.1. Twin structures for “in situ” measurements

An alternative to investigating experimentally the dynamic behavior of insulating materials is represented by the building of a small construction exposed to the outdoor environment, with the aim of taking into account the real conditions affecting the envelope. If a comparative analysis is desired, one way to carry out these investigations consists of the building of two identical structures, positioned close each other, so as to be exposed to the same outdoor conditions [16]. One or more walls of the small buildings could be equipped with the low-e material and the other with a reference insulation; a comparison between the two solutions is obtained from the energy values necessary to maintain the same thermal conditions inside the two structures. The effectiveness of this method is linked to the effective equivalence of the two structures, in terms of materials, geometry, exposition, air leakages and measurement chains; therefore, particular care has to be taken in ascribing the different results obtained by parallel measurements to real differences in materials performance.

2.2.2. Single construction with movable wall

In order to get by these problems, a single construction was built, with one movable wall where the low-e panel is inserted, and with all the other surfaces of the envelope strongly insulated (see next section). The wall is instrumented with heat flow meters and thermocouples and it is tested with and without the panel, thus assessing a differential evaluation of its performance in dynamic conditions with real outdoor driving forces, and leaving the possibility of evaluating the stationary properties thanks to the method described in ISO 9869 [17]. Other methods are available for assessing the steady-state thermal resistance of walls through in situ measurements [18], but, even if the procedure proposed by ISO 9869 implies the use of a complex algorithm, this shared and standardized approach was preferred in the present research.

3. Experimental setup

The need to evaluate thermal properties of a building wall made with two different configurations guides the setup of the experimental apparatus.
ISO 9869 imposes the establishing of a high temperature gradient between the interior and exterior environment; therefore, a closed room was built, with high insulation, except for the test wall. The temperature inside the room is kept constant by an electrical heat pump.

The structure has the shape of a parallelepiped, with four vertical walls, a flat roof and an asphalt floor in direct contact with the ground (Fig. 1).

The test wall was built with two different stratigraphies (Fig. 2); the first has two parallel vertical layers of hollow bricks (0.120 m thick) plus 0.010 m of lime and sand plaster, separated by an air gap of 0.050 m, for a total thickness of 0.310 m. The second differs from the first only by the insertion of a low-e panel in the middle of the air gap, leaving the rest of the wall unchanged (not rebuilt), to maintain the same characteristics.

The exterior layer of hollow bricks and plaster was installed in a steel frame with shackles; thus it is possible to hook and translate the test wall with the help of a mechanic lifter. The structural continuity is assured by bolting and a polyurethane foam insulates the contact surface between the extractable layer and the rest of the construction.

This protocol allows the thermophysical properties definition of the structure alone, so that, when the low-e panel is installed, it is easy to extract the performance of the sole package panel-air gaps, reducing the errors due to the interference of the rest of the stratigraphy.

The tested low-e material consists of two layers of bubble polyethylene and two layers of low-emissivity aluminum film, continuously thermowelded to have two faces made of low-e material. This material is installed with expanded polyethylene bi-adhesive strips; the thickness of the strips is about 0.021 mm, with the aim of creating an assembly made of two air gaps of 0.021 m each, divided by the low-e panel (0.008 m thick).

ISO 9869 requires the use of at least one heat flow meter and a temperature sensor for each side of the wall; the tested wall was equipped with two heat flow meters and 9 thermocouples on the inner side and 9 thermocouples on the outer side, all distributed over a central square 0.500 m wide.

It was verified that the inner surface emissivity and the heat flow meter emissivity were similar, while the colour of surface temperature sensors has to be close to that of respective substrates only on the outside, since the interior is kept dark.

The orthogonal heat flow is not uniform along the wall, showing different behavior in the upper and lower part because of the typical thermal-fluid dynamic field of natural convection in a closed cavity.

In these zones, in fact, the mass transfer is parallel to the direction of the main temperature gradient; on the contrary, in the central part the air flow is vertical, therefore orthogonal to the direction of the main heat flow (horizontal) [13]. These considerations suggest that the positioning of the heat flow meters in the centre of the wall gives only an estimation of a local heat exchange, and this value is much closer to the average heat transfer of the entire wall the higher is the ratio between the horizontal thickness and the vertical height ratio $L_h/L_v$ (cavity aspect ratio). The CFD analysis will allow an assessment of the difference between these values.

4. Measurement results: steady-state properties

The ISO 9869 Standard imposes a measurement time of at least 72 hours to obtain the wall resistance in steady-state conditions; in
The present campaign this requirement was fulfilled and the recording interval was set to 10 minutes. Firstly, the thermophysical performance of the wall with the empty gap was defined; afterwards, the same procedure was executed for the wall with low-e material. With the comparative analysis of the two sets of measurements, it is possible to isolate the contribution of the low-e panel.

The Standard proposes two different methods for the analysis of the data: the average method (corrected) and the dynamic method. The former evaluates the wall thermal conductance from the specific heat flux, the temperatures and the storage effect that depends on the specific heat, density and thickness of each layer; the latter uses numerical regression techniques and gives more accurate results when the temperature and heat flow rate variations are significant. Both methods were used in the measurement campaigns.

The average method requires the evaluation of thermophysical properties of the different layers, and an iteration procedure has to be implemented until the hypothesized conductance and the evaluated one fulfill a series of matching requirements.

Characteristics of the wall without the low-e panel were calculated hypothesizing a gap thermal resistance of 0.164 m²K/W, according to ISO 6946; thermophysical properties of plaster were obtained from [19] (lime and sand plaster), and, regarding the bricks, the manufacturer declared only the apparent density. The apparent thermal conductivity of the bricks as well as the apparent specific heat were considered as variables, resolving at the same time the steady-state evaluations and the dynamic analysis. Bricks could not in fact be considered horizontally symmetric; therefore, even if the characteristics of the single components were known (thermal conductivity and specific heat of clay and air), it is not possible to define in a simplified manner either the equivalent thermal conductivity (which necessitates at least a bi-dimensional numeric analysis [20]) or the equivalent specific heat. In fact, if the latter were calculated as a simple weighted average (by mass) of all specific heats it would not be useful in applications concerning the dynamic thermal behavior, since the geometric distribution plays an important role on the final result [21].

The definition of properties of the wall with the empty gap was done through the results of ISO 9869 (where the most influent parameters are constituted by thermal conductivities) and the theoretical dynamic analysis described in section 5, where the specific heat instead plays an important role.

Table 1 sums up the results obtained by the dynamic method; the corrected average method produces values differing by less than 1%.

The overall wall thermal resistance uncertainty (and as a consequence, the uncertainty regarding the bricks thermal resistance value), evaluated according to the procedure of Annex B of ISO 9869, is estimated to be within ±10%, providing a level of confidence of 95%.

The manufacturer supplied the composition of the low-e panel, giving the possibility of defining the specific heat; furthermore, the apparent density is available, as well as the results of the thermal resistance certification for the panel alone (0.244 W/m²K), obtained for a small survey with the hot plate and heat flow meter method.

It is therefore possible to define the properties of the entire wall starting from the experimental data as described by ISO 9869, since the only unknown quantity is the thermal resistance of the two gaps. The results of the wall with the low-e panel are given in Table 2; also in this case, the difference between the average corrected method and the dynamic method is less than 1%.

The thermal resistance of the entire package constituted by the low-e panel and the two air gaps could be calculated from Table 2; this value had been obtained with other methods, described as follows.

The low-e panel manufacturer has a certificate that gives the total emittance (0.06 ± 0.03) measured by a Fourier transform infrared spectrometer in the range 1.4 ± 35.0 at θ = 300 K; this value, together with the thermal resistance relative to the panel alone makes it possible to apply the procedure described in ISO 9869, dynamic method.

### Table 1
Thermophysical properties of materials constituting the wall with empty gap (ISO 9869, dynamic method).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [m]</th>
<th>Density [kg/m³]</th>
<th>Thermal conductivity [W/m K]</th>
<th>Specific heat [J/kg K]</th>
<th>Thermal resistance (dynamic method) [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (lime and sand)</td>
<td>0.010</td>
<td>1600.0</td>
<td>0.800</td>
<td>1000</td>
<td>0.012</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.120</td>
<td>541.0</td>
<td>0.343</td>
<td>700</td>
<td>0.350</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.050</td>
<td>1.2</td>
<td>0.315</td>
<td>1000</td>
<td>0.164</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.120</td>
<td>541.0</td>
<td>0.343</td>
<td>700</td>
<td>0.350</td>
</tr>
<tr>
<td>Plaster (lime and sand)</td>
<td>0.010</td>
<td>1600.0</td>
<td>0.800</td>
<td>1000</td>
<td>0.012</td>
</tr>
<tr>
<td>Total with empty air gap</td>
<td>0.310</td>
<td>522.3</td>
<td>0.349</td>
<td>–</td>
<td>0.889</td>
</tr>
</tbody>
</table>

* Apparent values.

### Table 2
Thermophysical properties of materials constituting the wall with low-e panel (ISO 9869, dynamic method).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [m]</th>
<th>Density [kg/m³]</th>
<th>Thermal conductivity [W/m K]</th>
<th>Specific heat [J/kg K]</th>
<th>Thermal resistance (dynamic method) [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (lime and sand)</td>
<td>0.010</td>
<td>1600.0</td>
<td>0.800</td>
<td>1000</td>
<td>0.012</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.120</td>
<td>541.0</td>
<td>0.343</td>
<td>700</td>
<td>0.350</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.021</td>
<td>1.2</td>
<td>0.036</td>
<td>1000</td>
<td>0.578</td>
</tr>
<tr>
<td>Reflective panel</td>
<td>0.008</td>
<td>62.0</td>
<td>0.033</td>
<td>1865</td>
<td>0.244</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.021</td>
<td>1.2</td>
<td>0.036</td>
<td>1000</td>
<td>0.578</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.120</td>
<td>541.0</td>
<td>0.343</td>
<td>700</td>
<td>0.350</td>
</tr>
<tr>
<td>Plaster (lime and sand)</td>
<td>0.010</td>
<td>1600.0</td>
<td>0.800</td>
<td>1000</td>
<td>0.012</td>
</tr>
<tr>
<td>Total with reflective panel</td>
<td>0.310</td>
<td>523.8</td>
<td>0.146</td>
<td>–</td>
<td>2.125</td>
</tr>
</tbody>
</table>

* Apparent values.
6946, considering an average temperature of 300 K and thus calculating the total thermal resistance.

A further certification of the panel plus two gaps is available from a test done with the guarded hot plate method; in addition, a hot box test was carried out at the University of Perugia Lab (Fig. 3) on a single gap sample (dimensions 0.800 x 1.300 m) installed with a support panel of known characteristics.

For each method, the overall wall thermal resistance uncertainty evaluation is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%. All results are given in Table 3.

The guarded hot plate with procedure seems to slightly overestimate the system thermal resistance, probably because of the absence of convective motions in the experimental setup; the other techniques take into account both heat exchange mechanisms, although with different modalities.

The sample used in the hot box has a wider surface: the thermal resistance shows to be lower than the one calculated with the hot plate method, even if the height limited to 1.300 m does not allow the formation of the free convection pattern that is found in the full height wall (3.000 m).

### 5. Dynamic thermal characteristics

Data obtained from the experimental apparatus with movable wall could be also used for the dynamic thermal analysis of the test sample. It is in fact possible to measure directly heat fluxes and temperatures of both sides of the wall under real outdoor conditions. Therefore, when the thermophysical properties of the wall layers are known and the time-dependent temperatures of the wall interior and exterior sides are recorded, a one-dimensional mathematical model could be applied, predicting the inner heat flux to be compared with the measured one. Thus, it is possible to verify the reliability of the chosen model and to validate, at the same time, the steady-state analysis.

As far as the mathematical model, although response factor and conduction transfer functions methods are widely used in building simulation programs [22,23], the cyclic trend of temperatures and heat fluxes suggested the use of the harmonic approach.

With the hypotheses of a one-dimensional multilayer plane wall where each layer is homogeneous, isotropic and has constant

<table>
<thead>
<tr>
<th>Method</th>
<th>Thermal resistance (W/m² K)</th>
<th>Uncertainty (W/m² K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 9869</td>
<td>1.400</td>
<td>±0.140</td>
</tr>
<tr>
<td>ISO 6946</td>
<td>1.482</td>
<td>±0.158</td>
</tr>
<tr>
<td>Guarded hot plate</td>
<td>1.570</td>
<td>±0.020</td>
</tr>
<tr>
<td>Hot box</td>
<td>1.528</td>
<td>±0.098</td>
</tr>
</tbody>
</table>

Fig. 3. Hot box apparatus for the evaluation of the low-e panel thermal resistance.

Fig. 4. External temperature of the wall with low-e panel: comparison of Discrete Fourier Transforms with measured data.
thermal properties, the equation for heat conduction is written as follows:

\[
\frac{\partial \Theta(x, \tau)}{\partial \tau} = \frac{\lambda}{\rho C} \frac{\partial^2 \Theta(x, \tau)}{\partial x^2} \tag{3}
\]

where \( \lambda \) is the thermal conductivity, \( \rho \) is the density and \( C \) is the specific heat.

As previously described, each layer was considered homogeneous, defining an equivalent thermal conductivity and an equivalent specific heat for bricks while the air gap was given the apparent thermal conductivity obtained in conjunction with the ISO 9869 analysis.

Defining as surface \( i \) the innermost face of the wall and with the index \( e \) the outermost side, the relation that defines the variations of heat flow rates entering into the component on both sides of the wall as a function of temperature variations (supposed sinusoidal) becomes:

\[
\begin{pmatrix}
\bar{q}_i \\
\bar{q}_e
\end{pmatrix}
= 
Y \begin{pmatrix}
\Theta_i \\
\Theta_e
\end{pmatrix}
\tag{4}
\]

where \( Y_{\alpha \omega} \) is the generic complex component of the matrix that depends on the depth of each homogeneous layer as well as on the periodic penetration depth of the heat wave [14]:

\[
\bar{\theta} = \sqrt{\frac{\lambda \Theta}{\pi \rho C}} \tag{5}
\]

In the case under examination, since the quantities \( \bar{\Theta}_i \) and \( \bar{\Theta}_e \) are known from the experimental campaign, and the components of the matrix could be calculated once the properties of each layer are defined, Eq. (4) makes it possible to compare the theoretical approach with measured data, extracting, for example, \( \bar{q}_i \) from the following relation:

\[
\bar{q}_i = Y_{ii} \bar{\Theta}_i - Y_{ie} \bar{\Theta}_e
\tag{6}
\]

and comparing the results with measured data.

Since this approach gives only the complex amplitudes of the heat flow rate, the average value has to be defined through the stationary analysis.

The use of the Discrete Fourier Transform is necessary both for interior and exterior wall temperatures, choosing a sufficient number of harmonics \( \Theta_{1,n} \) and \( \Theta_{e,n} \) to reasonably approximate the measured values. The analysis has been conducted for 72 hours: the discrete temperature values recorded every 10 minutes for the ISO 9869 calculation were transformed into sums of sines and cosines with different frequencies and amplitudes, according to Eq. (7) [24]:

\[
\Theta(\tau) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \left( \frac{2 \pi n \tau}{72} \right) + \sum_{n=1}^{\infty} b_n \sin \left( \frac{2 \pi n \tau}{72} \right) \tag{7}
\]

where

\[
a_0 = \frac{2}{432} \sum_{j=0}^{432-1} \Theta_j \tag{8}
\]

\[
a_n = \frac{2}{432} \sum_{j=0}^{432-1} \Theta_j \cos \left( \frac{n \pi j}{432} \right) \tag{9}
\]

\[
b_n = \frac{2}{432} \sum_{j=0}^{432-1} \Theta_j \sin \left( \frac{n \pi j}{432} \right) \tag{10}
\]

In Fig. 4, exterior wall temperatures obtained from experimental measurements in the wall with the low-e panel are reported together with their representation of the 3- and 9-harmonics Fourier series. It is evident that if certain differences could be found limiting the series to 3 harmonics, the graphs practically overlap with 9 harmonics, therefore, limiting the sum to 9 terms gives a good approximation. These considerations are accentuated considering the inner wall temperature.

Equation (5) could be applied to each of these harmonics, obtaining a correspondent value of the complex amplitude \( \bar{q}_{i,n} \). The sum of all contributions defines the total heat flow rate.

The walls with characteristics described in Tables 1 and 2 were also analyzed with a Computational Fluid Dynamic code [25]. The brick layers were considered solid and homogenous, assigning its apparent thermal conductivity and specific heat obtained previously; the plaster and the low-e panel were treated as solids. In the

**Fig. 5.** Comparison of experimental data with theoretical and CFD analysis for the wall without low-e panel.
air gap, where free convection is established, the flow is driven by buoyancy forces; this phenomenon is described by equations of mass, momentum and energy conservation, together with the definition of turbulent flow variables. The time-averaged momentum equation is written starting from the Reynolds form, with an additional term derived by the Boussinesq approximation [26], which specifies the coupling between temperature gradients and velocity in natural convection. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation:

\[
\left(\rho - \rho_{\text{op}}\right)g = -\rho_{\text{op}}\beta(\Theta - \Theta_{\text{op}})g \tag{11}
\]

where \(\beta\) is the thermal expansion coefficient and \(\rho_{\text{op}}\) is the (constant) density of the air at the operating temperature \(\Theta_{\text{op}}\) that is chosen equal to the average between exterior and interior wall temperatures (300 K). The renormalisation group \(k - \varepsilon\) model was chosen to simulate the air motion inside the gap, as suggested in [27]; besides, the wall effect on the air motion has been taken into account using the enhanced wall treatment: a near-wall modelling method that combines a two-layer model with enhanced wall functions. The radiation between the gap faces was modelled using the Discrete Ordinate Radiation model [25], giving the low-e surface an emissivity value of 0.06, while the other faces were given a value of 0.90. The upper and lower part of the wall are considered adiabatic, while the inner and the outer walls were given the unsteady temperature conditions obtained from experimental data.

A grid independence check was done through a series of grid refinements and the optimal size for the two-dimensional approach was found for a grid of around 330,000 cells; each further refinement gave a difference of less than 5% on the main thermo-dynamic parameters.

In Fig. 5 theoretical predictions and CFD simulation results for the wall without the low-e panel are sketched together with experimental data obtained for a grid of around 330,000 cells; each further refinement gave a difference of less than 5% on the main thermo-dynamic parameters.

The comparison among the heat flux measured by the heat flow meters, the one obtained by the theoretical analysis for a 24 hours time period and the results of numerical simulation, show differences never greater than 1 W/m² K. This result could be considered a CFD model validation and the way to define the thermophysical properties of all layers but the low-e panel.

In Fig. 6 the experimental inner heat flux for the wall equipped with the low-e panel is compared with the CFD results and with the ones obtained with the theoretical analysis (3 and 9 harmonics).

Both the numerical analysis and the more accurate theoretical approximation show good agreement with the measured data; the theoretical model that takes into account only a few harmonics is in any case found to be reasonably precise. It is showed therefore that, in the dynamic analysis, air gaps could be treated as equivalent conductive layers, whose thermal resistance is derived from the steady-state calculations.

Once validated, the numerical code makes it possible to control the thermal field in the whole dominion; the temperature values in the horizontal section at middle height analyzed during an entire day (see Artwork 1) confirms the hypotheses made regarding the maximum temperature differences between the gap surfaces (lower than 5 K) and the edges of \(\Theta_{\text{m}}\) range variation.

As discussed in section 3, boundary effects on heat flux are present on top and bottom of the cavity (see Artwork 2); however, the CFD simulation shows that considering the central local specific heat flux instead of the average heat flux of the entire inner wall, gives an error of less than 3% in all conditions.

6. Conclusions

The experimental approach proposed for the evaluation of low-e insulators installed on vertical walls makes it possible to define the stationary and dynamic properties of these solutions under real outdoor conditions. The possibility of verifying the entire wall without the low-e material permits the precise definition of the thermophysical properties of all the other components, guaranteeing, therefore, that the differential measurement could underline the performance of the low-e panel alone. The same approach could be used if the radiant panel is installed in horizontal walls.

The in situ campaigns demonstrated that ISO 6946 represents a good approximation of the low-e material and air gap behavior in stationary conditions, provided that the total emittance is defined accurately. The hot box method also gives a high degree of
reliability, especially when the sample dimensions are close to the real ones, while the hot plate technique seems to overestimate the thermal resistance, because of the limited size of the survey analyzed (free convection is not occurring) and the emissivity of the plates, generally lower than that of common building materials facing the low-e panel. As for dynamic characteristics, the experimental apparatus proposed allows the direct defining of the contribution of the low-e panel in situ; besides that, a full summer campaign developed on a pilot wall in central Italy showed that once the equivalent thermophysical properties of all the other components are correctly defined (in particular the density, the specific heat and the thermal conductivity), the theoretical predictions based on the monodimensional approach of ISO 13786 makes it possible to reach a high degree of precision on the low-e panel performance evaluation, even with highly variable outdoor conditions. The results were confirmed by a CFD analysis that, once validated, allows verification of the hypotheses made for the theoretical evaluations, and constituting another possibility to define the thermophysical properties of radiant barriers.

Appendix A. Supplementary information

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.buildenv.2009.10.009.

References

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