Experimental validation of CFD model of thermal fluxes through a multilayer wall

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Abstract. The evaluation of thermal losses through building envelope is complex due to the presence of different components such as geometrical and structural thermal bridges, multilayer walls, windows and shadow areas. In particular, in presence of material and/or shape discontinuities, the heat flux becomes two-dimensional or three-dimensional and loses its one-dimensionality. Thermal bridges are weak points of the building envelope; the measurement of heat losses through the walls is quite complicated and in particular the detection of bidimensional or tridimensional thermal flux. The integration between the cfd analysis and the experimental study aims the improvement of the measurement technique and the assessment of the dispersion of heat fluxes through multi-layer walls both in the steady and unsteady measurement conditions. The numerical study has been directed for modelling, by means of the commercial numerical code Fluent, of the experimental test section consisting of a multi-layer wall, in which a structural thermal bridge has been inserted in order to make accurate measurements of the three-dimensional heat flux in steady state condition. The study has been developed to validate the CFD model by the experimental set-up, with the aim to investigate possible measurement methodologies of heat fluxes.

1. Introduction
A European directive estimated that buildings are responsible for the 40% of the total energy consumption of the European states [1]. For this reason, the reduction of the heat losses through the buildings plays an important role on an energy saving policy and for the achievement of the reduction of 20% of energy requirement within 2020; the directive 2012/27/UE [2] establishes a series of objectives to reach. In the past few decades, the growing interest to reduce the energy used in the building sector has led to walls characterized by appropriate thermal properties [3]. In fact, an appropriate construction technique and an appropriate selection of the materials for the walls, can reduce the energy requirement for heating and cooling. The thermal properties of the walls can be evaluated by theoretical models or by stratigraphy. But the experimental values measured in-situ can be very different from those predicted [4, 5]. The discrepancies may be due to imperfection during the construction phase, to aging, to moisture. So, it’s necessary to measure the characteristics of the walls in-situ during the normal exercise.

The presence of different building components, such as geometrical and structural thermal bridges, multilayer walls, windows and shadow areas can take to a result not always in compliance to the actual case. In particular, in presence of material and/or shape discontinuities, the heat flux becomes two-dimensional or three-dimensional and loses its one-dimensionality. Thermal bridges are weak points...
of the building envelope; the measurement of heat losses interesting the walls is quite complicated and in particular the detection of thermal flows bi-tridimensional; they present the greatest analysis complexities. In fact, the thermal bridges determinate heat losses higher than those characterizing a common dispersing surface (i.e., walls without discontinuities). This phenomenon induces uncontrolled thermal losses and hygiene problems, connected to the possible vapor condensation and mold growth. The powerful programs for energy audit of buildings - as DOE-2 [6] and EnergyPlus [7] - do not provide an accurate assessment of thermal bridges and still search and optimization problems require more precise calculation methods. The scientific literature proposes different methods for the analysis of thermal bridges, according to both approaches statistical and numerical. Ceylan and Meyers [8] and Ouyang and Haghighat [9] have implemented the use of Conduction Transfer Function (CTF) for the solution of problems of transient heat transfer. They proposed a new approach to calculate the thermal response factors of a multi-layer wall without finding the roots through calculation of the state transition matrix of a system. Even Stephenson and Mitalas [10] and later Hittle [11] and Hittle and Bishop [12] studied heat transfer through the multi-layer plates. Wang and Chen [13] proposed a stable series expansion approach based on the Routh stability theory declaring that the calculation of TRFs may not be convergent with increase of the terms in expansion polynomials and provided a detailed analysis of the problem.

Afterwards, Renon [14] upgraded the methods developed by Seem [15] and Seem et al. [16], by modelling thermal bridges and showing techniques suitable for transferring the methodology into EnergyPlus [7]. Deque et al. [17, 18] proposed a numerical methodology aimed to characterize thermal bridges, by means of the state-space representation, while Ben Larbi [19] suggested a statistical model for the evaluation of the equivalent thermal transmittance of linear thermal bridges with a development of a library using common geometries. Gao et al. [20] proposed a reduction model of the building heating load, including also the thermal extra-flows due to thermal bridges; their methodology has been, later on, implemented in TRNSYS [21]. Ascione et al. [22], presented a comparison between the results obtained by means of the simplified 1-D models and those obtained by more sophisticated models 2-D or 3-D, in order to point out differences in terms of equivalent conductivity and thermal transmittance, showing that a proper modelling is necessary. In particular, an over estimation of the heat losses, determined by an approximate evaluation, induces higher cost of refurbishing, higher cooling energy requests in summer, minor thermal comfort in naturally ventilated buildings. Asdrubali et al. [23] proposed a methodology to perform a quantitative analysis of some types of thermal bridges, through simple thermography surveys and subsequent analytical processing. From the simple measurement of the air temperature and the analysis of the thermogram, the thermal bridge effect can be estimated as a percentage increase of the homogenous wall thermal transmittance. This term is obtained without further information on the structure of both the thermal bridge and the stratigraphy of the wall. Capozzoli et al. [24] believe that it is necessary to identify an accurate numerical method in order to appreciate the benefits of a proper design. A sensitivity analysis based on an extensive study of the linear thermal transmittance value of many types of thermal bridge, based on the methodology specified in EN ISO 10211, has been carried out. After defining the input design variables and considering a range of variation for each of them for the linear thermal transmittance evaluation, a non-linear regression model has been specifically developed for each analyzed thermal bridge, considering the output values of a numerical code as data set. A method has been performed, based on the obtained results, in order to assess the contribution of each input design variable to the deviation of the linear thermal transmittance for each kind of thermal bridge. Ascione et al. [25] investigated a typical L-shaped thermal bridge and the numerical methodology – compared to the experimental study – reveals very satisfactory results in reliability and accuracy. The percentage gap between calculated and measured heat fluxes varies between −12% and +6%, with an average value close to zero. A satisfactory agreement has been evaluated also with reference to the heat rate through the investigated envelope element.

The integration between the numerical-experimental researches aims the improvement of the measurement technique through knowledge and assessment of the dispersion of heat fluxes in multi-
layer wall in the three-dimensional field, both in the steady and unsteady measurement conditions. The study here proposed is aimed to validate the developed CFD model by means of comparisons with experimental measures with the aim of improving methodologies for heat fluxes measurement. The numerical study has been directed to modeling, by means of the commercial numeric code Fluent, an experimental test section consisting of multi-layer wall, in which a structural thermal bridge has been entered in order to make accurate measurements of the three-dimensional heat flux under steady state condition. Globally, the carried out comparisons get very satisfactory results, demonstrating reliability and accuracy of the developed CFD model.

2. Experimental test section
A model of a multilayer wall, composed of two plasterboard panels interleaved by an I-shaped thermal bridge, has been built in order to analyze thermal behavior of the multilayer wall under radiative and convective fluxes. In Figure 1, layout of wall stratigraphy is presented. In particular the stratigraphy is composed of: plasterboard, iron I-shaped thermal bridge and premixed plaster in the middle section and again a plasterboard panel. One of a plasterboard panel was placed in front of an hot panel used as heat source. Dimensions and thermal characteristics are summarized in Table 1. The thermal flux, provided by an electrical resistive panel, will be described with more details in the section 2.2.

![Figure 1. Layout of wall stratigraphy: experimental section](image_url)

Table 1. Stratigraphy of multi-layer wall: test section

| layer materials        | height/m | length/m | thickness/m | thermal conductivity/ (W/m K) | c/(J/kg K) |
|------------------------|----------|----------|-------------|-----------------------------|------------|
| 1st layer              |          |          |             |                             |            |
| Plasterboard           | 0.490    | 0.450    | 0.010       | 0.500                       | 1138       |
| Iron thermal bridge (2a)| 0.470    | 0.430    | 0.005       | 16.270                      | 502        |
| 2nd layer              |          |          |             |                             |            |
| Premixed plaster x 2 (2b)| 0.380    | 0.190    | 0.005       | 0.032                       | 1138       |
| 3rd layer              |          |          |             |                             |            |
| Plasterboard           | 0.490    | 0.450    | 0.010       | 0.500                       | 1138       |
2.1. Sensor apparatus
The thin film heat flux sensor used in the experimental tests represents the first stage of the measurement chain. It detects the heat flux that invests a sensible surface by radiation and convection mechanisms. The measurement principle of heat flux sensors is based on measuring the temperature difference across the thermal resistance when a heat flux passes through. Therefore, this kind of sensor in output provides both heat flux and temperature signals. Table 2 summarizes the physical and metrological characteristics of the thin film heat flux sensors attached to the wall and connected to the data logger. The sensors were glued to the surface wall using thermally conductive paste or a thermal pad (100x100 mm², 0.5 width and conductivity equal to 5 W(mK)^{-1}), in order to ensure a good thermal contact. A better estimation of heat flux can be achieved acquiring a larger number of punctual signals by heat flux sensors, on the examined surface. In order to complete the monitoring campaign, the internal and external air temperatures were measured with a sampling interval equal to 60 s by two PT100 temperature probes, whose metrological characteristics are summarized in Table 3. As shown in Figure 2, they were used 18 sensors, which measure flux and/or temperature.

| Table 2. Heat flux sensors: physical and metrological characteristics |
|---------------------------------------------------------------|
| **Heat flux sensors**                                        |
| Dimensions | 35.1x28.5 mm |
| Nominal resistance | 175 Ω |
| Nominal sensitivity | 2.0 μVW^{-1}m^{-2} |
| Response time to a step function (63%) | 0.60 s |
| Upper temperature limit | 150 °C |
| Relative uncertainty | ±5% |
| Repeatability | 0.6% |

| Table 3. Temperature probe: metrological characteristics |
|-----------------------------------------------------------|
| **Sensor type RTD Pt100, Class 1/3B (DIN/IEC751)**         |
| Dimensions | 020 x 3 mm |
| Response time | 8 s |
| Operating range | -50 °C to 125 °C |
| Uncertainty | ± 0.10 °C (at T = 20 °C) |

Figure 2. Test section: heat flux sensors attached to external (on the left) and internal (on the right) surfaces

The heat flux sensors are indicated with the numbers from 1 to 9 for the internal surface and from 10 to 18 for the external surface of the test section. Ten k-thermocouple sensors, connected to a data
logger, were glued to the same position of the thin film heat flux sensors with the aim to acquire the
temperature signal in the same time to obtain better measurement accuracy.

2.2. Heat flux supply
The heat flux supply was composed by the following components (see Figure 3):

- radiative heat source panel;
- multimeter;
- power supply;
- reference resistance (shunt).

In particular, the heat source consists of an upper surface made of a thin copper layer that is able to
conduct electric current well, instead the bottom and lateral surfaces are insulated by fiberglass. The
copper layer was grooved using a drill press to obtain a series of separated electrical resistors linked in
series by electrical bridges. It also was added a transparent plastic film on top of the copper layer to
achieve electrical insulation.

Figure 3. Heat flux source (left side); particular of resistance connections (right side)

Figure 4. Electrical power supply and data acquisition system for heat flux source panel. Left side:
reference electrical resistance, multimeter and data logger. Right side: electrical scheme
This resistance (Figure 3) is linked with an electrical supply (with appropriate safety fuse 5 A) and one of the two power cables (negative pole) is connected in series with a standard reference electric resistance (shunt): $R_C = 0.00066 \, \Omega$.

Across the shunt, it was possible to measure the voltage and, consequently, the current circulating in the resistance that is the same circulating in the copper resistance of the heat source plate. This allows to evaluate the heat flux provided by the heat source panel once measured the voltage difference across the heated panel.

Before every experimental tests run, verification of heat flux provided by source panel was carried out. In Table 4 the comparison between theoretical and experimental results is reported.

### Table 4. Validation of heat source panel

| Voltage | Current | Power | Theoretical Heat flux | Measured Heat flux | Percentage |
|---------|---------|-------|-----------------------|--------------------|------------|
| 10 V    | 1.10 A  | 11 W  | 60.44 W/m²            | 54.85 W/m²        | 9.24%      |
| 15 V    | 1.65 A  | 24.75 W | 135.98 W/m²          | 123.81 W/m²      | 8.95%      |
| 20 V    | 2.20 A  | 44 W  | 241.75 W/m²          | 219.74 W/m²      | 9.10%      |

\[
\phi_{\text{board}} = \frac{P_{\text{power supply}}}{A_{\text{board}}}
\]

### 2.3. Experimental test conditions

The test conditions and the experimental set up are reported in Table 5 and Figure 5, respectively. In particular, in the left side a lateral view of experimental setup can be observed, instead the right side shows a sketch of experimental apparatus with the reference Cartesian axes. The distance between wall and heat source panel is equal to 10.0 cm.

**Figure 5.** Layout (left side) and experimental apparatus (right side)

### Table 5. Test conditions

|                     |       |
|---------------------|-------|
| Measurement duration | 60 min|
| Scan interval       | 5 s   |
| Sampling interval   | 60 s  |
| Environment temperature | 26 °C |
| Voltage imposed to generate Heat flux | 10 V |
3. **CFD analysis: numerical simulation**

In this section, a CFD numerical simulation of the experimental apparatus is presented. The Figure 6 shows the CFD domain. Dimensions and material properties of the wall stratigraphy are the same used in the experimental apparatus (Table 1).

To obtain the temperature and velocity fields, the three-dimensional Navier Stokes equations (Fluent user’s guide, 2005) combined with k–ε standard turbulent model in the steady state conditions were numerically solved. To take into account the radiative contribute, the DO model was used. The mesh was realized in Gambit ambient. Due to the mesh size should be neither too sparse, because it would lead to an inefficient analysis of the model, not too dense, because it would require excessive computational time, a sensitivity analysis of the solution on the mesh sizes was carried out. In the computational domain there are areas in which it is interested in having more detailed information, such as area in which there are convective flows. In particular, these convective flows can arise inside the air zone between the copper board and the hot side of the box. In these zones, a boundary layers mesh with the following characteristics was adopted:

- First row (a) = 0.001 m;
- Growth factor (b/a) = 1.3;
- Rows = 7.

The mesh size values in X and Y directions are both equal to 0.01 m, instead in Z direction, it has been adopted different interval spacing, depending on each volume (see Table 6). In Table 7, operative and boundary conditions are summarized.

![Figure 6. CFD domain and volume discretization](image)

| Volume Zone                                | Cell size in Z direction/m |
|--------------------------------------------|----------------------------|
| Hot Plate                                  | 0.001                      |
| Box-Hot (volume between hot plate and wall surface) | 0.002                      |
| Thermal bridge                             | 0.001                      |
| Gypsum                                     | 0.001                      |
| Air                                        | 0.030                      |
Table 7. Operative and boundary conditions

| Operative Conditions                  | Pressure=101325 Pa, Temperature=26 °C, g=9.81 m/s |
|--------------------------------------|--------------------------------------------------|
| Models                               | k-ε model, DO (20,20,10,10) radiative model       |
| Materials                            | Solids: iron, copper, premixed, plasterboard, air|
| Boundary Conditions                  | Heat generation imposed on the hot plate: 140400 W/m^3, pressure inlet and outlet conditions imposed on boundary surface of domain |

4. Results and Discussion
In this section, both experimental and numerical results are presented and compared to validate the CFD model proposed. The results are given in terms of field and profiles of the total heat flux and temperature in the x, y and z directions. In Figures 7 and 8 heat flux and temperature fields are shown, respectively (on x-y plane). Table 8 summarizes the relative percentage errors between experimental measurements and numerical predictions. It is possible to note that the greatest relative percentage error is equal to 6.1%. Globally, the comparison gets very satisfactory results, demonstrating reliability and accuracy of the developed numerical method.

Figure 7. Comparison between experimental and numerical results in terms of heat flux

Figure 8. Comparison between experimental and numerical results in terms of temperature
Table 8. Comparison between experimental and numerical results: percentage relative error

| Sensor position | heat flux | temperature |
|-----------------|-----------|-------------|
| 11              | -3.6%     | -2.6%       |
| 10              | -4.1%     | 0.3%        |
| 12              | -6.1%     | 3.6%        |
| 14              | 3.1%      | 1.8%        |
| 13              | 3.5%      | 4.3%        |

The Figure 9 shows the temperature and heat flux inside the wall under investigation. The temperature profiles show that on the vertical symmetry axis the temperature are almost constant, in correspondence of thermal bridge, and decrease from hot surface to cold one; in the same positions, the heat flux decreases rapidly, sign of bi-dimensional thermal field.

5. Conclusion
A numerical analysis for estimating heat flux in a multi-layer wall with a thermal bridges was experimentally validated by setting up an appropriate experimental apparatus. Globally, the comparison gets very satisfactory results, demonstrating reliability and accuracy of the numerical method. The CFD simulation could allow to evaluate, separately, the different heat transfer contributions. Besides, the numerical analysis could be used to design and optimize an experimental setup to measure the different thermodynamic parameters such as the heat transfer coefficient or the thermal transmittance of the wall.
6. References

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