MEASUREMENT AND PREDICTION OF HEAT TRANSFER AND MASS FLOW OF A VENTILATED FACADE

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ABSTRACT
Opaque ventilated facades (OVFs) can be an effective retrofit solution to improve the energy performance of existing commercial buildings. The paper presents a modelling approach for OVFs in Trnsys simulation software coupling thermal and airflow models. The test facade adopted for this research is part of an experimental application built on an existing industrial building in Turate (Como, Italy) whose thermal behaviour is monitored by a wireless system network (WSN). The simulation of the thermal behaviour and the monitoring of the built envelope allows validating a comparison of ventilated façade actual performance and expected performance in real context.

INTRODUCTION
Beyond the advantages in terms of protection against atmospheric agents, opaque ventilated facades (OVFs) can be an effective retrofit solution to improve the energy performance of existing commercial buildings. Recent studies (Lopez F. P., 2012) (Sanchez M.N., 2013) and research projects (BRICKER, 2014) have been focusing on these aspects. OVF's are based on a cladding system made up of panels anchored to the building load-bearing structure by means of a metal structure. The cladding panels are placed in such a way that air flows in the intermediate cavity driven by the buoyancy effect. An insulation layer is also applied to the existing wall. If properly designed, those facades enable to control and reduce energy consumption providing high thermal insulation, shading from solar radiation, protection against humidity penetration, an opportunity for PV technologies and solar thermal systems integration.
However, OVF influence on indoor environment is difficult to predict/quantify due to the unsteady convection flows in the air cavity.
Many different approaches exist to predict the thermal performance of OVFs and ventilated facades in general: analytical and lumped models, non-dimensional analysis, network models, control volume models, zonal approach and computational fluid dynamics (CFD). Among these models, the airflow network model is the most promising one as it can provide fast useful information about bulk flows without consuming high computational resources, and can be coupled with the thermal network in building energy simulation tools (DeGracia A., 2013).
The paper presents a modelling approach for OVFs in Trnsys simulation software coupling thermal and airflow network and its experimental validation on a test building.

TEST FACADE
The test facade adopted for this research (Figure 1) is part of the experimental application ‘Permanent ProTeA – Aderna research Laboratory’ built on the manufacturing headquarters of GL Locatelli ADERMA Group in Turate (Como, Italy). The pre-existing building was refurbished by applying an OVF.

Figure 1. Aderma manufacturing building. South façade.

The whole building is the experimental setup of an ongoing research project (Arlati E., 2006) (Arlati E., Tarantino S. et al., 2012), which aims, among other goals, at providing a built experimentation field to support the development of thermal simulation environment and tools by the data of thermal performances from on-site measurements.
Table 1

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness [m]</th>
<th>Thermal conductivity [W/mK]</th>
<th>Density [kg/m³]</th>
<th>Absorptivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete panel</td>
<td>0.20</td>
<td>0.316</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.08</td>
<td>0.036</td>
<td>45</td>
<td>-</td>
</tr>
<tr>
<td>Cladding panel 1: Stone</td>
<td>0.04</td>
<td>0.93</td>
<td>1065</td>
<td>0.36</td>
</tr>
<tr>
<td>Cladding panel 2: Brick</td>
<td>0.04</td>
<td>0.7</td>
<td>1970</td>
<td>0.93</td>
</tr>
<tr>
<td>Cladding panel 3: Fibrocement</td>
<td>0.01</td>
<td>0.029</td>
<td>1920</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The experiment concerns the on-site thermal performance testing of a number of built alternatives for ventilated facades’ assembling, different for materials and layers composition.

The façade of the building is insulated with 8cm of Polystyrene. Cladding panels anchored to the existing wall by means of a metal structure cover the insulation layer creating 5 cm airgap for airflow (Figure 2). Three cladding panels type are installed at different façade height:

1. Stone panel (from ground to 1 m height)
2. Brick panel (from 1m to 3.8 m height)
3. Fibre cement panel (from 3.8m to 6m height)

The motivation for adopting three different cladding panels resides in the paradigms that drove the design of the Adera manufacture building: research interests and applications had to coexist with the owner's request for an appealing headquarter building. Table 1 reports the thermal properties of the existing wall, the insulation layer and the cladding panels based on the technical sheets provided by the manufacturers.

The façade is classified as open joints ventilated façade. The cladding panels’ arrangement of the test façade is such that it forms open gaps between them, allowing the surrounding air to enter and leave the cavity all along the façade. The façade has also open grills, i.e. bottom and top of the façade are opened for airflow.

MONITORING AND MEASUREMENTS

The surveying of data is operated on the four façades (oriented to North, East, South and West) of the Adera manufacturing building. For this research, we analysed only the south façade thermal behaviour. Clusters of sensors, positioned as in Figure 3, are connected around three nodes in each vertical section of façade object of monitoring: located at the base (0.4m), around the higher-middle (2.6m), at the top (5.5m) of every vertical section. The monitoring modular areas associate three homogeneous modules of 50 cm wide and of the full building’s height: of the three, only the central module is the setting place of thermal and air velocity sensors, while the two modules at its sides assure the absence of non desired influences due to different border-side conditions (Arlati E., 2006).

The following surface temperatures are measured at the base (0.4m), around the higher-middle (2.6m) and the top (5.5m) of the vertical section on south facade:

- T1: Wall inside surface temperature
- T2: Wall outside surface temperature
- T3: Surface temperature of the insulation layer
- T4: Surface temperature on the back side of the cladding panel

The air temperature and the air velocity within the ventilated cavity are measured at the base (0.4m) and the top only (5.5m). A meteorological station installed...
on the roof measures the environmental air temperature, wind speed and direction, relative humidity and the overall environment irradiation both directed and diffused. A pyranometer measures the sun direct irradiated energy on the South wall.

In this paper we refer to the measured data taken in the summer week from August 28th to September 3rd 2010 and in the winter week from December 3rd to December 10th 2010. All measurements are taken at 10min intervals.

MODELLING SETUP

The test façade is modelled using two thermal zones: one representing the indoor environment and one representing the ventilated air cavity (Figure 4). The radiative zone representing the ventilated air cavity consists of three air nodes. Building surfaces are assigned to each air node. The heat exchange between building surfaces and the airnode is based on convection only whereas the shortwave radiation distribution and the longwave radiation exchange is performed over the whole radiative zone. The airnodes within the radiative zone have a convective coupling. Thereby, the model predicts temperatures at three building heights, corresponding to air nodes 1, 2 and 3 in Figure 4.

![Figure 4. Sketch-up model view with airflow network scheme.](image)

Since no information on indoor internal gains and usage pattern are available, the air temperature of the thermal zone representing the indoor environment is set equal to the measured one.

The exterior convection coefficient for each cladding panel is calculated by an average linear correlation (McAdams W.H., 1954) which is function of wind speed.

As shown in the graph in Figure 5, the air cavity temperature at façade base is on average 2.5 K higher than the outdoor temperature. This difference increases when outdoor temperature is higher than 25°C. Up to 10K temperature difference is encountered between the air temperature measured by the weather station and the temperature of the air cavity measured at the base of the wall, probably due to an underestimation of the longwave radiation exchange with the ground (asphalt paved road).

![Figure 5. Outdoor temperature measured by the weather station vs measured air cavity temperature at the façade base.](image)

Therefore, the weather file ambient temperature is set equal to the inlet air temperature in the air cavity.

The modelling approach combines the features of a wall model with exterior air gap (Type 1230 - (Duffie J.A., Beckman W.A., 2013)) with the one of the airflow network model (Trnflow - (Weber A., 2003)) into two iterative steps, which are described in the following paragraphs.

**Step 1**

First, the ventilated air cavity is modeled as a stack of three thermal zones adjacent to the external insulated wall. The three thermal zones representing the air cavity are coupled to an airflow network which includes inlet and outlet openings (Link 1 in Figure 4) and links between the stack zones (Link 2 in Figure 4). The coupling between thermal and airflow model allowed estimating the air mass flow rate induced by natural draft.

Air links between ventilated air cavities at each floor level and between external nodes and air cavity are calculated by assuming a large opening condition. The inlet and outlet openings width is supposed to be the same as the wall width (2m) and the openings height is equal to the air gap thickness (0.052m).

Discharge coefficients are set to 0.3 as they take into account also the dynamic pressure loss along the channel. The flow through the façade air cavity is assumed to be similar to the one in a straight duct where the flow becomes fully developed and the pressure does not vary over a cross section. Therefore, the discharge coefficient is derived by the overall resistance coefficient, which is a sum of the resistance factor due to wall shear stress and the loss coefficient.
According to the calculation method reported in (Etheridge D., 2012), since no detailed measurements of wind pressure on the test façade are available, we derived the wind pressure coefficients used in the airflow network model from the AIVC database (Liddament M.W., 1986) for flat roof rectangular buildings. However, the pressure of wind blowing from south-west direction (i.e. 45° wind direction) might be overestimated since the effect of the adjacent wall obstruction is neglected. This assumption can be considered acceptable since wind prevailing direction during the analysed period is south-east and wind speed is most of the time below 5m/s.

The open joints between the cladding panels are not modelled as a previous study (Marinosci C., 2011) concluded that the results for closed joints with open inlet and outlet façade can be applied also to open joints façades with open inlet and outlet.

Step 2
Second, the overall thermal behaviour of the OVF is modelled in Trnsys by coupling the building thermal zone representing indoor environment (Type 56) to Type 1230, able to model an exterior wall where the outside surface is massive and has a ventilated air gap behind it. The model derives from first principles heat transfer and the algorithms for solar energy collection presented in (Duffie J.A., Beckman W.A., 2013). The moisture effects of the air in the channel behind the wall material are neglected. The model represents the ventilated wall as an opaque solar collector. The back side of the air gap has small resistive layer, the temperature and resistance of which are connected to the Type 56 wall for modelling the interior wall heat transfer. The model accounts for:

- absorption of solar energy on the exterior surface;
- long-wave radiation exchange with the sky from the outside surface;
- convection to the ambient air;
- energy storage in the massive wall;
- conduction through the wall;
- radiation exchange through the air gap;
- convective exchanges to the air stream from both air gaps surfaces and conduction through the resistive layer (insulation).

Type 1230 is coupled to Type 56 through the surface temperature of the wall within the air cavity (T5). Type 1230 accepts this surface temperature from Type 56 and calculates the temperature on the interior surface of the air gap. Type 56 accepts this boundary temperature from Type 1230 and calculates the surface temperature of its exterior wall (which is actually the temperature beneath the insulation layer, or other outermost wall layer).

The airflow network model provides Type 1230 for mass flow rates and flow direction within the air cavity at each time step, while, for the stack thermal zones, Type 1230 provides the surface temperature on the inner side of the air cavity as a boundary condition. Each of the surface zones where the ventilated façade has to be installed is connected to a Type 1230 unit where the ventilated wall sizes and the cladding panel properties are specified.

Comparison with monitored data
The scatterplots in Figure 6 to Figure 9 compare the simulation predicted and measured air cavity temperatures at the base and the top of the façade and during the periods analysed.

The graphs in the Appendix (Figure 10 to Figure 15) shows the measured and predicted variable trend in detail.

During the summer week, air cavity temperatures vary within a much broader range (13 – 35°C) compared to the winter week (5 – 13°C) because of the solar radiation effect. In fact, incident solar radiation on the vertical plane has peak values of around 600 W/m² (Figure 11) during the summer week and peak values of around 50 W/m² only during the winter week (Figure 14).

Comparisons between modelled and measured results were based on the coefficient of variation of the root mean square error (CV-RMSE) (ASHRAE guideline 14 - 2002). The CV-RMSE indicates how well a model fits the measured data and is calculated by dividing the root mean squared error by the measured mean of the data. A CV-RMSE value of 10% for example, indicates that the mean variation in measurement variable not explained by a prediction model is on tenth as large as the mean value of the actual measurement variable. According to the ASHRAE guideline 14 (ASHRAE guideline 14 - 2002), the model can be considered as calibrated if the CV-RMSE relative to hourly data is below 10%.

The CV-RMSE of the air cavity temperature at the façade base is 6% both during the summer and winter week. The CV-RMSE of the air cavity temperature at the façade top is 9% during the winter week and 11% during the summer week.

Indeed, during peak solar radiation time, the model overestimates surface temperatures on the inner side of the cladding panels.

The graph in Figure 12 and Figure 15 compare the measured air velocity within the air cavity with the predicted air velocity obtained by averaging over the whole air cavity section the flow rate predicted by the airflow network model. Since the mass balance equation shall be zero at each node, the airflow network model predicts a constant airflow along the façade.
Therefore, it cannot predict different air velocities along the air cavity. Furthermore, the airflow network models neglect the momentum effect and turbulence effects are represented by an equivalent pressure difference profile, neglecting complex turbulent flows. Therefore, the higher surface temperature predicted by the model compared to the measured one can be a consequence of the underestimation of the air velocity within the air cavity and the convection effect. Furthermore, the model has proven to be sensitive to the solar radiation effect. As the material with higher solar absorptance (brick cladding panel) is located in the middle part of the façade, the model predicts similar air cavity temperatures at top and at middle height of the façade, during the summer period as well. This reduces the buoyancy effect and, therefore, wind force is more likely to prevail on buoyancy effect leading to counter flow situations. During the winter period analysed, the predicted surface temperature peaks (Figure 14) are not observed in the measured data and correspond to the time when airflow direction (and airnode inlet temperature) changes in the model.

**DISCUSSION**

The performance of the ventilated façade is strictly dependent on climate variables and their interaction with the building envelope (wind pressure distribution) and the urban surroundings (wind obstructions, heat island effect, ground reflectance). Measurements of the inlet air temperature at façade base and wind pressure measurements at façade base and top would contribute to define model inputs in a more detailed way. The airflow network model allows to calculate bulk airflow along the air cavity but does not estimate in detail the air velocity patterns. It has to be verified if this level of detail is enough to support OVF design. The predicted airflow rate is affected by uncertainty in airflow network input parameters like:
- large opening model used to calculate inlet and outlet flow resistances;
- discharge coefficients and dynamic loss coefficients;
- wind pressure coefficients and wind speed profile.

A deeper analysis of measured data can lead to a better definition of airflow network input data.

CONCLUSION

The paper presented a modelling approach for OVF using a building energy simulation software that couples thermal and airflow network. The test facade is part of an experimental application built on an existing industrial building. A dense network of nodes collects data from a bunch of sensors and supply a detailed survey of the temperature of different assembled packages/layers in their daily and seasonal dynamics, of the air mass flow through the vertical cavity of the ventilated façade, of the weather data from a meteorological station. Model predicted and measured thermal and airflow performance comparison allowed to evaluate the model robustness leading to the following conclusions:

- the performance of the ventilated façade is strictly dependent on climate variables and their interaction with the building envelope (wind pressure distribution) and the urban surroundings (wind obstructions, heat island effect, ground reflectance) which needs to be properly assessed;
- predicted air cavity temperatures are generally in good agreement with the measured ones except during peak solar radiation time, when the model also over estimates inner surface temperatures of the cladding panels;
- the airflow network model allows to calculate bulk airflow along the air cavity but does not estimate in detail the air velocity patterns;
- airflow network input parameters like the large opening model used to calculate flow resistances, discharge coefficients and dynamic loss coefficients, wind pressure coefficients and wind speed profile needs a more detailed assessment.

The modelling approach can be suitable to model OVF using building energy simulation for energy savings assessment.

In order to apply the modelling approach to deeper analysis on ventilated façade design optimization, a better definition of airflow network input data is needed.

REFERENCES


ASHRAE (n.d.). Measurement of energy and demand savings.


APPENDIX

Figure 10. Measured and predicted air temperatures within the ventilated cavity during the summer week.

Figure 11. Measured and predicted surface temperature of the inner side of cladding panels ($T_s$) during the summer week.

Figure 12. Measured and predicted (averaged) air velocity within the air cavity during the summer week.
Figure 13. Measured and predicted air temperatures within the ventilated cavity during the winter week.

Figure 14. Measured and predicted surface temperature of the inner side of cladding panels ($T_{surf}$) during the winter week.

Figure 15. Measured and predicted (averaged) air velocity within the air cavity during the winter week.