A software to optimize the design of ventilated rainscreens

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Abstract

Ventilated rainscreens are one of the most effective solutions for the realization of the opaque parts of buildings, subjected to particularly high environmental stress: rain water pushed by the wind, warming effect of sunshine, frost. They fully enable the outer shield to separate from the building core, thereby allowing, inter alia, also to realize dark color of skins, up to absolute black, unrealizable with ETICS, unless we accept the high risk of serious pathologies. Ventilated rainscreens have been studied since the 70s by Research Organizations like CSTB s Groupe Spécialisé n. 7, and now are currently used, designing them in an intuitive and synthetic manner, on the basis of the relevant literature. Up to this time it wasn't a calculation algorithm that would allow to optimize their design; fills this gap a specific calculation software, developed by the authors as part of the research activities of La.Te.C. - Laboratory of Building Technology, active in the School of Engineering of the University of Basilicata - Potenza.

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Keywords: ventilated rainscreen, aeraulic behaviour, computer aided design

1. Introduction

Ventilated rainscreens are one of the most effective solution for the realization of the opaque parts of buildings, subjected to particularly high environmental stress: rain water pushed by the wind, warming effect of sunshine, frost. They enable fully to separate the outer shield from the building core, thereby allowing, inter alia, also to realize dark color of skins, up to absolute black, unrealizable with ETICS, unless we accept the high risk of serious pathologies.

Nomenclature

\[ A_{\text{def}} / A_1 \] Intake Area \([\text{m}^2]\);
\[ A_2 \] Output Area \([\text{m}^2]\);
\[ A_{\%} \] Part of solar radiation absorbed \([-]\);
\[ \alpha_0 \] Convective heat transfer coefficient between the outside panel and the air \([\text{W/m}^2\text{K}]\);
\[ \alpha_{c1} \] Convective heat transfer coefficient between the outside panel and the cavity \([\text{W/m}^2\text{K}]\);

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$\alpha_{c2}$</td>
<td>Convective heat transfer coefficient between the cavity and the insulation [W/m$^2$K];</td>
</tr>
<tr>
<td>$\alpha_{dbh34}$</td>
<td>Heat transfer coefficient (conduction, radiation and convection) of insulation [W/m$^2$K];</td>
</tr>
<tr>
<td>$\alpha_{db45}$</td>
<td>Heat transfer coefficient (conduction, radiation and convection) of base layer [W/m$^2$K];</td>
</tr>
<tr>
<td>$\alpha_{in}$</td>
<td>Convective heat transfer coefficient between the base layer and the room [W/m$^2$K];</td>
</tr>
<tr>
<td>$\alpha_r$</td>
<td>Radiant heat transfer coefficient between the outside panel and the insulation [W/m$^2$K];</td>
</tr>
<tr>
<td>$q_{sun}$</td>
<td>Solar radiation [W/m$^2$];</td>
</tr>
<tr>
<td>$C_{a}$</td>
<td>Specific heat of the cavity air [J/KgK];</td>
</tr>
<tr>
<td>$C_{1}$</td>
<td>Specific heat of the given exterior panel/layer of the façade [J/KgK];</td>
</tr>
<tr>
<td>$C_{3}$</td>
<td>Specific heat of the insulation [J/KgK];</td>
</tr>
<tr>
<td>$C_{p1}$</td>
<td>Pressure coefficient for walls (it is 0.6 for windward side, it is -0.3 for downwind side);</td>
</tr>
<tr>
<td>$C_{p2}$</td>
<td>Pressure coefficient for roof (it is -0.3);</td>
</tr>
<tr>
<td>$C_{ij}$</td>
<td>Admittance coefficient [-];</td>
</tr>
<tr>
<td>$d_{cavity}$</td>
<td>Cavity thickness [m];</td>
</tr>
<tr>
<td>$d_{1}$</td>
<td>Thickness of the given exterior panel/layer of the façade [m];</td>
</tr>
<tr>
<td>$d_{3}$</td>
<td>Thickness of the insulation [m];</td>
</tr>
<tr>
<td>$\Delta P_s$</td>
<td>Pressure difference relating to stack effect [N/m$^2$ or Pa];</td>
</tr>
<tr>
<td>$\Delta P_{wind}$</td>
<td>Pressure difference relating to wind effect [N/m$^2$ or Pa];</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity force [9.81 m/s$^2$];</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of observation [m];</td>
</tr>
<tr>
<td>$h_{z0}$</td>
<td>Height of neutral pressure level [m];</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of interest for recording wind velocity [m];</td>
</tr>
<tr>
<td>$H_{met}$</td>
<td>Anemometer's height on ground level [m];</td>
</tr>
<tr>
<td>$\theta_0$</td>
<td>Temperature of external air [°C];</td>
</tr>
<tr>
<td>$\theta_{1.1}$</td>
<td>Temperature of the exterior face of the given exterior panel/layer [°C];</td>
</tr>
<tr>
<td>$\theta_{1.2}$</td>
<td>Temperature of the interior face of the given exterior panel/layer [°C];</td>
</tr>
<tr>
<td>$\theta_{2}$</td>
<td>Temperature of the air in the middle of the cavity [°C];</td>
</tr>
<tr>
<td>$\theta_{3}$</td>
<td>Temperature of the external face of insulation layer [°C];</td>
</tr>
<tr>
<td>$\theta_{4}$</td>
<td>Temperature of the internal face of insulation layer [°C];</td>
</tr>
<tr>
<td>$\theta_{5}$</td>
<td>Temperature of the internal face of base layer [°C];</td>
</tr>
<tr>
<td>$\theta_{room}$</td>
<td>Temperature of room [°C];</td>
</tr>
<tr>
<td>$\theta_{cavity}$</td>
<td>Entry air temperature [°C];</td>
</tr>
<tr>
<td>$q_{sun}$</td>
<td>Solar radiation [W/m$^2$];</td>
</tr>
<tr>
<td>$q_{cavity}$</td>
<td>Airflow in the cavity [m$^3$/s];</td>
</tr>
<tr>
<td>$q_{stack}$</td>
<td>Airflow generated from stack effect [m$^3$/s];</td>
</tr>
<tr>
<td>$q_{v turb}$</td>
<td>Airflow generated by wind turbulence [m$^3$/s];</td>
</tr>
<tr>
<td>$\rho_{a}$</td>
<td>Density of cavity air [Kg/m$^3$];</td>
</tr>
<tr>
<td>$\rho_{1}$</td>
<td>Density of the given exterior panel/layer [Kg/m$^3$];</td>
</tr>
<tr>
<td>$\rho_{3}$</td>
<td>Density of the insulation [Kg/m$^3$];</td>
</tr>
<tr>
<td>$\rho_{in}$</td>
<td>Density of the internal air [Kg/m$^3$];</td>
</tr>
<tr>
<td>$\rho_{out}$</td>
<td>Density of the external air [Kg/m$^3$];</td>
</tr>
<tr>
<td>$T_{in}$</td>
<td>Absolute inside temperature [°K];</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>Absolute outside temperature [°K];</td>
</tr>
<tr>
<td>$V_{win}$</td>
<td>Wind velocity [m/s];</td>
</tr>
<tr>
<td>$V_{1}$</td>
<td>Air velocity in $A_1$ [m/s];</td>
</tr>
<tr>
<td>$V_{2}$</td>
<td>Air velocity in $A_2$ [m/s];</td>
</tr>
<tr>
<td>$V_{w}$</td>
<td>Wind velocity [m/s];</td>
</tr>
<tr>
<td>$V_{w,h}$</td>
<td>Wind velocity on the building wall at the height of interest [m/s];</td>
</tr>
<tr>
<td>$V_{w,met}$</td>
<td>Wind velocity as recorded by meteorological station [m/s];</td>
</tr>
<tr>
<td>$\varepsilon_{ij}$</td>
<td>Resistance coefficient [-];</td>
</tr>
</tbody>
</table>
Ventilated rainscreens have been studied since the 70's by Research Organizations like CSTB’s Groupe Spécialisé n. 7 (Fleury & Abraham, 1982), and are now currently used, designing them in an intuitive and synthetic manner, on the basis of the relevant literature (Lembo, 1990). Up to this time it wasn’t a calculation algorithm that would allow to optimize their design, responding analytically (both in the case of continuous screens, and in that the elements’ contour of the screen has open joints) to a series of questions, of capital importance for their economic optimization: what is the optimum/minimum thickness of the ventilated cavity? It is correct the statement (formulated by the above mentioned CSTB’s Groupe Spécialisé n. 7) that it must have a maximum height of 23.50 m, beyond which it must be interrupted with a horizontal subdivision, and then present it again above it? Is it necessary the vertical partitioning of the single-sided façade (when the system does not provide it already in any modulus, for its own constitutive mode), so as to avoid that, under the wind pressure, the air flow in the cavity go horizontally, instead of vertically? The continuous screens are more efficient than those with open joints, or is it true the reverse? The presence of horizontal internal structural elements, which reduce the passage section of the air flow, makes the flow turbulent? And if that happens, under what conditions relating to the battens’ interaxis and the thickness of the passage section of the air flow? The color of the outer coating influences the aeraulic behavior of the ventilated rainscreen? The reflective quality of the surface layer of insulation, which receives the radiation produced by the heating of the outer shield, is it important? (i.e., the usual black kraft paper sheet is fine, or, to coat the heat insulating, it would be better to employ a perforated aluminum sheet?)

To all these questions, and many others, a specific calculation software, developed by the Authors as part of the research activities of La.Te.C. - Laboratory of Building Technology, active in the School of Engineering of the University of Basilicata - Potenza (Italy), provides analytical answers.

In the common understanding of those who read it must be assumed that a ventilated rainscreen consists of: 1.) a basic structural layer, which supports it and provides it (if desired) the useful thermal inertia requested, performs security tasks to the mechanical and thermal loads belonging its use, can perform an important role for sound insulation to air noise from outside or from the upper and lower levels, is located on its thickness and distributes internal installations and so it is necessary for them, and realizes the interior finishes; 2.) a layer of thermal insulation, made with one or more materials of adequate characteristics for the intended use, to the dimensional characteristics of the building and to the thermo-hygrometric and acoustic performance desired; 3.) a ventilation layer which, as is known from the relevant literature, must comply with the minimum requirements of the intake air area, of the current airflow area and of the output area, so that the stack effect can be activated, and the rainscreen can be effectively defined “ventilated”; 4.) a support layer, that is a skeleton, normally made of wood or aluminum, which holds the external screen and is supported by the structural base layer by means of metallic shelves (made in stainless steel, common carpentry steel or galvanized steel, or aluminium) that cross the layer of thermal insulation and thus constitute, or may constitute, punctiform thermal bridges; 5.) and, finally, by the outer coating layer, which forms the protective shield around the envelope, more or less continuous and therefore also more or less impermeable to air and water from rain and more or less efficient for the airborne sound insulation. The simulation hypothesis is that behind the ventilated rainscreen there is a room of 4.00 x 4.00 m, 3.00 m tall.

2. Physical-mathematical modeling of a ventilated rainscreen functioning

The model developed for ventilated rainscreens is directly derived from the one previously studied by the authors to model, simulate and analyze the behavior of the DSF - Double Skin Façades (Lembo, Marino & Lacava, 2007 and 2009) and to optimize their design. It is based on the use of MATLAB® Simulink software platform, and is organized on interaction between three subsystems:

- the thermal model (see Fig. 1a);

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y, \alpha$</td>
<td>Parameters relating to the type of site;</td>
</tr>
<tr>
<td>$z_1$</td>
<td>Distance between the center of intake area and height of neutral pressure level [m];</td>
</tr>
<tr>
<td>$z_2$</td>
<td>Distance between the center of output air area and height of neutral pressure level [m];</td>
</tr>
</tbody>
</table>
- the airflow model (see Fig. 1b);
- the wind velocity model (see Fig. 2).

2.1. The thermal model

The thermal model simulates the thermal exchanges that occur between the different elements of the ventilated rainscreen, by conduction, convection and radiation, under the action of temperature differences (see Fig. 3). The required inputs are the external climatic conditions, the coefficients of heat transfer and air flow, resulting from the airflow model.

![Diagram of thermal and airflow models](image_url)
Fig. 2. Wind velocity model: (a) wind generator; (b) wind pressure

Fig. 3. The ventilated rainscreen thermal network and horizontal section of the continuous ventilated rainscreen StoVentec R

The outputs are the temperatures of all the layers that make up the wall and the internal ambient and the speed of the air flow in the cavity. In every node acts a dynamic system which can be described in non-stationary conditions resorting to differential equation’s solution (from 1 to 5).

\[
\frac{dT_1}{dt} = \alpha_0 (\theta_1 - \theta_1) + \alpha_{c1} (\theta_2 - \theta_1) + \alpha_T (\theta_1 - \theta_1) + \Delta T_s \cdot q_{\text{sun}} \cdot \left( C_1 \cdot \rho_1 \cdot d_1 + C_a \cdot \rho_a \cdot d_a \right)^{0.5}
\]

(1) for T1

\[
\frac{dT_2}{dt} = \alpha_{c1} (\theta_{1,2} - \theta_2) + \alpha_{c2} (\theta_3 - \theta_2) + \rho_a \cdot C_a \cdot q_{\text{cavity}} \cdot \left( \theta_{\text{cavity}} - \theta_2 \right)
\]

(2) for T2

\[
\frac{dT_3}{dt} = \alpha_T (\theta_{1,2} - \theta_2) + \alpha_{dh34} (\theta_4 - \theta_3) + \alpha_{c2} (\theta_2 - \theta_3)
\]

(3) for T3

\[
\frac{dT_4}{dt} = \alpha_{dh34} (\theta_4 - \theta_3) + \alpha_{in} (\theta_{\text{room}} - \theta_3)
\]

(4) for T4

\[
\frac{dT_5}{dt} = \alpha_{dh34} (\theta_4 - \theta_3) + \alpha_{in} (\theta_{\text{room}} - \theta_3)
\]

(5) for T5

The air inlet temperature in the cavity is evaluated with the following formula (6):

\[
\theta_{\text{cavity}} = \frac{q_{\text{stack}}}{q_{\text{stack}} + q_{\text{turb}}} \cdot \theta_0 + \frac{q_{\text{turb}}}{q_{\text{stack}} + q_{\text{turb}}} \cdot \theta_0
\]
For the windward side, the turbulent flow is (7):

\[
q \cdot v_{turb} = 0.05 \cdot A_{defl} + 0.0035 \cdot v_{in} \cdot A_{defl}
\]  

(7)

For the side not exposed to the wind, the turbulent flow is (8):

\[
q \cdot v_{turb} = 0.05 \cdot A_{defl} + 0.009 \cdot v_{in} \cdot A_{defl}
\]  

(8)

The heat exchange coefficients, used in the thermal model, were calculated from the general principles of physics and in agreement with the experimental studies by Di Maio & Van Paassen (2001), Stec & Van Paassen (2002), Stec & Van Paassen (2003), Stec (2006) at the University of Technology - T.U. - Delft, The Netherland.

2.2. The airflow model

The airflow model consists of four sub-systems:

- the stack effect generator, which allows to determine the pressure differences generated by the stack effect or buoyancy, on the basis of the following inputs: external temperature, temperature in the cavity, air density, height of the cavity. The difference in pressure determined by the temperature variation is defined (as in Di Maio & Van Paassen, 2001) by the equation (9):

\[
\Delta P = (\rho_{out} - \rho_{in}) \cdot g \cdot z + P_{z_0} - P_z = (\rho_{out} - \rho_{in}) \cdot g \left( h_{z_0} - h \right) =
\]

\[
= \rho_{in} \cdot g \cdot \left( h_{z_0} - h \right) \left( \frac{T_{in}}{T_{out}} \right)^{\frac{2}{\gamma}} \left( \frac{T_{out}}{T_{in}} \right)^{\frac{\gamma - 2}{\gamma}} = \rho_{out} \cdot \frac{A_2}{A_1} \cdot \frac{z_1}{z_{out}} \cdot \frac{T_{out}}{T_{in}} \cdot \frac{\rho_{out}}{\rho_{in}}
\]  

(9)

\[
A_{1} \cdot z_{1} \cdot \rho_{out} = A_{2} \cdot z_{2} \cdot \rho_{in} = \frac{2}{\gamma} \cdot \rho_{in} \cdot \frac{A_2}{A_1} \cdot \frac{z_{1}}{z_{out}} \cdot \frac{T_{out}}{T_{in}} \cdot \frac{\rho_{out}}{\rho_{in}}
\]  

(10)

Through a series of simple further equations, it is possible to determine the trend of the pressure in the ventilated cavity and the position of the medium pressure level, in relation both to the area of the input section than to that of the outlet section (10):

- the wind effect generator allows to determine the pressure difference generated by the effect of the wind on the façade, on the basis of the following inputs: air density, pressure coefficient on the façade of the building; pressure coefficient on the building roof, wind speed, local security coefficient. On the basis of known indications of the ASHRAE 1997 and Swami & Chandra (1987), and the tests carried out in the wind tunnel at the T.U. Delft (Stec, 2006), it is possible to calculate the pressure difference due to the action of the wind, through Swami & Chandra (1998) formula (11):

\[
\Delta P_{wind} = \left( C_{p1} - C_{p2} \right) \frac{1}{2} \cdot \rho_{out} \cdot v_{w}^2
\]  

(11)

- the airflow generator, which allows to define the value of all the air flows, at the input, in the cavity, and at the outlet, from the following input data: the difference in pressure due to the wind; pressure difference due to the stack effect in the cavity; coefficients of admittance, at the input, in the cavity and at the outlet. Starting from the equation which expresses the Bernoulli’s Theorem, in the case of an ideal fluid and considering the resistance to motion by friction, due to the distributed and localized load losses and to the nature of motion, laminar or turbulent (see Reynolds number), they were adopted the resistance coefficients \( \xi_{ij} \) experimentally determined in the Laboratory of

\[
C_{ij} = \sqrt{\frac{1}{2} \cdot \xi_{ij} \cdot \rho_{air} \cdot v_{w}^2}
\]

(12)
Refrigeration and Indoor Climate Technology of the TU Delft, which have served to calculate (12) the coefficients of admittance $C_{ij}$, as a function of the ventilated wall geometry.

2.3. The wind velocity model

The wind velocity model transforms the wind speed measured by the meteorological station in the speed of the wind acting on the surface of the building (13), starting with the following input data: wind speed by the weather station, weather station height, height of the ventilated rainscreen, parameters dependent on the type of ground and the local situation, protected or not (Sherman & Grimsrud, 1980; Burns & Deru, 2003):

$$v_{w,h} = v_{w,met} \cdot \alpha \left( \frac{H}{H_{met}} \right)^y$$  \hspace{1cm} (13)

3. Simulations carried out

The software thus developed was applied to two of the most widespread ventilated façades on a global scale, both produced and marketed by StoSE & Co. KGaA in Weizen, Germany:

- the model StoVentec R (see Fig.4a) is characterized by the outer coating to organic plaster in opera performed on recycled glass slabs 12 mm thick, with the most various finishes, which may be continuous up to an area of 25 x 25 m (625 m$^2$) without any joint fractionation; the structure consists of a T vertical aluminium, supported by stainless steel shelves;
- the model StoVentec Glass/Stone Massive (see Fig.4b) is realized by hooking large sheets of tempered glass back-colored or natural stone, with or without supporting recycled glass plates of 24 mm thick, equipped on the rear face of hidden attacks, to a horizontal aluminum structure that is held up by the structure of the previously described version; the stone slabs are surrounded by open joints of a few millimeters of width (from 5 to 12 mm).
The simulations focused on the identification of the evolution, during the whole of the day and night:
1.) the temperature of the different points of the thermal network of the façade;
2.) the pressure inside the ventilation cavity;
3.) the airflow of the ventilation cavity;
4.) the air velocity in the ventilation cavity;
5.) the Reynolds number characteristic of the airflow.

They were made vary ing, and detecting their impact on the above mentioned parameters, the following variables:
- the color of the finishing material, from white to black;
- the height of the ventilated rainscreen, from 12.00 m to 23.50 m, 30.00 m, 50.00 m;
- the thickness of the air cavity (4 or 8 cm);
- the external wind (absent / present / present with different angles);
- the type of structure (no horizontal rafters / horizontal rafters at intervals of 30 cm or 60 cm);
- the absence / presence of micro ventilation (4 mm) to the contour of the cladding slabs.

Several hundred simulations were run, crossing the different planning solutions. The following figures show the most significant simulations regarding the continuous ventilated rainscreen – StoVentec R (see Figs. 5-8) and the rainscreen with microventilation – StoVentec Glass/Stone Massive (see Figs. 9-11).

Fig. 5. Continuous ventilated rainscreen: ventilation cavity 4 and 8 cm wide, 23.50 m height
Fig. 6. Continuous ventilated rainscreen: ventilation cavity 4 cm wide; height of 23.50 m, 30 m and 50 m

Fig. 7. Continuous ventilated rainscreen: ventilation cavity 4 cm wide, 23.50 m height, black and white exterior finish

Fig. 8. Continuous ventilated rainscreen: ventilation cavity 4 cm wide, 23.50 m height, in the absence and in the presence of wind
Fig. 9. Rainscreen with microventilation: ventilation cavity 4 and 8 cm wide, 23.50 m height, and step by horizontal rafters 30 and 60 cm.

Fig. 10. Rainscreen with microventilation: wall height 23.50 m, step by horizontal rafters 30 cm, ventilation cavity 4 cm wide, with and without microventilation.
4. Results and conclusions

The research results and the analyses conducted on two types of ventilated rainscreen (continuous and with micro-ventilation), have shown that variations in pressure and flow of air within the ventilation cavity are conditioned not only by the height of ventilated rainscreen but also by the thickness, the temperatures, the material and the color of the plaster coating, by the intensity of the wind and its angle of incidence with the ventilated façade, as well as by the presence of horizontal rafters that determine partial obstruction of the ducts ventilation.

In summary, as a result of the countless simulations, it can be stated as follows:

a.) StoVentec R (continuous rainscreen):
the façade with 8 cm ventilation cavity presents turbulent flows thus being less efficient than that by 4 cm; the height of the wall of 23.50 m marks the limit of the transition from laminar to turbulent flow; the color of the finishing and the type of the insulating coating do not affect so significant on the thermo-fluid dynamic variations; the simultaneous presence of the stack and the effect of the wind incidence generates limited turbulent flows, also below the height of 23.50 m.

b.) StoVentec Glass/Stone Massive (rainscreen with microventilation):
the presence of horizontal rafters implies narrowing and widening of the section of the ventilation cavity generating turbulent flows, regardless of the height of the ventilated rainscreen; the turbulence increases, and not decreases, both in the wide section that in that narrow, increasing the thickness of the air duct (it is therefore unnecessary to provide air ducts more than 4 cm); the turbulence decreases if the horizontal rafters are more closely spaced (30 cm instead of 60 cm); micro-ventilation around the elements of the ventilated rainscreen coating determines a greater flow of air flow that in turn generates turbulent flows; the combination of stack effect, wind incidence, and micro-ventilation generates turbulent flows greater than those present in the continuous ventilated rainscreen. It is therefore
not true as in general it is stated in commercial publications, that this type of wall is better than a continuous rainscreen, which therefore has advantages not only from the point of view of the air tightness and water proofing and of the isolation to airborne noise, but also in terms of fluid dynamics efficiency.

Contributions

Prof. Filiberto Lembo has coordinated and provided the objectives of the research. Msc. Eng. Francesco Paolo R. Marino has developed methodological and operational tools and verified search results. Msc. Eng. Vincenza Rabasco has done specific analysis in her thesis degree.

The contribution of the authors in editing and writing the text of the paper, was equal.

References