Assessment of an insulating air layer model of façade external system: contribution to fire simulation of facade performance fire test

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ABSTRACT

Ventilated façades as a part of external thermal insulation are useful systems when applied to building design, especially in bioclimatic construction. In the context of the fire safety engineering, well taking into account the air layer arranged in such systems is of importance to assess the fire behavior of a building. In fire engineering studies, CFD codes as FDS (Fire Dynamics Simulator) are widely used. However, mesh sizes used in simulation are generally greater than 100 mm. Thus, the air layer cannot be modeled accurately because of typical thickness lower than mesh size.

In the present study, a method based on an analytical formulation of the thermal resistance for building components is evaluated to approach the local air layer behavior. Radiative, convective and conductive mechanisms in the layer are then accounted. The proposed method could be implemented in a numerical model when a ventilated layer must be considered through an equivalent thermal conductivity for the air layer.

CFD simulations are performed with FDS for fire exposed façade during LEPIR II performance tests where the ventilated façades with the larger air layer thicknesses are modeled. Ambient conditions in terms of flow temperature and velocity inside the air layer are evaluated in several locations of the façade.

These façade models are then modified to replace the air layer by an equivalent thermal conductivity analytically assessed. Its local internal temperature is then compared with the one predicted with CFD, using 2D thermal calculations with the FEM code SAFIR. Extrapolations for smaller thicknesses of air layers that cannot be model with FDS can then be assessed numerically.

This preliminary work shows encouraging application for air layer reserved in façades during a fire. Further development and validation are in progress to apply this method to other configurations of air layering.

KEYWORDS

Fire modeling; Performance-based design; Façade fires; Heat transfer; Fluid dynamics; CFD; thermal analysis FEM; External thermal insulation.
INTRODUCTION

Ventilated façades as a part of external thermal insulation are useful systems when applied to building design, especially in bioclimatic construction. Actual energetic situation encourages engineers and architects to install such a solution in buildings to potentially improve their energy performance. However, in the context of the fire safety engineering, quite well accounting the air layer reserved in such systems is important to assess the fire behavior of a building, and in particular, the fire spread through façades.

A ventilated façade is a complex multi-layered structural system. It consists, in a simplified way, of an external façade cladding, a frame structure generally made of steel, aluminum or wood profiles anchored to the wall of the building, an insulating material and an air gap between the cladding and the insulation. In a ventilated cavity, as defined in [1], with openings at top and bottom, there is a continuous stream of air through the cavity. The air layer thickness is generally with a minimum of 20 mm to a maximum of 100 mm.

For combustible or weakly combustible insulation materials, further to its heating by radiation of the external cladding and by convection with the ambient conditions in the air layer, pyrolysis gases are released and can ignite, leading to a decrease of the system performances. The system with the lowest thickness of air layer is the most penalizing in case of a façade fire, the insulating material being closer of the cladding submitted to the flames. However, the low thickness of the air layer limits the inflammation of gases of pyrolysis released and transported in the layer. When the air layer presents a more important thickness, the insulating material is more distant from the cladding submitted to the external flames, and then less heated. However, the chimney effect, allowing the convection of hot gases, is more important for this configuration and the inflammation of released gases of pyrolysis is then favored. The temperatures in the air layer can also be high enough to reduce significantly the performances of the structure linking the cladding to the wall building. In particular, structural frame performances decrease at lower temperatures for aluminum or wood than for steel structures.

The building geometry is often modeled numerically in fire safety studies. CFD codes, as for example FDS [2], are widely used for this purpose in the French fire community. However, mesh sizes used in simulation are generally greater than 100 mm to ensure a reasonable calculation time. Thus, the air layer cannot be modeled accurately with only one or two cells. This study attempts to evaluate a method that could be implemented in numerical model when a ventilated layer as double-skin façade configuration must be considered. Based on an analytical formulation of thermal resistance for building components [1], the radiative, convective and conductive mechanisms in the layer are introduced through an equivalent thermal conductivity for air layer. CFD simulations are performed with FDS for fire exposed façade during LEPIR II tests [3]. Ventilated façades with larger thicknesses of 50 and 100 mm are modeled. Ambient conditions in terms of flow temperature and velocity inside the air layer are evaluated in several locations of the façade. These façade configurations are then modified to replace the air layer by the equivalent thermal conductivity assessed analytically. Its internal temperature is then compared with the one obtained with CFD using 2D calculations with the FEM thermal analysis code SAFIR [4]. Extrapolations for smaller thicknesses of air layers that cannot be model with FDS can then be assessed numerically.

EQUIVALENT MODEL FOR AIR LAYERS

Heat transfer across cavities in buildings is a complex process, made up of a combination of conduction in still air, convection from air movement within the cavity and radiation between the cavity sides. Some information is available on the air movement through wall cavities ([15] to [15]). For practical calculations of wall and air layer thermal transmittance, known as U coefficient, it is assumed in [1] that the heat transfer can be replaced by a standard thermal resistance, which depends on the direction of the heat flow. A similar method was used in [6] and [7]. The principle of the calculation method is to determine a thermal resistance R, expressed in m².K/W, for each thermally homogeneous layer of the system. For air layers, it is calculated in function of convective, conductive and radiative coefficients representative of flow condition in the cavity (Fig. 1). Then, these individual resistances are associated to determine the total thermal resistance of the system, expressed as a combination of resistors connected in series. The U coefficient is the inverse of the thermal resistance R. It is expressed in W/m².K and is representative of the thermal conductivity and the thickness of the layer.

The method applies for air gaps limited by two parallel faces, perpendicular to the direction of the heat flow, and whose emissivity are at least 0.8. The thickness of the air gap must be less than 300 mm and less than 10% of the two other dimensions (length and height) taken individually.

The formulas indicated in [1] are accounted directly to calculate the total transmittance of the air layer, without considering their derivation. However, the expression of the convective transmittance is easily
comparable with the one used in FDS or more generally expressed as (1) for the heat transfer coefficient depending on the local Nusselt number, or Reynolds and Prandtl numbers. The radiative transmittance (5) is close to the expression used to calculate the radiation between two parallel planes using the view factor.

\[ h_{\text{conv}} = \frac{1}{e} Nu = \frac{1}{e} Re^{1/3} Pr^{0.8} \]  

(1)

The conductive thermal transmittance \( U_{\text{cond}} \) is expressed in function of the air layer thickness \( e \) (m) and the air thermal conductivity \( \lambda_{\text{air}} \) (W/m.K) as given by the formula (3). The air layer is considered still. Convective is practically non-existent in air layers less than 4 mm thick. Beyond 20 mm thickness for air layers, the convective regime changes from viscous to dynamic domain. The empirical formula (4) allows calculating the convective transmittance \( U_{\text{conv}} \) in this region.

The energy exchanged by radiation between two plane and parallel surfaces separated by a distance \( e \) small relative to the dimensions of the surface is independent of this distance as well as the presence of a gas (transparent medium). However, the radiative transmittance \( U_{\text{ray}} \) strongly depends on the average temperature and of the nature of the walls as indicated by the formula (5), with \( \sigma_B \) (W/m².K⁴) the Boltzmann constant, \( \Delta T \) (K) the average temperature of the walls delimiting the air layer, and \( \varepsilon \) their respective emissivity. The radiative transmittance is large compared to the conductive and convective ones.

In thin air layers, conduction, convection and radiation contribute to the total transmittance \( U_{\text{tot,air}} \) (W/m².K) as expressed in (2). Thus, for a given cavity thickness \( e \), the more \( U_{\text{tot,air}} \) is high (inversely, the more \( R_{\text{tot,air}} \) is low), the more the equivalent thermal conductivity of the layer is elevated.

\[ U_{\text{tot,air}} = U_{\text{cond}} + U_{\text{conv}} + U_{\text{ray}} \]  

(2)

\[ R_{\text{tot,air}} = \frac{1}{U_{\text{tot,air}}} \]  

(3)

\[ U_{\text{cond}} = \frac{\lambda_{\text{air}}}{e} \]  

(3)

\[ U_{\text{conv}} = 0.73 \Delta T^{1/3} \quad (\Delta T > 5K) \]  

(4)

\[ U_{\text{ray}} = \frac{4\sigma_B \Delta T^3}{e_1 + \frac{1}{e_2} - 1} \]  

(5)  

Fig. 1. Thermal resistance calculated in function of convective, conductive and radiative mechanisms

Calculating a local thermal transmittance \( U_{\text{tot,air}} \) in the cavity is then representative of local flow conditions and captures the main heat transfer phenomena. In the specific case of a façade fire, the heat transfer inside the cavity is mainly driven by the external fire loads, inducing a chimney effect inside the air layer from the fire exposed bottom to the colder top. The external wind pressure coefficient is neglected in calculation. Despite the ascendant flow movement in the cavity, the cladding temperature exposed to fire and flame radiation is higher than the air gap temperature if there is no flame passage in the air cavity. Thus, the heat flow can be locally considered as horizontal.

For given temperatures in the cavity, representative of the parameter \( \Delta T \) in (4), the air conductivity \( \lambda_{\text{air}} \) used in (2) is known. Thus, \( U_{\text{tot,air}} \) can be evaluated for given flow condition assuming a horizontal heat flow. The equivalent \( U_{\text{tot,air}} \) calculated for air layers with thicknesses \( e = 20, 50 \) and \( 100 \) mm are indicated in Fig. 2. The layer thickness shows reduced influence on the value of \( U_{\text{tot,air}} \) in function of the air temperature.

An equivalent thermal conductivity of the air gap can be then calculated in function of the layer thickness and of the average temperature in the layer as (6).

\[ \lambda_{\text{air}} = U_{\text{tot,air}} \times e \]  

(6)

The implementation of this model in a heat transfer analysis is then possible, remembering that the thermal transmittance of the cladding is directly calculated using external thermal loads and material conductivity. The
results for the equivalent thermal conductivity show that the value of $\lambda_{\text{air}}$ for vertical air gaps increases, when the width $e$ of the air gap increases. Same result is observed in [6], both analytically and experimentally. However, the reader should be careful in the analysis of this result and must remember that the equivalent conductivity is calculated analytically in function of a generic average temperature $\Delta T$ in the cavity. Thus, for larger air cavities, the local average temperature is generally smaller than for thin cavities, and so will be the equivalent thermal air conductivity.

Fig. 2. Evaluation of the equivalent thermal transmittance and thermal conductivity of air gap with the average temperature for different air layer thickness and a height $H$ of $1.5$ m

**NUMERICAL MODELING OF THE AIR LAYER**

**Thermal environment**

In this study, fire exposed façade during LEPIR II [3] tests are addressed. A numerical model of the facility was validated [16] based on experimental results for two concrete calibration façades (Fig. 3 a and b). Thus, the fire source and the thermal loads imparted to the tested façade can be evaluated numerically with confidence. Simulations are performed with the CFD code FDS V6.5.2 [2]. In this study, the cladding consists in external panels made of cement fiber sheets of thickness $e = 8$ mm, a ventilated air layer, and a glass wool insulation with a thickness of $e = 300$ mm. Air layer thicknesses $e = 50$ mm and $e = 100$ mm are considered in simulation. In this paper, only results for $e = 50$ mm air gap are presented. In the vicinity of the façade, the mesh size is refined enough to capture the main flow phenomenon and cells with dimensions of $50$ mm are used. Cell size of $12.5$ mm is used for the air layer.

The thermal loads received at the exposed face of the system are then known and can be used locally to evaluate the heat transfer within the façade at different positions (Fig. 3 c, thermocouples in the air gap). Thermocouples TC 1 and TC 2 are located in the façade area directly exposed to flame outgoing from the windows of the fire room. Thermocouples TC 3 and TC 4 are rather located in the façade area exposed to radiation from external flames. Thermocouples TC 5 to TC 9 are in the façade area not impacted by flames.

Fig. 3. a) Numerical and b) experimental LEPIR II facility – c) location of thermocouples
Results for the air layer

Thermal transfer calculations are performed using the FEM code SAFIR [4]. A local 2D model with 1.5 m high is considered. The façade configuration is then modified to replace the air layer by the equivalent “air material” with the equivalent thermal conductivity assessed analytically. Simulations are performed at thermocouples location using the imparted heat fluxes obtained with FDS as boundary conditions for the cladding. The temperature of the air gap is then compared with the FDS ones on Fig. 4. The temperatures evaluated with SAFIR are very close to the FDS ones for thermocouples above the fire room of the facility (TC 2, 3 and 4). However, some overestimation is observed for TC 2, located directly above the fire room: the thermal analysis model cannot account for the strong convective effects at this location. For TC locations at the center of the facility not directly exposed to flames (TC 6, 7 and 8), good agreement is observed for temperatures, excepting for TC 8. At this location, the air layer is heated by the hot air coming from below and can be hotter than the cladding, so the heat flow is no more horizontal. In the case studied, the temperatures in the air layer are locally high enough to reduce the performances of the structure linking the cladding to the wall building.

Extrapolations to small air layers

Extrapolations for smaller thicknesses of air layers that cannot be model with FDS are then addressed. 2D simulation with the equivalent thermal conductivity of air are performed with SAFIR for thickness $e = 20$ mm and compared with temperatures obtained for air layer thickness of $e = 50$ mm in Fig. 5. We observe that temperatures are higher in the thinnest air layer at thermocouples location above the fire room (TC 1 and 2) and in the fire plume above the first level openings (TC 3 and 4). The system with the smallest thickness of air layer appears to be the most penalizing in the case studied, the insulating material being closer to the flames. When the air layer presents a more important thickness, the insulating material is more distant, then less heated. However, the chimney effect depending on temperature gradient is more important.
CONCLUSION

This preliminary work shows encouraging application for air layer reserved in façades during a fire. Good agreement is observed for air layer temperature evaluated with CFD simulations using FDS compared with simulations performed using the FEM thermal analysis code SAFIR using the equivalent air thermal conductivity model. This method will help to predict whether the critical temperatures for insulation and/or cladding frame are achieved or not, depending on the air gap configuration. Extrapolations to small air layers that cannot be modeled with FDS are then possible. Once fully validated, this method could be integrated in studies when ventilated systems exist and cannot be modeled accurately.

The analytical air layer model captures the main heat transfer phenomena in the cavity due mainly, in case of façade fire, to radiation between panels and convection by chimney effect. When applying the fire loads imparted to the cladding as boundary conditions, the heat transfer through the system will be representative of thermal gradients in the system and thus in the cavity. The local air temperature accounts for local chimney effect and radiation through the temperature evolution in the cavity, representative of the local convective and radiative transmittance. However, the model failed to predict the air layer temperature when strong convective effects occurred or when the heat flow is no more horizontal (ascendant hot gases hotter than cladding). The model is no more applicable if hot gases pass through the cladding, but can reasonably be used to assess local system performances in heat transfer analysis further to fire study.

Further development and validation are in progress for applying this method to other configurations of air layering. The model will be improved on more simple configurations to assess the thermal and fire behavior in ventilated systems. Specific small scale fire tests are necessary to appreciate the 3D convective phenomena in the air layer by measuring temperature, but also velocity. This will be part of the model validation process.

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