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Review

A co-simulation modelling approach for the assessment of a ventilated double-skin complex fenestration system coupled with a compact fan-coil unit

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ABSTRACT

Facade integrated ventilation systems have the potential to improve local air quality and occupant comfort, reduce building energy consumption and provide economic retrofit opportunities. However, existing modelling and evaluation methods are not able to sufficiently address the technology's potential capabilities. In this paper, a new model is developed specifically adapted to facade-integrated air handling units interacting with ventilated fenestration systems. The new modelling approach is based on the co-simulation of two different models through a Functional Mock-Up Unit (FMU) Interface. An airflow network model of the air handling unit is developed in Modelica and exported as an FMU based on this specification. The FMU is then simulated within an updated version of the building simulation program Fener that includes a physical model that calculates the window heat fluxes and temperatures, as well as the window gap air outlet temperature in case of ventilated facades. The different sub-models are first validated versus experimental data from a test chamber in Villafranca di Verona, Italy. Then, the full co-simulation approach is applied to a case study in which different control strategies for the fenestration system are investigated.

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List of symbols and acronyms

DGU	double glazing unit
$h_{cv,closed}$	convective heat transfer in a closed cavity [$W\,m^{-2}\,K^{-1}$]
$h_{cv,vent}$	convective heat transfer coefficients inside a cavity [$W\,m^{-2}\,K^{-1}$]
F	mass flow rate [$kg\,s^{-1}$]
F_G	correction factor
FIV	facade integrated ventilation
FMU	Functional Mock-Up
HVAC	heating, ventilation and air-conditioning
I_{max}	fan maximum current [A]
k	empirical parameter
LMTD	log-mean temperature difference [K]
N_{ph}	number of fan motor phases
P	air pressure [Pa]
PF	fan power factor
$\dot{Q}_{coil}$	total rated capacity of a coil [W]
UA	heat transfer coefficient of a heat exchanger [$W\,m^{-2}\,K^{-1}$]
v	average air speed in the cavity [$m\,s^{-1}$]
V_{rated}	fan rated voltage [V]
β	calibration factor

1. Introduction

Decentralized heating, ventilation and air-conditioning (HVAC) systems rely on the treatment of the outdoor air at the zone level. These systems are often less complex to install and control than centralized ones, which in many cases imply achieving a lower primary energy consumption [2]. In addition, facade integrated ventilation (FIV) systems have the potential to reduce space requirements for HVAC equipment while allowing more local control and increased responsiveness to user comfort [10,8]. FIV can also be better adapted for retrofits if an already existing centralized HVAC system is not available.

While the perceived advantages of FIV systems are numerous, and despite its current level of installation in Europe, this technology is not yet fully-mature [8]. New control strategies, as well as the use of thermal energy from renewable sources, are required in order to realize the potential of FIV technologies [2]. However, FIV research has mostly involved in situ examinations of either real or test systems. Computational examinations are limited and have not been able to sufficiently address the FIV technology's potential capabilities.

This paper presents a novel modelling approach specifically developed to assess a compact heat-recovery capable, packaged terminal air-conditioner with a ventilated window that features a between-pane, movable shading device. In such a hybrid system, a variety of performance goals may be achieved, such as minimizing the coils' energy consumption by preheating supply air through the ventilated window in winter or reducing the solar heat gain coefficient of the fenestration system by exhausting air from the HVAC system in summer. The general motivation was not to optimize this particular system but to develop a flexible method capable of contributing to the design of next-generation FIV systems, which may exploit the technology's full potential.

The new approach is based on the co-simulation of two different models in a common simulation interface. The Functional Mock-Up Unit (FMU) Interface defines a general method for coupling input and outputs across simulation tools. An airflow network model of the air handling unit is developed and exported as an FMU based on this specification. The FMU is then simulated within an updated version of the building simulation program Fener [1] (written in Python), which is specifically designed to evaluate the performance of complex fenestration systems and their control. The updated version of Fener includes the ISO 15099 Standard [12], a physical model that calculates the center-of-glazing heat fluxes and temperatures, as well as the window gap air outlet temperature in case of ventilated facades.

In this paper, first, a description of the proposed modelling approach is presented. Then the different sub-models of the ventilated fenestration system and air handling unit are validated against experimental data from a prototype of a ventilated double-skin complex fenestration system coupled with a compact fan-coil unit located in Villafranca di Verona (Italy). Finally, control strategies for the fenestration system are analysed by using the co-simulation approach.

2. Model description

The complete FIV system modeling problem has been decomposed into two sub-problems: the complex fenestration system acting as a ventilated window and shading device and the compact fan-coil unit.

2.1. Ventilated double-skin complex fenestration system

A model of a ventilated window has been developed based on the ISO 15099 Standard [12]. The physical model calculates the center-of-glazing heat fluxes and temperatures, as well as the facade air outlet temperature when ventilated. This method provides a normative approach, in which each layer, represented as a single temperature node, is assumed to be infinitely long, planar and parallel. An energy balance at each node accounts for radiation, convection and conduction heat transfer (i.e., blinds, air and glass layers) and for the node's absorbed solar energy.

The convective heat transfer coefficients inside the cavity $h_{cv,vent}$ are treated in a simplified way:

$$h_{cv,vent} = 2h_{cv,closed} + 4v, \quad (1)$$

where $h_{cv,closed}$ is the convective heat transfer in a closed cavity and v is the average air speed in the cavity. The ISO 15099 Standard handles the convective heat transfer in a simplified way in which convective heat transfer coefficients are assumed constant over the cavity height resulting in an exponential temperature profile. A more detailed calculation could use correlations that depend on the Reynolds number for forced flow between two plates.

For each layer, four variables exist: the front and back temperature of the layer, the longwave heat flux leaving the layer by the front surface and the longwave heat flux leaving the layer by the back surface. For each layer, four equations are derived from the energy balance. In case of a ventilated gap, one more variable, the gap average temperature, and one more equation, convective exchange with the cavity air, are added. This system of equations is then solved for every timestep. For the external boundary, the Standard uses the work of [5] to calculate convective heat transfer coefficients. These depend on the wind velocity and direction, differentiating between windward and leeward surfaces. For the radiative part, the model considers view factors, ground temperature, air temperatures and sky temperature. For the internal boundary, the convective heat transfer coefficients are calculated considering natural convection between the vertical internal glass pane and the interior air.

The model of a ventilated window is implemented in Fener [1], a building simulation model specifically developed for the evaluation of complex fenestration systems. The Fener model uses the three-phase method [14] and Bi-directional Scattering Distribution Functions (BSDF) to calculate the transmission of solar irradiance