Energy and Buildings 104 (2015) 97–107

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A simplified mathematical model for transient simulation of thermal performance and energy assessment for active facades

Hagar Elarga*, Michele De Carli, Angelo Zarrella

Department of Industrial Engineering—DII, Applied Physics Section, University of Padova, Via Venezia 1, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form 11 May 2015
Accepted 4 July 2015
Available online 7 July 2015

Keywords:
Double skin façade
Simplified mathematical models
Dynamic simulation
Room energy consumption
TABS

ABSTRACT

The extended use of double skin façade (DSF) in different kinds of buildings imposes HVAC (Heating Ventilation Air Conditioning) designers to use quick and accurate software to help in taking the right decisions related to energy consumption and thermal comfort. The lack of such methods was the motive to present this paper. Validation of a simplified mathematical model for dynamic simulation of the thermal performance of DSF was presented by comparing results with another detailed simulation model DIGITHON, for a complete year. Moreover the mathematical model was developed to calculate thermal energy due to convection losses from outer facade layer, solar gains and internal loads. A more detailed comparison of energy consumption at different climatic conditions of four cities in Europe has been shown. Implementation of the simplified model in thermo-active-building-system-(TABS) also was illustrated, and how such a model could be useful in one of four methods mentioned in standard ISO-11885-4 to predict heat transfer on TABS. This particular method needs the solar gains and losses due to transmission determined with a constant room temperature by another software which the mathematical model could be implemented in.

1. Introduction

Multiple-skin facade is an envelope construction, which consists of two transparent surfaces separated by a ventilated cavity. This intermediate space is an excellent zone to locate devices sheltered from weathering and soiling [1]. Double Skin Facades (DSF) can allow full height glazing while meeting thermal comfort and energy performance requirements of most perimeter zones for optimal performance. The building research and design community has an obligation to improve the currently available information and modelling tools so that design engineers can supply the increasing market demand with DSFs that meet all the performance expectations. Moreover, there are some lacks in the simplified modelling programs. Although CFD would provide greater accuracy and flexibility in evaluate thermal performance of DSF but it would increase the runtime substantially and increase the potential for incorrect input with users who are not familiar with it [2]. Todorovic and Maric [3] developed a model for evaluating the thermal performance of a DSF system. Different methods for estimating the inter-space air temperature and the associated cooling/heating loads were presented. Calculations are made for the climatic conditions of Europe mid-latitude (45°N). Results showed that in winter double façade reduces heat losses by more than 50%, due to both the higher inter-space temperature and the decreased infiltration. In summer period air circulation is essential. The air flow velocity strongly influences the inter-space temperature, and hence the heat gains by transmission. Arons [4] developed a simplified numerical model of a typical DSF. The purpose of steady state model is to predict the energy performance of multiple types of DSF. The basic configuration for the window under study has a layer of insulating glass on the exterior, an air cavity and a single interior layer of glass. An inlet is assumed at the bottom and an outlet at the top of the DSF. The model runs into difficulty with evaluating very low mass flow rates because the difference of temperature in the channel is defined relative to the inverse of the mass flow rate. Stec and van Paassen [5] developed a complete procedure to calculate the airflow and temperature distribution in the double skin façade using a static thermal heat balance network and considering wind and stack effect on the airflow, as well as the wind turbulence flow in the openings. The performance was analyzed based on heat recovery efficiency and the g-value. Heat recovery efficiency for the average winter day may reach even 50%. Nevertheless, the yearly average efficiency calculated by a dynamic simulation can be much lower due to the fact that the preheated ventilation is not always needed. Saelens et al. [6] presented a numerical model that evaluates the thermal behaviour of active envelopes and compared

---

* Corresponding author. Tel.: +39 049 827 6884; fax: +39 049 827 6896.
E-mail address: etchy1682@gmail.com (H. Elarga).

http://dx.doi.org/10.1016/j.enbuild.2015.07.007
0378-7788/

Nomenclature

$a_{(i)}$	solar absorption coefficient
A_f	area of facade
c_p	specific heat capacity (J/(kg K))
IL	internal loads
h_c	convection heat transfer coefficient (W/(m^2 K))
I_B	beam solar radiation (W/m^2)
I_D	diffuse solar radiation (W/m^2)
$I_{abs(i)}$	absorbed solar radiation (W/m^2)
I_{st}	total solar radiation (W/m^2)
$I_{\mathrm{st}-i}$	transmitted solar radiation through glass layer (i) (W/m^2)
L	plate length (m)
$\dot{m}$	supply air mass flow rate to façade cavity (kg/s)
R_C	convection thermal resistance per unit area (m^2 K)/W)
R_K	conduction thermal resistance per unit area (m^2 K/W)
R_{rad}	radiation thermal resistance per unit area (m^2 K/W)
Q_t	transmission heat loss (W)
Q_{sg}	solar gains (W)
Q_v	heat flux through cavity by ventilation (W)
Q_{room}	thermal load of the room (W)
T_{exh}	exhaust air temperature from the façade cavity (°C)
T_i	inside air room temperature (°C)
T_e	external air temperature (°C)
T_1	first glass pane left surface temperature (°C)
T_2	first glass pane right surface temperature (°C)
T_3	second glass pane left surface temperature (°C)
T_4	second glass pane right surface temperature (°C)
T_5	third glass pane left surface temperature (°C)
T_6	third glass pane right surface temperature (°C)
T_{23}	cavity-1 air temperature (°C)
T_{45}	cavity-2 air temperature, in case of no blinds (°C)
T_b	venetian blinds temperature (°C)
T_{b1}	air temperature in front of blinds (°C)
T_{b2}	air temperature behind blinds (°C)
T_g	inner glass temperature (°C)
T_m	mean temperature (°C)
V	flow velocity (m/s)
x	glass thickness (m)
σ	Stefan–Boltzmann constant, 5.67×10^{-8} (W/(m^2 K^4))
ρ	air density (kg/(m^3)
τ_i	transmission coefficient (–)
μ	dynamic viscosity (kg/(m s))
ε_i	emissivity (–)
λ	thermal conductivity (W/(m K))
θ_B	beam solar radiation incident angle (°)
θ_D	diffuse solar radiation incident angle (°)

with in site measurements. Agreement between the measurements and the simulations is considered good for the mechanical flow active envelope, but less so for the natural flow variant. The results were compared to those of a traditional cladding system, active envelopes proved to have lower transmission losses but higher transmission gains. The energy demand analysis shows that the energy performance strongly depends on the way the return cavity air is used. Manz et al. [7] presented an experimental and numerical study of a mechanically ventilated DSF with integrated shading device. Optical properties are calculated and a transient 2D computational fluid dynamic model. Simulated results are compared with data derived from an experimental investigation of a mechanically ventilated glass double façade built in an outdoor test facility it was concluded that a total solar energy transmittance of 7% means that solar energy absorbed in the façade is removed efficiently by mechanical ventilation. The use of numerical models to simulate the thermal and fluid dynamic behaviour of active transparent façade can therefore be considered extremely useful to assist designers' during the concept phase and to develop suitable control and integration strategies of the facade with the building installations [8]. Balocco and Colombari [9] presented a dimensionless model of a mechanically ventilated facade; this methodology applies the Buckingham theorem to create correlations depending on dimensionless numbers, hence the same parameters might describe the process at different scales. Fuliotto et al. [10] discussed decoupling method to separate the radiative heat transfer effects on the thermal and flow features inside a ventilated DSF in order to overcome the limitation of CFD computationally demanding modelling of radiation heat transfer models; the authors assumed that optical analysis may be conducted separately from the thermal analysis. The effect of solar radiation on a DSF was considered through a separate program [11].

Gosselin et al. [12] proposed a four step computational method that uses both computational fluid dynamics and coded radiation calculations to determine airflow and heat transfer through an airflow window. Experimental tests on a full-scale dual airflow window system were used to obtain various indoor and outdoor air and window surface temperatures for validating the computer method. The difference obtained between the computed air and surface temperatures and the measured data was less than 1 K. Jiru et al. [13] presented the application of the zonal approach for modelling airflow and temperature in a ventilated double skin facade (DSF). The zonal airflow equation, power-law, was employed to calculate the airflow through the shading device and cavities. The zonal energy equation was used to evaluate the temperature distribution in the DSF system. The inlet-outlet temperature difference increased as height of the DSF increased and when venetian blinds were installed but it was found to decrease as the airflow rate increased. Guardo et al. [14] evaluated, by means of computational fluid dynamics [15], the influence of several construction and operation parameters of the Active Transparent Facades (ATF), such as optical properties of the materials, geometrical relations of the facade or flow stream conditions, in terms of energy savings, measured as a reduction of the solar load entering the building. It was seen that an increase of the length-to-depth ratio causes a decrease on the ATF efficiency in terms of solar load gains. For the tested cases, an increase on the turbulence intensity does not lead to improvements in the reduction of solar load gains. Grabe [16] developed and validated a simple simulation algorithm based on energy transport and Bernoulli equations to predict temperature field in naturally ventilated DSF, the model proves the difficulty of modelling flow resistances in the air channel. Ciampi et al. [17] presented an analytical method in order to evaluate energy performance of ventilated DSF. The model did not consider solar radiation separation into beam and diffuse as well as the effect of solar incident angle. It was stated that the use of well designed ventilated facades in buildings can reduce the electricity consumption for summer cooling by more than 40%. Since the facade plays a role in creating the indoor comfort it can be considered as a component of the HVAC system. That is why the design of both HVAC system and facade should be optimized to reduce the costs and the energy consumption [18]. It is shown that it is possible to improve the building's energy efficiency in some way by using multiple-skin facades. Unfortunately, most typologies are incapable of lowering both the annual heating and cooling demand. Only by combining typologies or changing the system settings according to the particular situation, a substantial overall improvement. In order to correctly evaluate the energy efficiency, an annual energy simulation