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Heat transfer and air movement behaviour in a double-skin façade

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ABSTRACT

Theoretical and practical evaluation of a naturally ventilated double skin façade has been undertaken. The study has shown that the double skin façade (DSF) system is capable of supplying adequate ventilation to various levels with little or no additional heating during winter thus saving the bulk percentage of the heating load on the building. However there was an element of overheating in the DSF which may have contributed to an additional cooling load on the building. Even though the operational strategy of mixing return air with trapped air in the cavity helped to minimise the overheating effect, there was still some considerable level of temperature increase in the DSF. Effective thermal management control strategies and systems are therefore encouraged in the design and operation of DSFs.

1. Introduction

Within the framework of modern building design concepts, double skin façades (DSFs) have emerged as one of the potential energy saving design features being promoted around the world. For instance recent rapid economic development in China has seen a rising number of new commercial buildings with DSFs especially in the hot-summer and cold-winter regions such as Shanghai and Hangzhou (Zhou & Chen, 2010). DSF systems normally consist of internal walls and additional external walls with air cavity between the inner and outer skins. As compared with conventional facade systems, DSFs are credited with providing significant reduction in energy consumption, providing for natural ventilation even in skyscrapers, controlling valuable noise reduction from outside and helping to adjust indoor climates in both new and some existing buildings (Marques da Sliva, Gomes, Pinto, Pereira, & Moret Rodrigues, 2006; Poirazis, 2006; Rovers, 2012). DSFs have also the benefit of creating a visually transparent architecture that is impossible with conventional curtain wall facades with similar properties.

Even though these studies support the energy efficiency potential of DSFs, there is an issue relating to overheating during warm periods which tend to create additional cooling load in buildings through solar heat gains on the façades especially at higher floor levels (Faggembauu, Costa, Soria, & Oliva, 2003; Gratia & De Herde, 2004a; Gratia & De Herde, 2004b; Perino, Corgnati, & Serra, 2007; Tanimoto & Kimura, 1997). In some DSF cases shading devices such as mid-pane blinds and internal blinds are being used in providing solar shading but they are believed to contribute to additional heat source linked with complex long wave radiation exchange, increased air temperature and buoyancy effect in the cavities (Kalyanova & Heiselberg, 2009a). These interrelated parameters are all part of the difficulties facing thermal management of DSFs. Other dynamic factors such as air flow rate, variable convective surface film and radiation heat transfer coefficients and transmission of solar radiation also make modelling and simulation of DSFs difficult.

Meanwhile a number of studies (Hanby et al., 2008; Hoseggen, Wachenfeldt, & Hanssen, 2008; Jiru & Haghighat, 2008; Park, 2003) have been undertaken and reported about flow visualisation and thermal performance of DSFs but there is still inadequate research information about their true effectiveness during cold, hot and humid seasons. In order to gain more understanding and to acquire reliable data for future design and simulation exercises, the current study evaluates the airflow and thermal performance behaviour of a DSF building located in a hot and cold region.

2. The DSF building

The building under evaluation is located at Ningbo China which has a subtropical climate, featuring mild temperatures, moderate to high humidity and distinct seasons. The hottest month is normally July, where temperatures could reach about 39 °C whereas the coldest month is January, with temperature around about −5 °C at night. The building incorporates a double skin façade south facing wall which tilts forward from both the top and the base of the wall. The tilted surface helps to deflect most of the solar radiation and thus reduce solar transmission through the façade during summer period. During winter period the opening at the top of the DSF is closed to allow fresh air to enter the building through openings

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Nomenclature

$C_{1\varepsilon}$,C_2	Constants
c_p	specific heat (J/kg K)
E	total energy (J/kg)
G_b	generation of turbulence kinetic energy due to buoyancy (J/s m^3)
G_k	generation of turbulence kinetic energy due to the mean velocity gradients (J/s m^3)
g_i	component of the gravitational vector in the ith direction
h	specific sensible enthalpy (J/kg)
h_j	specific sensible enthalpy of species j (J/kg)
k	thermal conductivity (W/m K)
k_{eff}	effective thermal conductivity (W/m K)
p	pressure (Pa)
Pr_t	turbulent Prandtl number for energy
σ_k, σ_ε	turbulent Prandtl numbers for k and ε models
S	modulus of the mean rate-of-strain tensor
S_k, S_ε, S_{ij}	user-defined source terms
T	temperature (K)
T_{ref}	reference temperature (K)
t	time (s)
V	velocity (m/s)
v	component of the flow velocity parallel to the gravitational vector (m/s)
u	component of the flow velocity perpendicular to the gravitational vector
u_i,u_j,u_k	velocity for different direction (m/s)
x	length (m)
x_i, x_j,x_k	length in different direction (m)
Y_j	mass fraction of species j

Greek letter

β	thermal expansion coefficient
ε	dissipation rate
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	density (kg/m^3)
τ	deviatoric stress tensor

in the base of the inner glass façade. The return air supply is evacuated through the top opening in the light-well as shown in Fig. 1a. In summer, the DSF serves as a thermal buffer for reducing heat gain into the building and for removing the extract ventilation from the building as shown in Fig. 1b.

3. Mathematical modelling

FLUENT software (Inc, 2007a) was used to simulate the airflow and temperature distribution in the cavity of the DSF. Normally this requires the geometric space to be divided into a finite volume grid. By default grid regions are spaced uniformly using a system that is calculated to be as close as possible to the user-defined default grid spacing. However, very narrow regions resulting in long, narrow grid cells or cells having a high aspect ratio need to be avoided since they tend to result in unstable solutions that can fail to converge. Large numbers of key coordinates can also lead to overly complex grids and correspondingly high calculation run times and excessive memory usage. Therefore for the benefit of saving computational resources and calculation time as well as minimising errors, an initial grid size of 0.5 mm was varied in steps to a maximum size of 2 mm (i.e. about 1.5 times the initial mesh size) until the solution became independent of the mesh resolution. The mesh volumes were solved to a residual of less than the default criterion of 10^{-3} ($<10^{-3}$) and that of energy to a residual less than 10^{-6} ($<10^{-6}$). The model was also simplified to a two dimensional section of the building.

3.1. Generalised transport equations

The Boussinesq approximation (Eq. (1)) was used to solve the buoyancy-driven air flows and natural convection. For the turbulence model, the Standard k-epsilon (k-ε) model (Inc, 2007b) was applied since it is one of the most frequently used models in fluid dynamics and also the most common turbulence model for fluid flow simulations. It is also preferred to other models since it is able to deal with laminar and transitional flow patterns at the same time.

The governing flow equations for the fluid density as a function of temperature, conservation of heat, mass and momentum were expressed as follows:

Flow density:

$$(\rho - \rho)_g \approx -\rho_0 \beta (T - T_0) g \tag{1}$$

Energy equation in vector form

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot (k_{eff} \nabla T) + S_h \tag{2}$$

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{3}$$

Momentum conservation equation

$$\frac{\partial}{\partial x}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{4}$$

The modelled transport equations for k and ε are expressed as:

3.1.1. Turbulent kinetic energy (k-equation)

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon + S_k \tag{5}$$

3.1.2. Dissipation (ε-equation)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1s}\frac{\varepsilon}{k} C_{3s} G_b + S_\varepsilon \tag{6}$$

The generation of turbulence kinetic energy due to the mean velocity gradient in accordance with Boussinesq hypothesis (Inc, 2007c) is given as;

$$G_k = \mu_t S^2 \tag{7}$$

$$G_b = \beta g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \tag{8}$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{9}$$

In FLUENT and by default, the generation of turbulence dissipation energy due to buoyancy is neglected. G_b, is therefore taken as zero in the dissipation ε-equation.