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CFD SUPPORTED MODELLING OF DOUBLE SKIN FACADES IN HOT ARID CLIMATES

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ABSTRACT

Previous simulations predict the possibility of reducing cooling demands in office buildings in hot arid areas if a selective double skin facade is used. The reductions on cooling loads in rooms range between 19%-40% depending on the glazing thermal and visual performance characteristics of the exterior glazing of the double skin façade. However considerable uncertainty exists about the air flow rates and temperatures experienced within the channels of these facades. In this work a CFD model is used to predict these conditions for the case of an air-conditioned building in a hot arid climate. This case uniquely allows a CFD model to be applied to the facade independent of the simulation of the main building and its plant. Results show appreciable flow rates and temperatures generated mainly by buoyancy flow over the outer facade skin.

INTRODUCTION

In Egypt annual electricity demand is increasing by 6-7%, this is attributed to the increase in electricity consumption for industrialization, and in the built environment. The built environment consumes 52% of the gross national production of generated electricity. Within the public electricity consumption domain, office buildings stand out as a major energy consumer. Since the late 1970s, the public sector dependence on air cooling systems has been continuously rising, which in turn increases the energy consumption of these buildings. The configuration of office building facades in hot arid areas has a major impact on reducing/increasing the building's energy demand, depending on the building location, micro-climate and occupancy the façade's configuration is responsible for up to 40% of the cooling loads. The dynamic relation between the building -with its façade configuration, the age and type of the building services and systems, the building occupational patterns- and the building exposure to its micro-climate indicates the pattern of energy consumption.

THE CONTEXT

Facade retrofits and the implementation of energy conservation measures are regarded as a cost effective means of reducing building energy consumption. Cairo (Egypt) is situated in a hot arid climate, with growing demands on the installation of cooling systems to maintain suitable work environments. With a migration of North American and European architectural styles and working hours from 9-5, coinciding with peak day temperatures, Cairo as a case study is similar in socio-cultural, and thermal comfort requirements to other cities in hot arid climates in developing countries.

Office buildings in Cairo date back to the 1880's, due to economic restrictions these buildings had undergone limited façade refurbishment. Wooden shutters have been removed as occupants thought they blocked the view out, and collected dust. Split air-conditioning systems perforated building facades, indicating indoor thermal discomfort. The energy consumption in these buildings increased, burdening the national gross energy production. Energy production increased 57% in ten years, while energy use in commercial buildings has been increasing by 7-8% annually.

Applying second building skin technologies has been experimented by several leading architects in Europe, Australia and Japan. This paper explores the potential of double skin façades as an energy conscious architectural technology. Double skin façades scenarios have been simulated on a virtual base-case. The physical and architectural configuration of the base case facades are based on analysis of an existing 33 office building facades in Cairo-Egypt. A dynamic integrated Environmental Systems software (IES v 5.1) was used to predict the thermal performance of double skin façade in the hot arid climatic context of Cairo.

Monitored performance of double skin configurations in moderate climate (Oesterle et al, 2001 and Saelens 2002) and predictions for its performance in hot arid climates (Hamza 2004, and Afifi 1999) indicate that on warm and hot days the exterior leaf would reduce direct solar heat gain in rooms; trapped heat in the gap induces natural buoyancy which in turn would reduce elevated air temperatures away from the inner building skin.

This may result in additional reduction of conductive heat gains through the inner façade layers into the occupied space. However, the building simulation tool can not predict the air change rate in the cavity and its effect on cooling loads in office rooms.

A methodology has been developed to use CFD to find out peak and minimum predictions for the air change rate within the double skin cavity rate. Results of CFD simulations are then fed into a whole building simulation tool to test the influences of cavity air flow rate and inner surface resistances on room cooling demands.

This work departs from previous attempts on double-skin facade modelling in that the special case of an air conditioned building in a hot arid climate is considered from the perspective of air conditioning load reduction. Most of the previous work concerning double skin facades has focused on naturally-ventilated buildings in temperate climates from the perspective of enhancing ventilation rates.

USING CFD IN MODELING DOUBLE SKIN CAVITIES

The modelling of double skin facades, Trombe walls and solar chimneys have received substantial attention over the years. Simplified steady-state models using coupled lumped-parameter and nodal methods have been reported for solar chimney-enhanced natural ventilation by Raman *et al.* 2001; a multi-storey double skin façade model by Hensen *et al.* (2002) and for low rise ventilated facades by Balocco (2002). Other researchers have investigated these applications using the more sophisticated modelling approach of computational fluid dynamics (CFD). Safer *et al.* (2004) dealt with single storey double skin facades with Venetian blinds; Gan (1998) modelled a single storey Trombe wall and Ding *et al.* 2005 investigated a multi-storey double skin façade application with an added solar chimney in a naturally-ventilated building application using CFD.

A CFD approach to this type of problem usually demands a high computational cost due to the various flow field interactions within the double skin channel and the attaching ventilated spaces. Indeed this argument was used by Hensen *et al.* 2002 as a basis for the development of their simplified nodal network model. However, in air conditioned buildings within which double skin details may be considered as a means of reducing heat gain loads, the internal zones of the problem domain are isolated from the channel flow phenomena leading to a simpler problem definition with better amenability to treatment using CFD.

In network air flow modelling, a procedure is needed to determine the convection coefficients at the internal surfaces of the channel. The buoyancy-driven channel flow rate is dependent on the temperature difference between the discharge and inlet of the channel and the discharge temperature will depend on the rate of heating of the buoyant air stream as it moves up the channel which in turn is dependent on the surface convection coefficients of the enclosing channel surfaces. In turn, the convection coefficient depends on the surface-to-air film temperature difference according to the Grashof number. Thus the channel air flow rate and temperature are inter-dependent. A network model therefore requires a relationship linking these variables to the prediction of the surface convection coefficient. Such a relationship might be obtained using CFD (relatively easy but of uncertain accuracy) or by measurement (potentially accurate but difficult and expensive). The use of CFD to solve the channel flow and temperature variables as a conjugate field problem bypasses this difficult completely. As pointed out by Hensen *et al.* 2002 a similar difficulty arises regarding the need to supply friction coefficients in order to predict pressure losses (and the consequential impact that these losses have on flow) through the channel. Again, preliminary modelling using CFD or measurements can be resorted to whereas the use of CFD at the outset bypasses this difficulty (though it is acknowledged that surface friction effects are likely to be insignificant in the present wide-channel flow problem).

Hence a CFD approach has to be preferable to simplified methods for this type of problem provided that it is possible to adequately and confidently describe the problem boundary conditions and the solution can be obtained within “acceptable” computational cost. The unique features of the present problem make the first of these issues possible and, as will be revealed later, the computational cost has been found to be very moderate. Therefore CFD has been adopted to identify the range of flow conditions likely within the channel together with the channel surface heat transfer coefficients. This range of results is then used in a traditional energy simulation to predict reductions in solar heat gain through the façade. The intention was not to use CFD to dynamically predict channel flow conditions but instead to identify the likely range of conditions that might be expected in order to improve the utility and accuracy of the traditional energy simulation method that was subsequently used for air conditioning loads analysis.

CFD MODELLING OBJECTIVES

The unique simplification afforded by this problem is due to the internal office zones being air conditioned and consequently maintained at a constant temperature during the day. The double skin façade has no flow coupling with the internal spaces. This means that the double skin channel can be modelled with reference to a constant internal boundary condition; there are no inter-dependencies and there is no particular need to attempt to couple the CFD simulation to a thermal simulation of the building and its plant as far as the performance of the façade itself under defined boundary conditions is concerned.

This leaves three straightforward CFD modelling objectives:

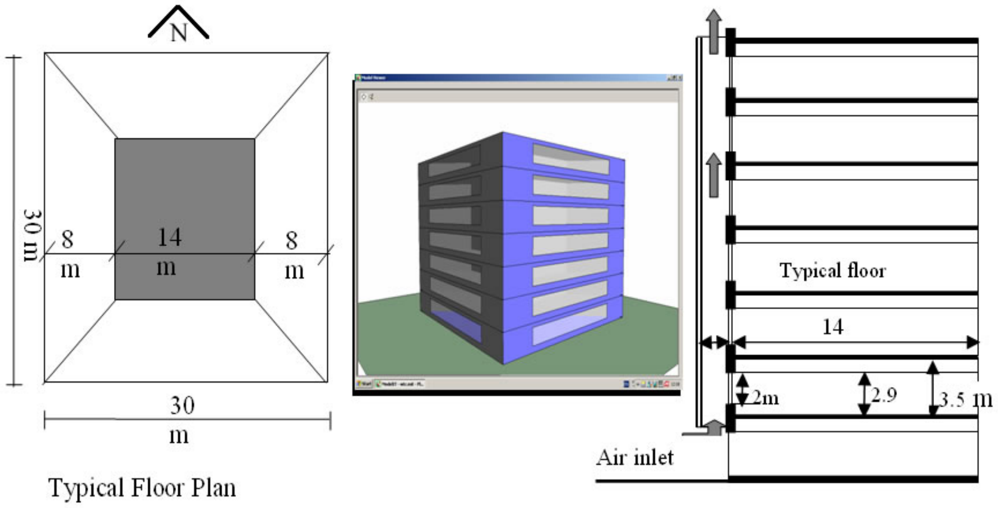
1. To determine the buoyancy-driven channel air flow rates and temperatures as a function of the incident solar radiation and external air temperature
2. To verify whether the assumed channel width (1.0 m) is appropriate
3. To determine maximum outer skin operating temperatures for comparison with safe operating limits

TMODEL AND THE OPERATIONAL PROFILE:

Figure (1) presents the physical attributes of the Base Case model. The model is not surrounded by other buildings. Glazing is assumed to be clear and covers a 40%WWR (Window to wall ratio). Walls are constructed of a single leaf un-insulated wall infill.

All simulation results are based on the predictions of the performance of the forth level of the model. This is to reduce the effect of ground reflectance, and over-heating from the roof on simulation results.

- The independent variables are:
- Outdoor air supply rates for sedentary occupants is 8 l.s^{-1} person^{-1}.
- Summer dry resultant temperature (operative temperature) in office buildings general spaces/ open plans should be between 22-24 C^0 (± 1.5).
- Humidity levels are controlled between 30-70%.
- Infiltration is calculated at 0.5ac/hr. Recent air tightness levels were shown to achieve 0.25ac/hr. Due to the age of office stock in Cairo and from experience with workmanship levels, the higher value was used in simulations.
- occupancy pattern from 9am-5p.m. is assumed. Occupancy sensible gains are at 90 W/person, and one person occupies 10 m^2.
- 16 W/m^2 and lighting maintained luminance levels of 500Lux were assumed for lighting electricity consumption. Fluorescent lighting fixtures utilize 100% of the installed power during office hours and 5% in non-office hours.
- For Office machinery sensible gains of 15 W/ m^2 were assumed.



Typical Floor Plan

Figure 1 : Single skin plan and isometric configurations, and Double Skin façade configuration

CHANGING THE GLAZING PROPERTIES ON THE OUTER SKIN:

Simulations indicate that compared to changing glazing properties on a single skin façade, double skin facades with tinted or reflective glazing produced significant reductions on cooling loads in office rooms on all four Orientations of the building. Refurbishing a clear glazed building with a reflective outer surface on the double skin façade is predicted to decrease the annual cooling load by 40% (Hamza, 2004). The use of reflective glazing on the exterior leaf of the double skin façade model was superior to changing the glazing on single skin facades to tinted (heat absorbing) glazing in reducing the total cooling load on monthly levels year round. Compared to Base case with its clear glass configuration (considered as a poor thermal performance façade) reductions of the annual total cooling loads were predicted to be 19% less.

However, daylight simulations indicate that contrary to using tinted double skin, using a reflective double skin façade substantially reduces daylight levels especially in cloudy conditions which may partially offset the reductions in cooling loads due to the need to switch on lighting. This effect is currently being studied to quantify this offset. Therefore in this paper the an absorptive tinted glazing is used for simulations.

PROBLEM DEFINITION

A three zone modelling domain was identified consisting of the channel with two boundary zones separated by the channel "skins". Though there are no flow connections between the three zones there is heat transfer across the skins. The outer skin, consisting of coated solar glass with a high absorptance (0.57), forms the main pathway for solar heat rejection partly due to reflection but mainly due to convection through the channel and from the external face. The inner skin, consisting of clear glazing and brick infill sections, absorbs most of the remaining solar energy transmitted from the outer skin. These skin heat exchanges required that the problem be defined as a conjugate one and the calculation mesh therefore included the skin material so that conduction transfers through them could be included.

A uniformly rectangular structured mesh was defined with 26 regions in x (i.e. through the cross sectional plane). With one region defined through each glass layer and three through the infill panel, this left 22 regions of equal width to be more or less uniformly divided amongst the three air zones. One region was used for the width plane (in y) due to symmetry and the height plane (z) was divided into 100 cells. Thus the overall calculation domain was divided into 2600 cells in two dimensions. Figure 2, gives a cross-section through the geometry.

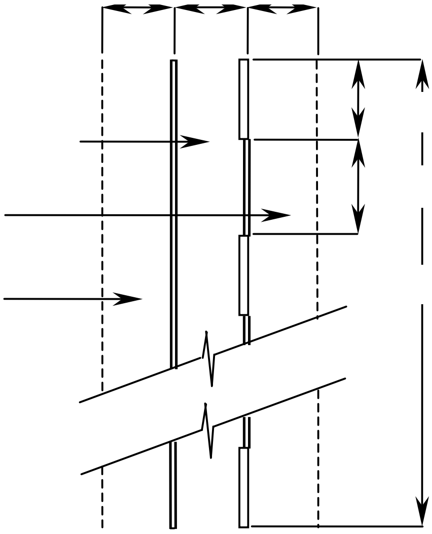


Figure 2: Cross-section through CFD modelling domain

METHODS USED

The problem was defined and simulated using Phoenics (version 3.5.1), Cham, 2004. After some preliminary tests using several low Reynolds number turbulence models, the Lam & Bremhorst low-Re version of the 2-equation k-ε turbulence model was selected due to its favourable stability qualities and acceptable computational cost demands. Buoyancy influences were included using the Boussinesq approximation. Under all conditions of boundary inputs 6000 iteration sweeps were found to be necessary to reach complete convergence. The typical processing time was 13 minutes based on a 2.4GHz Pentium 4 processor with 512 RAM. Longwave radiation exchanges both within the channel and with the sky vault were neglected.

Selection of Boundary Conditions and Inputs

With internal office zones air conditioned, the internal boundary zone was treated as a single volume of air at a constant temperature of 22^{o}C and an average velocity in z of 0.1 ms^{-1} to reflect a typical mean air velocity for an air conditioned space.

A review of a TMY data set for Cairo suggested dry bulb temperatures varying through the main summer months within the range of 20^{o}C (typical summer daytime minimum) to 39.7^{o}C (peak). Simulations were therefore conducted for three external dry bulb temperatures in this range (20°C, 30°C and 40°C).

Of course the ambient temperature may be higher or lower at street level than the value measured at some other reference point (e.g. due to "heat island" effect or due to air conditioning system "spillage" from the building near entry/exit points) but there can be no physical justification for altering the observed value. Saelens *et al.* 2003 argue that the inlet temperature to multiple skin façade systems is usually higher than the external temperature due to heat transfer in the inlet zone. They evaluate this for an application in a single storey building which has a multiple skin façade in which external air is drawn into an inlet grid which feeds into an inlet zone prior to entering the channel. We argue that any inlet zone should be included in the model so that any pre-channel heat transfer is then accounted for. Thus the external air temperature can be taken to be the same as the inlet air temperature. In the present work, air enters the channel through a plain horizontal opening which is 3m above ground level and thus this assumption is valid.

The effect of wind forces has not been included in this sheltered inner-city application. The choices of mean surface velocities for external channel surfaces have been made merely to enable the external surface convection effects to be dealt with. Typical wind speed data for the region suggest moderate values up to about 3– 4 ms^{-1} peaking beyond this during periods of sandstorms. Since the building of interest is located within the commercial heart of the city, a certain amount of shelter is to be expected and a nominal value of 2 ms^{-1} was therefore fixed across the outer surface of the outer skin. The entry and exit points to the channel were defined as connections to still external air at the appropriate dry bulb temperature value.

The absorbed portion of total solar radiation incident on the outer glazing layer forms a heat flux source to this glazing layer and the transmitted portion from this layer goes on to contribute to absorbed heat flux sources to the inner channel glazing and infill panels. These heat sources have been calculated for a range of conditions as follows. The normal incidence transmittance and reflectance of the outer glass skin were 0.15 and 0.28 respectively resulting in an absorptance of 0.57. The absorptances of the inner skin materials were taken to be 0.11 (clear glass) and 0.76 (brick infill cladding). An analysis of clear day total solar intensities normal to unshaded vertical construction elements located in Cairo suggested values varying from 100 Wm^{-2} (shaded surface); 250 Wm^{-2} (maximum, due south) and 650 Wm^{-2} (maximum, due east or due west). Therefore four "standard" solar intensities were chosen to represent a range of typical surface conditions: 100; 300; 500; 700 Wm^{-2}. Applying the outer skin transmittance and absorptance and the inner skin absorptance values leads to values of material heat sources arising from absorbed solar radiation (Table 1). The contributions of inter-reflected solar radiation within the channel were neglected.

Simulations were conducted for the three external air temperature boundary conditions together with the four sets of material heat fluxes given in Table 1 resulting in a total of 12 simulations covering the range of clear summer conditions that might be expected for an application of this kind in Cairo.

Table 1: "Standard" skin heat source values

Total Solar Intensity (Wm^{-2})	**Outer Skin (Wm^{-2})**	**Inner Glazing (Wm^{-2})**	**Infill Panel (Wm^{-2})**
100	57.0	11.4	1.7
300	171.0	34.2	5.0
500	285.0	57.0	8.3
700	399.0	79.8	11.6

Results and Discussion

Due to the large volume of data emerging from the 12 simulations, key outcomes have been plotted on two summary graphs designed to capture most of the results that directly address the modelling objectives. Figure 3 summarises mean channel outlet temperatures and velocities at the outlet of the channel. The mean velocity will in any case be uniform throughout the channel on account of continuity.

In Figure 4, the distribution of both temperature and velocity is plotted along *x* (i.e. channel cross section) at the channel outlet (where the temperature distribution will be at its maximum) for the case in which the external air temperature boundary condition 30°C.

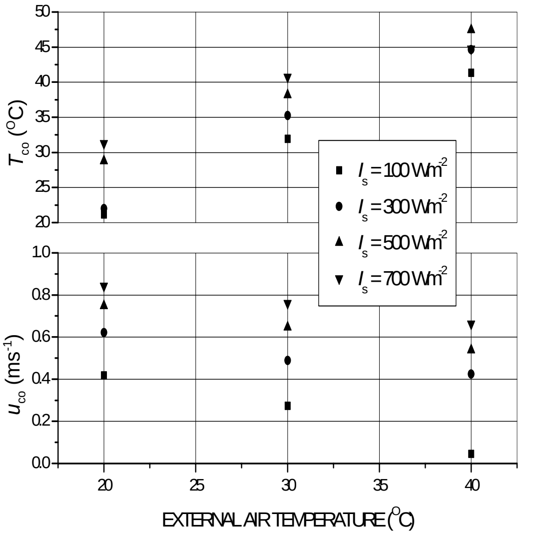


Figure 3: Channel air velocity and outlet temperature

(I_s = total solar intensity; T_{co} = channel outlet air temperature; u_{co} = mean channel velocity)

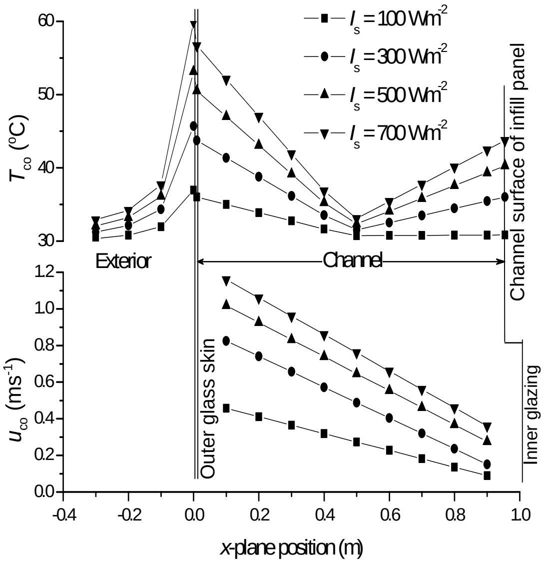


Figure 4: Temperature and velocity distributions at 30°C external air

(I_s = total solar intensity; T_{co} = channel outlet air temperature; u_{co} = mean channel velocity)

DISCUSSION

In relation to the three CFD modelling objectives:

Figure 4 illustrates the effectiveness of the high-absorptance outer skin in promoting a vigorous flow of air over its surfaces and, hence, entrained air in other parts of the channel. The influence of the inner skin materials is minimal in this application as might be expected. Figure 3 shows that the flow development through the channel increases with increasing solar intensity but reduced with increasing external air temperature at any given value of solar intensity.

The range of mean channel velocities were found to lie within 0.045 ms^{-1} – 0.84 ms^{-1} (with reference to conditions at the top of the channel for which the mean cross sectional temperatures were 41.3°C and 31.3°C respectively). This range corresponds to a minimum flow condition when the external temperature is a maximum and the solar intensity a minimum (e.g. hot cloudy or in-shade conditions) to a maximum when the external temperature is a minimum and the solar intensity a maximum (e.g. early summer with lower direct sun angles). The range of flow suggests very low flow resistances through the channel and the potential for a reduction in channel width with corresponding implications for reduced construction costs. This warrants further research.

Corresponding to the range of mean channel velocities, the range of mean channel surface convection coefficients obtained were 6.03Wm^{-2}K^{-1} – 62.45W^{-2}K^{-1}. The lower value corresponds to a “typical” internal building surface coefficient whereas the higher value is roughly twice the “typical” coefficient that might be used for the external surface of a building under “exposed” conditions (CIBSE 1999). These values were used to replace the default surface coefficients for those materials making up the channel space in the IES model.

Figure 4 confirms that the peak temperature region of the domain lies within the outer glass skin as expected and this, in turn, will be a maximum at the top of the channel when under maximum conditions of heating. The temperature at this point for the case in which the external air temperature and total solar intensity were maxima (not plotted) was found to be 66.0°C. Manufacturers would require to be consulted regarding the acceptability of this in relation to glass and fixing stresses.

Effect of air flow rates on room sensible cooling loads

Maximum and minimum mass flow rates in the cavity predicted by CFD were then inducted into the building simulation software IES v.5. and simulated. Results are averaged over July and August as the peak summer month of the year in Cairo to align with temperatures assumed in the CFD modelling.

The range of mass flow rates predicted based on the CFD simulations, is 0.5kg/s to 0.94kg/s

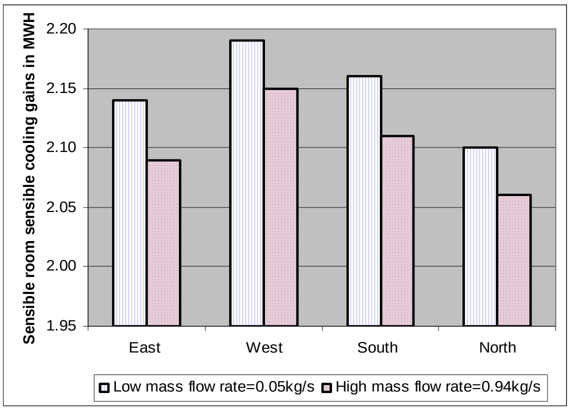


Figure 5: Comparison between sensible cooling loads in office rooms behind an absorptive double skin façade in a hot arid climate

Figure 5, indicates an inverse relationship between cooling demands and cavity flow rates. The higher flow rate the less sensible cooling demand was predicted. However, the differences between the higher and lowest predicted air change rates in the cavity results in a 2% reduction in the sensible cooling loads, which leads to the conclusion that the visual and physical properties of the external glazing are the most dominant factor affecting the cooling loads in rooms.

CONCLUSIONS

1. Although a reflective double skin facade has the most profound effect on reducing room cooling loads, in this paper an absorptive glazing double skin façade was found to be highly effective.
2. Results from CFD simulations predict that heat conducted into the cavity from the absorptive glazing combined with higher ambient temperatures leads to increasing the mass flow rate (and, hence , heat removal rate) within the cavity. Air flow rates of between 0.5kg/s and 0.94kg/s over the range of possible solar irradiances.
3. Results from building simulation software indicates that the effect of changing the mass flow rates in the range 0.5kg/s - 0.94kg/s has a minor effect on room sensible cooling loads (about 2%).
4. Further work is required to explore the impact of a range of ambient wind pressure conditions in order to increase the applicability of the present work to sites with significant wind behaviour. The impact of longwave radiation heat exchange between the skins and between the outer skin, sky and ambient environment also merit further work.

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