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Modeling and Simulation of a Double-Skin Façade System

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ABSTRACT

Starting from a practical design problem related to natural and hybrid ventilation systems, this paper looks at different airflow modeling methods that might be employed to assist in the decision-making process of a building design team. The question at hand is whether or not to make use of a double-skin façade system in a new office development. The airflow modeling methods considered are the mass balance network method and computational fluid dynamics (CFD).

The paper gives an overview of the methodology of the design study. The underlying modeling and simulation work is elaborated. The paper finishes with some conclusions, both in terms of the actual performance of the double-skin facade and in terms of the modeling and simulation work.

The main conclusions are that, for the foreseeable future, the network method is more suited for this type of "everyday" design support work. However, there are important areas where the network method in general might benefit from CFD, or vice-versa.

INTRODUCTION

In Europe and elsewhere, fully glazed façade systems are currently very popular with architects and investors. Even in moderate climatic zones, fully glazed buildings need shading devices in order to reduce cooling loads. External shading devices are much more effective than internal shading devices. However, external shading devices are not very popular due to mechanical, cost, and aesthetic reasons. An often-used alternative is a shading device positioned within the façade in a ventilated cavity. In the 1970s, the climate-window concept was developed, in which the cavity is ventilated with inside air. A more recent development is the double-skin façade concept, as shown in Figure 1, in which the cavity is ventilated with ambient air. If a design team decides for a double-skin façade, a logical next step is to make the cavity an integral part of the natural or hybrid ventilation system, for example, by operable office windows that open to the cavity or by using the cavity for preheating fresh supply air during the heating season.

To predict the performance of a double-skin façade is not a trivial exercise. The temperatures and airflows result from many simultaneous thermal, optical, and fluid flow processes, which interact and are highly dynamic. These processes depend on geometric, thermophysical, optical, and aerodynamic properties of the various components of the double-skin façade structure and of the building itself. The temperature inside the offices, the ambient temperature, wind speed, wind direction, transmitted, and absorbed solar radiation and angles of incidence—each of which are highly transient—govern the main driving forces. This typically results in highly erratic airflows, as indicated in Figure 2.

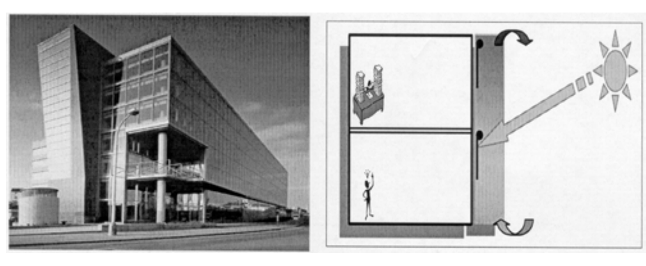

Figure 1 *Typical example and principle of double-skin façade.*

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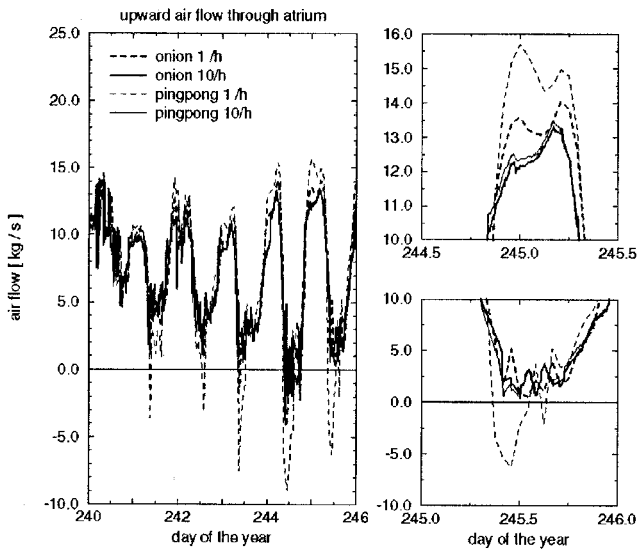

Figure 2 *Typical airflow variations in a natural ventilated glazed vertical building structure, such as a double-skin façade. Graphs on the right show different coupled and decoupled solutions for temperature and airflow (Hensen 1999b).*

It is obvious that for such a configuration, computer modeling and simulation are needed to predict the future performance in the real world. Since there are so many parameters and variables involved, it is practically impossible to prepare generally applicable design prescriptions for such a system. Therefore, modeling and simulation should be employed to support the design process directly. The methodology involved is basically an iterative process comprising the following main steps.

1. Analysis of the problem and re-expressing the building design in a validated and appropriate simulation model in terms of extent, complexity, and time and space resolution levels.
2. Calibration of the model.
3. Performing simulations against relevant inside and ambient boundary conditions during a suitable length of time.
4. Analyzing and reporting of results, perhaps followed by changing the model and further simulations.

This approach is demonstrated in the following sections by means of a design support study for a double-skin façade office development in Prague in the Czech Republic (Hensen and Bartak 2001).

MODELING THE DOUBLE-SKIN FAÇADE

The main objective of the study was to generate performance data in support of the design team by predicting the environmental conditions in the double-skin facade and the resulting cooling loads for the adjacent perimeter offices during extreme summer conditions. The temperatures in the cavity are of interest for the manufacturing and construction methods. The office cooling loads are needed for sizing the HVAC systems. In this case, the design team has actually very little interest in the flow field itself.

Since the layout of the building is very regular, there is no need to include the whole width or depth of the building. However, the model does need to include the offices adjacent to the façade plus the double-skin façade itself. The stack effect necessitates that the model cover the full height of the building.

The simulation period needs to cover at least a full day preceded by several simulation start-up days in order to account for thermal storage effects of the construction. Based on previous studies (e.g., Hensen 1999b), time steps of one hour are deemed the appropriate temporal resolution.

Although airflow is demonstrably an important aspect of building/plant performance assessment, the sophistication of its treatment in many modeling systems has tended to lag behind the treatment applied to the other important energy flow paths. The principal reason for this would appear to be inherent computational difficulties and the lack of sufficient data. In recent times, more emphasis has been placed on airflow simulation mostly focused on the following two approaches:

1. Computational fluid dynamics (CFD) in which the conservation equations for mass, momentum, and thermal energy are solved for all nodes of a two- or three-dimensional grid inside or around the object under investigation. In theory, the CFD approach is applicable to any thermofluid phenomenon. However, in practice, and in the building physics domain in particular, there are several problematic issues, of which the amount of necessary computing power, the nature of the flow fields, and the assessment of the complex, occupant-dependent boundary conditions are the most problematic (Chen 1997). This has often led to CFD applications being restricted to steady-state cases or very short simulation periods (see, e.g., Haghighat et al. 1992; Martin 1999; Chen and Srebic 2000).
2. The network method, in which a building and the relevant (HVAC) fluid flow systems are treated as a network of nodes representing rooms, parts of rooms, and system components, with internodal connections representing the distributed flow paths associated with cracks, doors, pipes, pumps, ducts, fans, and the like. The assumption is made that for each type of connection there exists an unambiguous relationship between the flow through the component and the pressure difference across it. Conservation of mass for the flows into and out of each node leads to a set of simultaneous, nonlinear equations, which can be integrated over time to characterize the flow domain.

Obviously there is a trade-off. The network method is, of course, much faster but will only provide information about bulk flows. CFD, on the other hand, will provide details about the nature of the flow field. It depends on the problem at hand and which of these aspects is the more important one.

In the current case the thermal side of the problem is very important. Given the extent of the model and the issues involved, this can only be predicted with building energy simulation. Both CFD and the network method can be integrated with building energy simulation. In case of CFD, this is still very much in development although enormous progress has been made in recent times (see, e.g., Bartak et al. 2002; Zhai et al. 2002). Integration of the network method with building energy simulation is much more mature (see, e.g., Hensen 1991) and more commonly used in practice. The reasons for this are threefold. First, there is a strong relationship between the nodal networks that represent the airflow regime and the corresponding networks that represent its thermal counterpart. This means that the information demands of the energy conservation formulations can be directly satisfied. Secondly, the technique can be readily applied to combined multizone buildings and multicomponent, multifluid (e.g., water and air) systems. Finally, the number of nodes involved will be considerably less than that required in a CFD approach and so the additional CPU burden is minimized.

Based on the above considerations regarding the requirements for the problem at hand and in view of the characteristics of the airflow modeling methods, it was decided to use the network approach fully integrated in a building thermal energy model (Hensen 1991; Clarke 2001). One of the very powerful features of this simulation environment is that it allows modeling of building airflow on different levels of resolution (from user-defined air change rates, via mass balance network approach, to computational fluid dynamics) and on different levels of integration (e.g., airflow on its own, or coupled with energy balance, and/or coupled with CFD).

As shown in Figure 3, the model comprises a typical 7.5 m wide section of the south side of the building, consisting of a "stack" of eight zones representing the office zones up to a depth of 5 m behind the façade and another seven "stacked" zones representing the double-skin façade itself. These seven zones are coupled by an airflow network that also includes the inlet opening (modeled by a connection between the bottom cavity zone and outside, i.e., the air temperature and wind pressure in front of the façade) and the outlet opening (a connection between the upper cavity zone and outside, i.e., the air temperature and wind pressure on the roof).

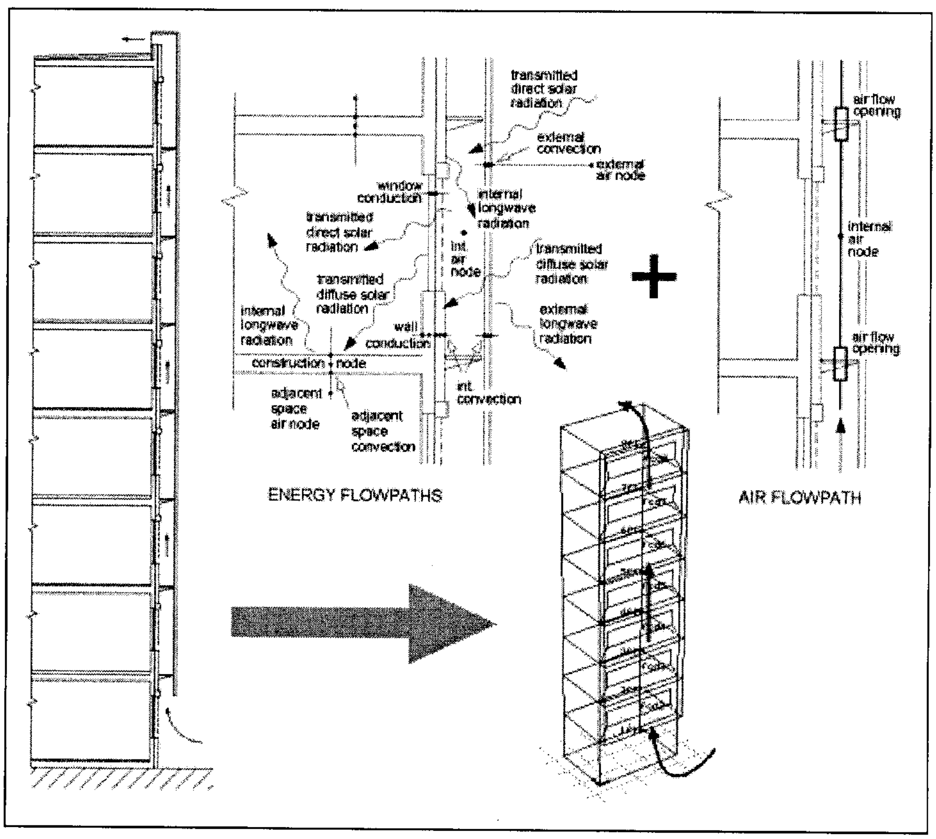

Figure 3 *The model of the double-skin façade. On the left: cross section of the double-skin façade system. Above: schematic representation of the super-imposed thermal and airflow network models. Bottom: graphic feedback from the simulation environment.*

It was assumed that the office windows and the shading devices are closed and that, effectively, there will be no air exchange between the offices and the cavity of the double-skin façade. Solar radiation passes through the double skin depending on the angle of incidence and the optical properties of the transparent systems. The outer layer of the double-skin façade is single-pane clear glass 6 mm thick. The office windows have advanced double glazing with blinds located in the cavity of the double-skin façade. For the case without the double-skin façade, inside blinds were assumed for the office windows. Further details of the model can be found in the appendix.

MODEL CALIBRATION

Due to lack of available resources, it has to be assumed in this—and many others—design study context that the models and the simulation environment that is being used have been verified (i.e., the physics are represented accurately by the mathematical and numerical models) and validated (i.e., the numerical models are implemented correctly). Nevertheless, it is critically important to be aware of the limitations of the modeling approach.

For example, when using the network approach, it should be realized that most of the pressure-flow relationships are based on experiments involving turbulent flow. Von Grabe et al. (2001) demonstrate the sensitivity of temperature rise predictions in a double-skin façade and the difficulty of modeling the flow resistance of the various components. There are many factors involved but assuming the same flow conditions for natural ventilation as those used for mechanical ventilation causes the main problem, i.e., using local loss factors ζ and friction factors from mechanical engineering tables. These values have been developed in the past for velocities and velocity profiles as they occur in pipes or ducts: symmetric and having the highest velocities at the center. With natural ventilation, however, buoyancy is the driving force. This force is greater near the heat sources, thus, near the surface and the shading device, which will lead to nonsymmetric profiles. This is worsened because of the different magnitudes of the heat sources on either side of the cavity.

One way forward would be to use CFD in separate studies to predict appropriate local loss factors ζ and friction factors for use in network methods. Strigner and Janak (2001) describe an example of such a CFD approach by predicting the aerodynamic performance of a particular double-skin façade component, an inlet grille.

As discussed elsewhere in more detail (Hensen 1999a), another limitation is related to assumed ambient conditions. This concerns the difference between the "microclimate" near a building and the weather data, which is usually representative of a location more or less distant from the building. These differences are most pronounced in terms of temperature, wind speed, and direction, the main driving potential variables for the heat and mass transfer processes in buildings!

These temperature differences are very noticeable when walking about in the summer in an urban area. Yet it seems that hardly any research has been reported or done in this area. There are some rough models to predict the wind speed reduction between the local wind speed and the wind speed at the meteorological measurement site. This so-called wind speed reduction factor accounts for any difference between measurement height and building height and for the intervening terrain roughness. It assumes a vertical wind speed profile and usually a stable atmospheric boundary layer.

It should be noted, however, that most of these wind profiles are actually only valid for heights over $20\,z_0 + d$ (z_0 is the terrain-dependent roughness length [m], and d is the terrain-dependent displacement length [m]) and lower than 60... 100 m; i.e., for a building height of 10 m in a rural area, the profiles are only valid for heights above 17 m, in an urban area above 28 m, and in a city area above 50 m. The layer below $20\,z_0 + d$ is often referred to as the urban canopy. Here the wind speed and direction are strongly influenced by individual obstacles and can only be predicted through wind tunnel experiments or simulation with a CFD model. If these are not available, it is advised to be very cautious and to use—depending on the problem on hand—a high or low estimate of the wind speed reduction factor. For example, in case of an "energy consumption and infiltration problem," it is safer to use a high estimate of the wind speed reduction factor (e.g., wind speed evaluated at a height of $20\,z_0 + d$). In case of an "air quality" or "overheating and ventilation" problem, it is probably safer to use a low estimate (e.g., wind speed evaluated at the actual building height) or to assume that there is no wind at all.

Calibration is a very difficult issue in practice. For existing buildings, there are usually no experimental results readily available. In a design context, there is not even a building yet. In practice, the only way to calibrate the model is to try to gain confidence by carefully analyzing the predictions and to compare these to expectations or "intuition" based on previous work. Unexpected results are usually the result of modeling errors. In rare—but interesting—cases, unexpected interactions take place and—after analyzing these—the simulations may have helped to improve the understanding of the problem. In any event, calibration should not be taken lightly and sufficient resources should be reserved for this activity.

SIMULATIONS

Because of the main interest in the summer conditions, the simulations were carried out for an extreme summer day in Prague. The office inside conditions were for a typical weekday (see the appendix). The simulation period was preceded by five simulation start-up days. All simulations were carried out with one-hour time steps.

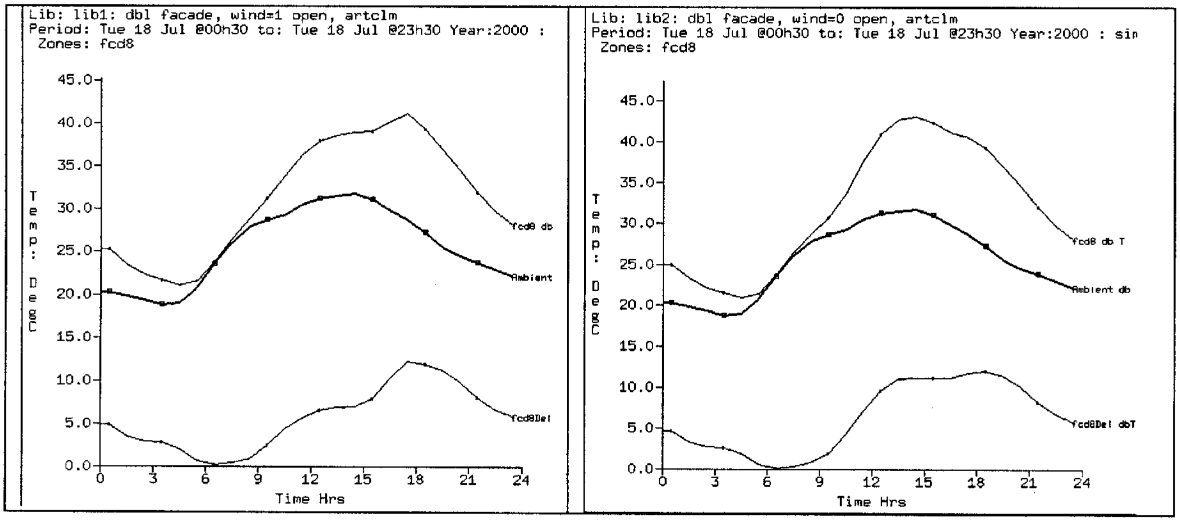

Figure 4 *Predicted air temperatures in the double-skin façade during one of the warmest summer days in Prague. Upper lines represent outlet temperatures. Middle lines represent inlet temperatures (ambient). Lower lines represent the temperature rise in the façade. The left graph corresponds to the final design of the double-skin façade with wind forces taken into account. The right graph represents the same situation without taking into account the airflow driving forces due to wind.*

In order to generate relevant design information, the following cases have been considered.

- A—A building without the double-skin façade and with internal venetian blinds.
- B—A building with the double-skin façade and blinds located in the façade cavity.
- C—Same as B, but now assuming that there would be no wind at all.
- D—Same as B, but now assuming that the damper in the double-skin façade outlet would be closed.

Case A serves as the reference case. A comparison of case B with case A would show the influence of the double-skin façade as designed. As explained above, Case C is needed in order to show what would happen if there were no influence of wind, e.g., because of sheltering by neighboring buildings. Case D would show what would happen if the outlet damper were closed, perhaps due to malfunctioning.

RESULTS AND DISCUSSION

Figure 4 shows the double-skin air temperature results for cases B and C. These are the air temperatures in the upper part of the double-skin façade, where normally the highest temperatures occur. It is clear that for this building, there is not much influence of the wind, i.e., the buoyancy forces are the dominant driving force for the airflow. For both case B and case C, the maximum temperature rise in the double-skin façade is about 12°C above ambient, which will occur in the late afternoon and early evening.

As can be seen in Figure 5, the air temperature rise would be considerably higher in case the outlet damper were not open. In that case, the air temperature could rise up to almost 50°C above the ambient temperature, and this would happen in the middle of the afternoon.

Figure 6 shows some results in terms of airflow rate through the double-skin façade for the case B conditions. During most of the day the flow is upward, basically because the average air temperature in the double-skin façade is above the ambient temperature. However, during part of the early morning, the south façade is in the shade. The thermal capacity of the façade delays the temperature rise of the cavity air relative to the more rapid rise of the ambient air temperature. Thus, the average air temperature in the double-skin façade is temporarily lower than ambient. This results in downward airflow through the cavity.

In general, the double-skin façade acts as a thermal buffer in front of the offices. This has three interacting thermal effects for the offices.

1. The air temperature inside the double-skin façade will be higher than ambient during most of the day. This will result in lower conductive heat losses (heating season) and higher conductive heat gains (summer) depending on ambient temperatures and solar radiation levels.

2. The extra outside pane of glass of the double-skin façade will reduce the amount of solar radiation on the inside façade, thus reducing the solar radiation load of the offices due to radiation transmission via the windows.

3. The double-skin façade allows blinds in the cavity of the double-skin façade as opposed to on the inside of the window, thus reducing the solar radiation load of the offices via the windows.

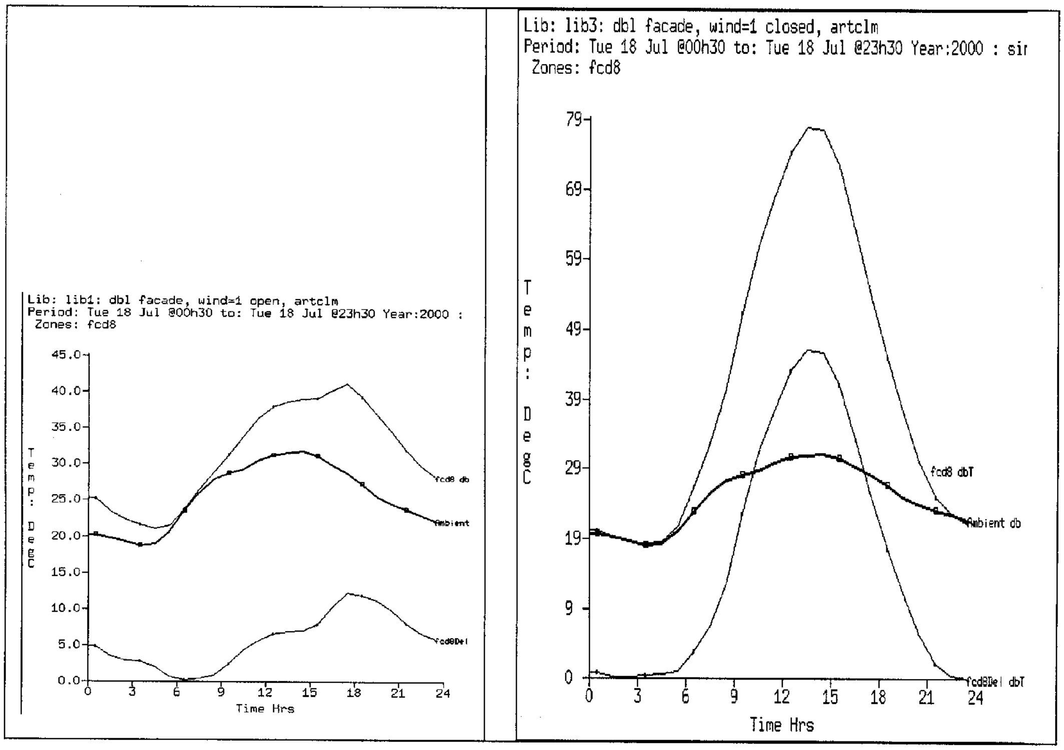

Figure 5 *Predicted air temperatures in the double-skin façade during one of the warmest summer days in Prague. Upper lines represent outlet temperatures. Middle lines represent inlet temperatures (ambient). Lower lines represent the temperature rise in the façade. The left graph corresponds to the final design of the double-skin façade. The right graph represents the situation where the outlet damper would be closed due to malfunctioning or control error. The temperature scales are approximately the same.*

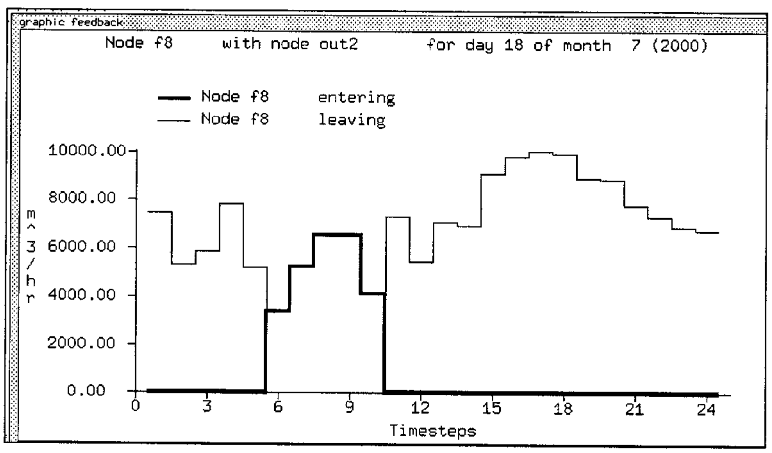

Figure 6 *Case B (as designed) airflow rate through the double-skin façade during one of the warmest summer days in Prague. The thin line indicates upward flow in the cavity. The thick line represents downward flow in the cavity. Note that 10,000 m^3/h corresponds to an average cross-sectional air velocity of about 0.7 m/s in the cavity. Due to smaller cross-sectional areas, this corresponds to about 1.3 m/s in the outlet, and about 2.0 m/s in the inlet opening of the double-skin façade.*

TABLE 1
Maximum Sensible Cooling Load for the Office Adjacent to the Façade on the Top Floor (Level 8) During One of the Warmest Summer Days in Prague and the Differences Relative to Case A (No Double-Skin Façade)

Case	Maximum Sensible Cooling Load kW	Difference Relative to Case A		
		W	W/m^2 Floor	%
A	3.53			
B	3.29	–240	–6	–7
C	3.32	–210	–6	–6
D	3.65	120	3	3

TABLE 2
Maximum Sensible Cooling Loads for the Offices Adjacent to the Double-Skin Façade During One of the Warmest Summer Days in Prague for Case A (without Double-Skin Façade) and Case B (with Double-Skin Façade)

Floor Level	Maximum Sensible Cooling Load		Sensible Cooling Load Reduction Due to the Double-Skin Façade		
	Case A kW	Case B kW	W	W/m^2 Floor	%
8th	3.53	3.29	240	6	7
7th	3.51	3.24	270	7	8
6th	3.50	3.20	300	8	9
5th	3.50	3.14	360	10	10
4th	3.45	3.08	370	10	11
3rd	3.38	2.95	430	11	13
2nd	3.14	2.67	470	13	15

Which of these three effects is most important at a particular point in time depends on optical and other properties of the structure and complicated dynamic thermal interactions between the façade, temperatures, and airflow in the double-skin façade and outside. As can be seen in Tables 1 and 2, for the offices adjacent to the façade, the result is a reduced maximum cooling load during hot summer days. Of course, in case the outlet damper would be closed, there would be no reduction but an increase in cooling load for the offices.

As evidenced by Tables 1 and 2, the cooling load reduction depends on the floor level. It is less for the higher floors because of the higher air temperatures in the cavity of the double-skin façade. This might lead to the suggestion that it would be advantageous to divide the cavity into segments with inlet and outlet openings at various heights. This is, however, not so easy to predict due to the strong thermodynamic coupling that exists between the airflow and thermal processes in a naturally ventilated double-skin façade structure.

IN CONCLUSION

The above work shows the advantages of a double-skin façade construction in terms of reducing the cooling load of the adjacent zones, especially on the lower floors.

Coupling a double-skin façade to a natural or hybrid ventilation system is common but represents challenges as shown in this paper. These are due to the temperature and airflow fluctuations in the façade construction. The airflow is not only highly erratic in magnitude but can even take place in reversed direction.

This paper has shown that to predict the performance of this type of system constitutes a nontrivial modeling and simulation exercise that should be based on a thorough methodology and good working practice.

When modeling these types of systems, it is typically necessary to take into account a large part of the building with dynamic interactions between several zones and ambient conditions. This has consequences for the practically possible level of spatial and temporal resolution that make CFD less appropriate in everyday practical design of these types of systems.

On the other hand, this paper has indicated several areas where the network method in general could be improved through separate CFD studies. An example would be to verify and/or improve the network pressure-flow relationships and local loss factors for airflow conditions typical of natural and hybrid ventilation systems. Another area of concern where CFD might be of benefit is the wind pressure distribution on the façade and roof of the building.

A final conclusion from this paper could be that both the network method and CFD have their own advantages and disadvantages for modeling this type of natural and hybrid ventilation systems. Either method can and should be used but at different stages.

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APPENDIX—MODEL DETAILS

Geometry

The model comprises eight stacked thermal zones (named 1flr, 2flr,..., 8flr according to floor level), which represent the office modules. The dimensions of each office module are: width 7.5 m, depth 5 m, height 3.7 m (except first floor, which is 4.15 m high). Therefore, each office module has a floor area of 37.5 m^2 and a volume of 138.75 m^3. The total building height is 30.05 m.

The model comprises another seven stacked thermal zones (named fcd2, fcd3,..., fcd8 according to floor level), which represent the double-skin façade construction. The dimensions of each double-skin façade module are: width 7.5 m, depth 0.636 m, height 3.7 m.

Construction

The office façade construction consists from outside to inside of 80 mm insulation + 200 mm concrete. The standardized thermal resistance R is 2.9 m^2K/W or U is 0.32 $W/(m^2K)$. The surface emittance is 0.9 [-]; the surface solar absorptance is 0.8 [-].

The roof construction consists from outside to inside of 150 mm insulation + 280 mm concrete. The standardized thermal resistance R is 4.35 m^2K/W or U is 0.22 $W/(m^2K)$. The floors consist of 280 mm concrete.

Windows

The double-skin façade outer glazing consists of 6 mm clear float with a visible transmittance of 0.87 [-] and a nominal U-factor of 5.40 $W/(m^2K)$. The direct solar transmittance at 5 angles (0°, 40°, 55°, 70°, 80°) is 0.78, 0.76, 0.72, 0.58, 0.35 [-]. The total heat gain factor at five angles is 0.82, 0.81, 0.77, 0.63, 0.40 [-]. The solar absorptance at five angles is 0.149, 0.163, 0.173, 0.179, 0.169 [-].

The glazing of the offices toward the double-skin façade consists of double glazing with external blinds and is composed of five layers (including air gaps) and has a visible transmittance of 0.72 [-] and a nominal U-factor of 1.60 $W/(m^2K)$. The direct solar transmittance at five angles (0°, 40°, 55°, 70°, 80°) is 0.07, 0.03, 0.02, 0.02, 0.02 [-]. The total heat gain factor at five angles is 0.09, 0.04, 0.03, 0.03, 0.03 [-]. The solar absorptance at five angles for each layer is layer 1: 0.570, 0.551, 0.526, 0.507, 0.507 [-]; layer 2: 0.001, 0.001, 0.001, 0.001, 0.001 [-]; layer 3: 0.042, 0.017, 0.013, 0.010, 0.010 [-]; layer 4: 0.001, 0.001, 0.001, 0.001, 0.001 [-]; layer 5: 0.014, 0.006, 0.005, 0.004, 0.004 [-].

Operation

Every office zone has an infiltration rate of 0.3 ACH continuously. The ventilation rate of the second floor zone to the eighth floor zone during office hours is based on 50 m^3 / (h/pers) = 187.5 m^3/h = 1.351 ACH.

For the office zones, the casual gains on working days 7:00–17:00: occupants 233 W sensible + 293 W latent, lights 750 W, equipment 1125 W. There are no casual gains outside working hours.

Control

The first floor office zone has free floating temperature. The cooling setpoint is 28°C for the other office zones during working days 7:00–17:00. Free floating temperature outside working hours.

Airflow Network

The inlet opening has a cross-sectional area 7 m × 0.2 m = 1.4 m^2. The outlet opening has a cross-sectional area 7 m × 0.3 m = 2.1 m^2. In case of the closed outlet damper, a leakage 7 m × 0.005 m = 0.035 m^2 is assumed. The horizontal openings at each floor level in the double-skin façade are 7 m × 0.6 m = 4.2 m^2.

Node out1 is external node, wind-induced pressure, south, at ½ the height of the building = 15 m. Nodes f2, f3, to f8 are nodes in the double-skin façade (number = floor level). Node out2 is external node, wind-induced pressure, roof, at height of 30.9 m.

DISCUSSION

John Straube, Assistant Professor, University of Waterloo, Waterloo, Ontario, Canada: Conclusions state that the double facade reduces the cooling load with respect to Case A. However, without knowing if the base case (A) has high performance glazing (e.g., SHGC = 0.3, VT = 0.55) or typical clear double glazing (e.g., SHGC = 0.6, VT = 0.7), the conclusions might be different. Can you provide the equivalent SHGC used for the double glazing in Case A and comment on how the use of low SHGC glass would impact the conclusions?

Jan Hensen: The base case does have high performance glazing. It is the same glazing as described in the Appendix of the paper, but with internal blinds instead of external blinds.

Professor Athienitis, Concordia University, Montreal, Canada: How do you model the blinds and choose the cavity width?

Hensen: The blinds were modeled as a transparent layer as described in the Appendix of the paper. The cavity width and all other details as described in the Appendix of the paper were provided by the facade manufacturer. The cavity width is 0.64 m.

M.J. Holmes, Associate Director, ARVP Research and Development, London, U.K.: Can you comment on the following: (1) How did you obtain convection coefficients for blinds? (2) Did you consider the situation when wind generated pressures are in opposition to the stack? (3) Did you look at the closed off position which may be of particular importance in winter?

Hensen: (1) The convection coefficients according to Alamdari and Hammond (BSERT 1983) were used. (2) We considered the case without wind (case C) and the case with wind direction according to the hourly prevailing meteorologic conditions in Prague (cases A, B and D). We did not check whether or not the wind generated pressures in opposition to the stack. (3) We looked at the closed off position but only for the summer situation (case D). This study did not include the winter situation.

Ian Beausoleil-Morrison, Natural Resources Canada, Ottawa, Ontario: What pressure vs. flow relationship did you use to represent to airflow between the nodes in the airflow network? How were pressure coefficients set for the upper and lower openings in the facade. How sensitive are the simulation results to these assumptions/inputs?

Hensen: The pressure vs. flow relationships for the connections representing the cavity of the double skin facade are common orifice flow relationships with the orifice opening set to the value as indicated in the appendix. The discharge coefficient is assumed to be 0.65. The wind pressure coefficients are taken from the standard set, as collected and published by the Air Infiltration and Ventilation Centre. The simulation results are not very sensitive to these assumptions, as evidenced by the relative small difference between cases B and C. (This is actually the result that we want, since the wind pressures have a very low confidence level.)