A Configurable Smart Facade Unit for On-site Calibration and Control Optimization

Tahar Messadi, Arch.D. **Godfried Augenbroe**

ABSTRACT

Application of "smart" technologies in the building envelope is an opportunity that is not yet broadly accepted as the "smart" way to save energy. This paper discusses a prototype that is designed to benchmark smart double-glass elements in existing facades. It consists of a configurable glass unit that can be temporarily installed in existing buildings to collect data, forecast the energy performance improvements, as well as simulate operational aspects. It provides building owners and occupants an opportunity to test the feasibility of new technologies, see them in action, and test them on different facades and orientations. The unit comes with an in-built, "Internet-ready," automatic data collection module. Another feature is the online, on-site design of optimal control strategies, while occupant interaction with the smart facade is enabled at all times through a ubiquitous web interface. The results of an ongoing demonstration installation are reported.

INTRODUCTION

The premise of the research reported here is that smart facade components with embedded adaptive control systems based on real-time optimization offer the potential to save energy. These control systems enable the building to dynamically react to real-time environmental input data and take optimal control actions given a set of occupant preferences regarding physical indoor environmental variables such as thermal comfort, lighting, and views through the transparent parts of the building envelope. Since the building envelope plays such an important role in the lighting and thermal regulation of the interior spaces, it is obviously the most suitable choice for the location of active control systems. There have been a number of studies that dealt with the potential energy savings of smart facade components (Ripatti 1984; Barakat 1987; Haddad and Elmahdy1998; Jones and Messadi 2000; Saelens and Hens 2001). However, none of these studies addressed the application of optimal control to increase performance. The falling costs and the higher stability of control technologies (sensors, actuators, active controllers) have rekindled interest in their incorporation in building enclosures.

Especially in Europe, experimental facade component technologies have received considerable attention of late, both in new constructions as well as in the refurbishment of buildings. Their introduction in the U.S. has not taken off, but research efforts are ongoing to study and optimize different variants. Slow introduction might be the result of a conservative industry waiting for proof that these systems perform in actual settings. That is why this research concentrates on deployment and prototyping in an actual setting, thus giving owners the chance to monitor and interact with the system in real life settings.

Past research (Lee and Selkowitz1998) has shown that an important aspect of any control strategy should be to allow the occupant to override the automated operation of the facade component at any time. In normal operation, the user is not attentive to the environmental variations and leaves operation to the automated system. At other instances, the occupant might want to override the system because of special preferences and in case indoor conditions are not to the user's satisfaction despite the fact that the system tries to reach an optimum comfort state (light and heat) at all times.

Tahar Messadi is an assistant professor and **Godfried Augenbroe** is an associate professor in the College of Architecture, Georgia Institute of Technology, Atlanta, Ga.

VENTILATED DOUBLE-PANED FACADES WITH CONTROLLABLE LOUVERS

In the following sections, we lay out the progress made in the development of the all-glass double-facade systems and highlight the attempts made in previous studies to model their inherent thermal dynamics that are considered essential in the formulation of a control strategy.

The application of glass in building envelopes procures the benefits of daylight penetration and the psychological connection to the outside, but it also exaggerates the heat loss and gain. In particular, the sash window type further aggravates the sick building syndrome. In the face of these challenges, major research was undertaken to develop energy-efficient glazing and to promote efficient ventilation systems through the building enclosure.

The recent efforts have led to the development of a more sophisticated facade system that combines both mechanical features and architectural systems to reduce the energy consumption by means of its active operation. In fact, the all-glass double-facade system is the child of an earlier system known as the *airflow window*, which consists of a ventilated cavity held within two glass panes to address the old problem of minimizing the energy load. Such windows originated in Scandinavia, where a related patent was filed in 1956. The first large-scale installation dates back to 1967 when the city of Helsinki used *airflow windows* in its building department offices (Brandle and Boehm1982). With the energy crisis of 1973, the savings potential of these systems has resulted in many applications—mostly in office buildings. The first *airflow windows* in the United States were installed in 1980 in an office building in Portland, Oregon (Ripatti 1984).

The existing typologies of double-skin enclosures are quite extensive (Compagno 1995; Wigginton and McCarthy 2000), ranging from the famous Trombe wall to the latest smart facades. However, the summary of previous research relevant to our investigation is limited to the double-paned glass systems with ventilated cavities, such as the *ventilated double-glass facade* and the *double-glass airflow window.*

Airflow Windows

In the existing literature, distinction is generally made between natural and forced ventilation facades (Saelens and Hens 2001). However, it is conceivable to accommodate both natural and forced ventilation in many *airflow windows*. For the sake of clarity, in natural ventilation, the air motion is induced by thermal buoyancy and air pressure difference, while in forced ventilation, the mass flow is assisted via a cavity located fan or the HVAC system blower. Furthermore, forced ventilation may not necessarily be achieved through physical connectivity to the HVAC system (Figure 1c) but could well be through separate systems that are controlled in an integrated fashion. Although the facade is not physically interacting with the airflow of the HVAC system (these airflows will be very moderate in comparison to forced mass flows), the control of the smart facade will be dependent on the control state of the HVAC system at any particular time. The findings from previous studies on the performance of three types of windows with forced airflow regime in the cavity are discussed (Figure 1).

The *exhaust airflow window system* (Figure 1a) allows the indoor air to flow through the cavity and outside. In the cooling season, the airflow helps reduce the cooling load when the heat picked up in the cavity is discharged outside. In the heating season, the exhaust airflow helps reduce the transmission loss through the fenestration. In addition, the exhaust airflow helps maintain interior glazing temperature close to the room temperature, resulting in better comfort (Haddad and Elmahdy 1999). Mueller (1984) tested ten different types of exhaust airflow windows in the laboratory by changing the height of window, pane distance, external glazing, and shading device (vertically laminated louvers and roller blinds), etc. He found that the interior glazing temperature does not differ more than 5°C (9°F) from room temperature during extremely chilly winter days. According to his research, the solar heat gain coefficient of this type of exhaust airflow window is extremely low—between 0.1 and 0.2—which can be achieved with conventional windows only by means of external solar control devices.

The *supply airflow window system* (Figure 1b) allows outdoor air to flow through the cavity and into the room. This system helps reduce the heating load when heat picked up in the cavity flows into the room. In addition, the outdoor air satisfies the fresh air requirement of the space. Haddad and Elmahdy (1998) developed a computer program to simulate the performance of a conventional triple-glazed window and the supply airflow window in the cold climate of Ottawa, Ontario, Canada. They found that in the cooling season, the supply air window may increase the cooling load when the heat picked up in the cavity is delivered to the space. But, the supply airflow window led to higher monthly net heat gains, especially during the winter when it is the most beneficial. This increase is due mainly to a reduction in the conductive heat loss rather than an increase in the solar heat gain. Their results also support the fact that the supply airflow window

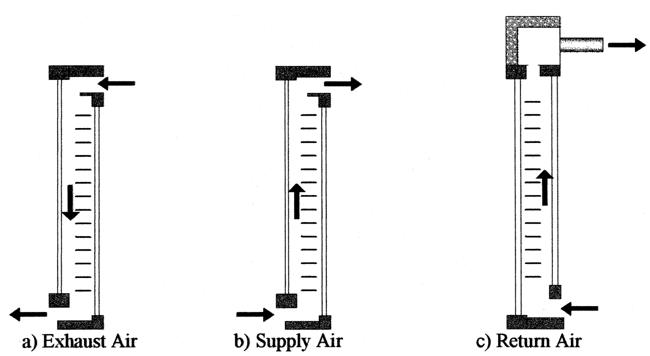


Figure 1 *Three types of airflow window system tested by Barakat (1987).*

can be employed continuously to satisfy the ventilation requirement of the space with a small penalty in the cooling load during the summer.

Barakat (1987) performed an experimental study to assess the performance of the supply air window during the heating season in Ottawa, Ontario, Canada, by comparing it to conventional double- and triple-glazed windows. Barakat found that the supply air window recovered 50% of the energy required to heat the ventilation air. Overall reduction in purchased energy compared to a double-glazed or triple-glazed window was 25% and 20%, respectively.

The third type is the *return airflow window system* (Figure 1c), which allows indoor air to flow upward through the cavity and then return via a duct system to the central HVAC equipment. Ripatti (1984) used the TRNSYS-E program to evaluate the performance of the return airflow window system at three different locations in the United States (Fort Worth, Tex., Columbia, Mo., and Madison, Wis.; each location represents a different type of climate) and the simulation results have shown that the thermal performance of return airflow window systems is superior to that of a standard double-insulated window.

Ventilated All-Glass Double Facades

The thermal behavior and expected energy savings from the all-glass double-facade systems depend on many variables. The properties of the glass, the shading element, and their geometric relationship with the sun are very influential. Furthermore, size and location of vents, climatic conditions, wind speed and direction, and vent inlet and outlet location relative to the neutral pressure level are also aspects to take into consideration. The interactions among these variables induce a great deal of uncertainty for the behavior and performance of these systems.

In naturally ventilated double skins, models to determine the expected thermal buoyancy and wind pressure difference throughout the cavity are very complex for both downward and upward flow. In addition, the specific application of operable horizontal louvers inside the cavity further complicates the proper modeling of the airflow rate and heat exchange within the cavity. There are few serious studies that have attempted to model the amplitude and direction of the airflow in a naturally ventilated envelope (Faist 1998; Jones and Messadi 2000; van Paassen and van der Voorden 2000; Todorovic and Maric 2001; Saelens and Hens 2001).

The findings from these studies are generally experimentally derived using procedures for thermal buoyancy (Andersen 1995; Li and Delsante 2001). Wind pressure differences are usually calculated from pressure coefficients (C_p values). Only Zhang et al. (1989) and Li and Delsante (2001) developed CFD models to determine the mutual effect of wind and thermal buoyancy. Other analytical and experimental studies were conducted to propose effective operation strategies or rules for the double-skin systems in different kinds of weather (winter, midseason, and summer) (Holmes 2000).

The numerical study by Todorovic and Maric (2001) shows that during the cloudy condition of winter months, the cavity temperature in their double-skin facade gets to be 6ºC to 8°C (10.8ºF to 14.4°F) higher than the outdoor temperature when the vents are closed. The temperature of the cavity can be 10ºC to 12 °C (18ºF to 21.6°F) higher during the clear sky condition. Furthermore, they conclude that the double-skin facade can reduce more than 50% of heat losses during winter months because the unvented cavity acts as a buffer that can reduce the temperature difference between the inside and outside and thus reduce the heat transfer. Both in midseason and in summer, the cavity temperature can be higher than that of the inside due to the solar radiation heat buildup. They conclude, however, that although the clear glass installed in the double-skin facade allows a lot of solar gain in summer, the heat on the glass can be removed by the convective heat exchange caused by the stack effect within the cavity. However, in winter when heat is needed, the heat buildup in the cavity due to the solar radiation can be circulated into the occupied space to reduce the need for electric heating.

Air Cavity Proportions

With respect to the proportion of the air cavity in the double facade, simulation studies conducted on a proposed retrofit with such a system of a four-story engineering school building in Luzern, Switzerland, produced some interesting results. In reviewing the output from the COMIS-TRNSYS (2001) simulation software, the authors determined that the stack ventilation of the double-skin facade may not always be thermally beneficial. Particularly, if there is some leakage of the built-up hot air into the occupied space at the uppermost floor, overheating and low air quality may result. Hence, this study suggests that such problems might be avoided by raising the neutral pressure plane, which can be accommodated by increasing the height of the outlet shaft above the roof level. In addition, they recommend a maximum cavity height of three to four stories.

Louver System Modeling

In a number of studies, the analytical modeling of the louver systems has been successful for a cavity-installed blind (fixed and operable) as it is impacted by the solar radiation and interreflections. These studies were concentrated on modeling the solar radiation transport through the slat-type blinds and the interaction between the diffuse or purely specular blind and the glass (Bilgen 1984; Rheault and Bilgen 1987; Talmatamar et al. 1995; Cho et al. 1995). From recent studies, the combined effects of the reflection from real surfaces that contain the mix of specular and diffuse reflection were well developed (Pfrommer et al. 1996).

DESCRIPTION OF THE SMART FACADE DEMONSTRATION UNIT (SFDU)

In this work, we opted for a naturally ventilated active envelope, which is developed to allow airflow through the cavity by thermal buoyancy and wind pressure differences. This natural flow implies that air can circulate according to the damper settings (Figure 2), all depending on the weather conditions and the fresh air intake option. While we also recognize that natural flow may not always be as effective as forced ventilation because of changing weather conditions and wind patterns, the installed inlet/outlet *airflow dampers* will help control the venting of the cavity. Obviously, later research is planned for the integration of the SFDU with the HVAC systems.

The smart facade demonstration unit (or SFDU, as it will be referred to) represents the adopted prototype that we consider in this two-track research. For the first track, the emphasis is put on the thermal behavior of the double-skin glass facade under natural conditions. In the concurrent second track, the optimized control and operation of the unit is undertaken, as explained below. Forced air through the cavity is not being considered at this time. The natural flow of air is controlled via the active operation of the dampers and the sun mediation by adjustable louvers.

The unit, developed for these purposes and shown in Figure 3, measures 3.05 m (10 ft) high, 1.19 m (46.85 in.) wide, and 0.20 m (8 in.) deep. The aluminum-built SFDU is currently under construction and will soon be attached to the south wall of a building in a university campus.

The demonstration unit consists of a glazed, double-envelope system with both outer and inner layers made entirely of 25.4 mm (1 in.) thick low-e glass panes, each held within an aluminum sash. Electronically controlled ventilation grilles are incorporated at the top and bottom of each glass layer for ventilation purposes (Figure 3). A 90 mm (3.5 in.) wide airfoil louver system is installed within a 0.2 m (8 in.) deep cavity at 38 mm (1.5 in.) away from the inner glass layer and braced throughout the cavity height.

The SFDU is fitted with wire channels for data acquisition and controls. The unit's sensors and motorized actuators

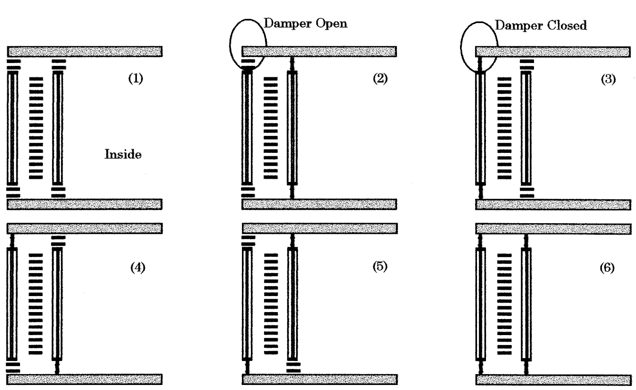


***Figure 2** Six settings chosen for assessing the thermal performance of the SFDU.*

are directly linked to a data collection and control system as will be explained in the next section. Although most ventilated cavities use roller blinds to minimize internal airflow turbulence (Mueller 1984), the decision to install horizontally laminated louvers was driven by the necessity to maintain visual comfort (i.e., connection to the outside).

The four controllable *airflow dampers* contain blades having an airfoil profile that is more aerodynamically efficient than the traditional flat ones. In fact, the airfoil blade damper has one-fourth to one-tenth less pressure drop across, compared with the traditional damper design (Kitchen and Moore 1978). Moreover, the inner glass window is operable, which also allows easy access for cleaning or hardware maintenance.

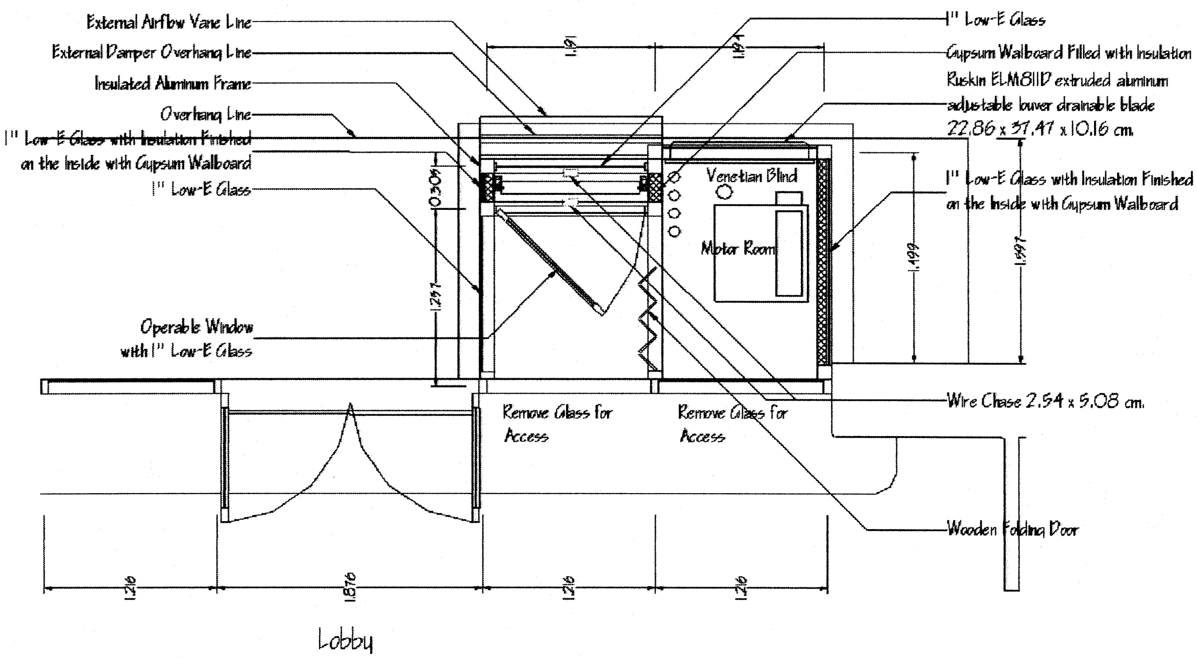
The wind scoop is placed on the outside at the exit of the upper damper. It functions as a vane that protects from the rain and the wind pressurization. The wind scoop blocks out the wind and prevents the equal pressurization by the wind that enters from the top and bottom dampers. Furthermore, the wind scoop helps create the negative pressure that attracts the airflow from the cavity by changing the direction of the wind or establishing positive pressure. In addition to the wind scoop, at the exit of the lower outside damper, an overhang is installed above the lower damper to prevent the water penetration.

Challenges in the Development of the Physical Model

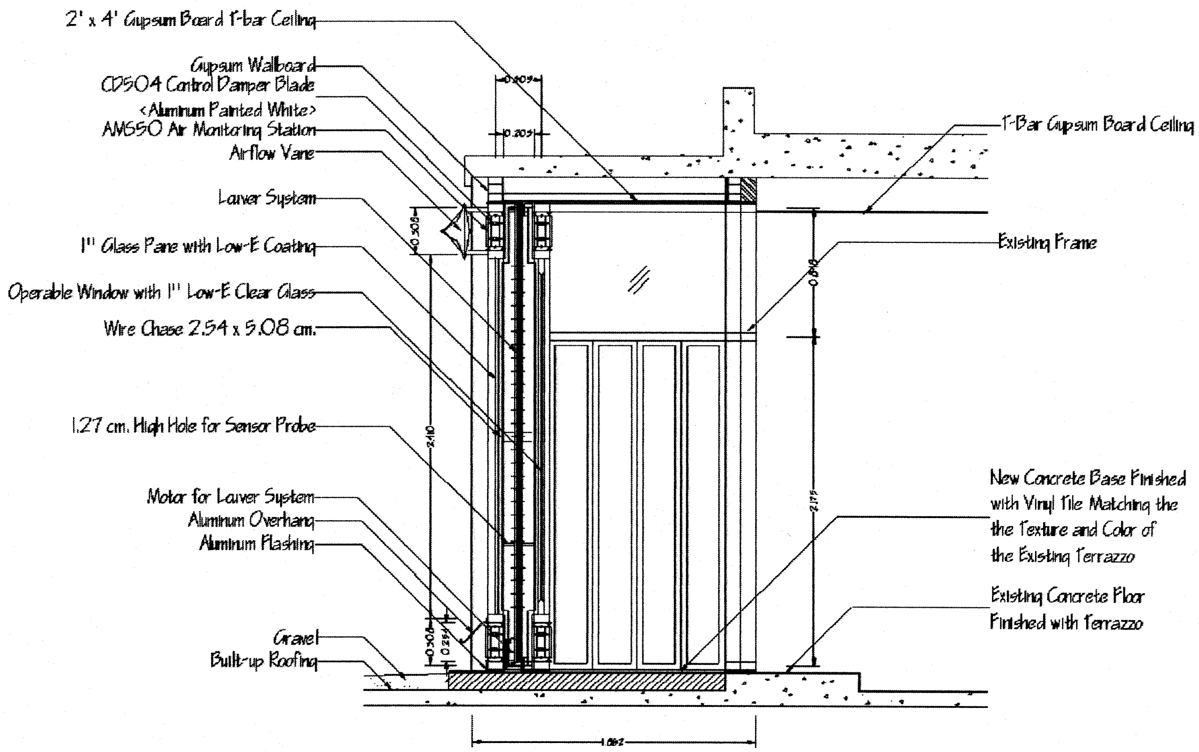
The method we will use to model the complex airflow regime for mass and heat transport is proposed by George Waltons (1989). The method, known as *airflow network model*, considers the building elements as nodes with airflow resistance. This approach is based on the conservation law of force in the form of pressure or normal force per area (Walton 1989; van Paassen and van der Voorden 2000).

The flow characteristics of the various types of airflow dampers used in ducts have been studied for a long time for the purpose of damper sizing. The damper is assumed to be the flow-resistance element in the flow path. The mathematical models of the pressure drop with regard to the blade angle have been developed for both opposed and parallel blade dampers. However, the positioning of our dampers generates abrupt contraction at the entrance and expansion at the exit, thus operating with different boundary conditions. We found that the quadratic relationship equation, which was originally established for modeling the flow through cracks, is more adaptable to our flow. Baker et al. (2000) studied this model to replace the power law equation that is not dimensionally homogeneous. Yakubu and Sharples (1991) also found that the quadratic fits are much better than those of the power law.

As to the louver system, it can be assumed as a system of an aligned array of flat plates, and the direction of flow is different from that of the damper. As such, the louvered fin heat exchanger is more similar in behavior to our system. There are a number of studies related to the characteristic of



a) Layout of SFDU Set-Up



b) Section Through SFDU (Drawings by Mate Thitissawat, Ph.D. Student)

Figure 3 *ACAD drawings of the SFDU currently under construction.*

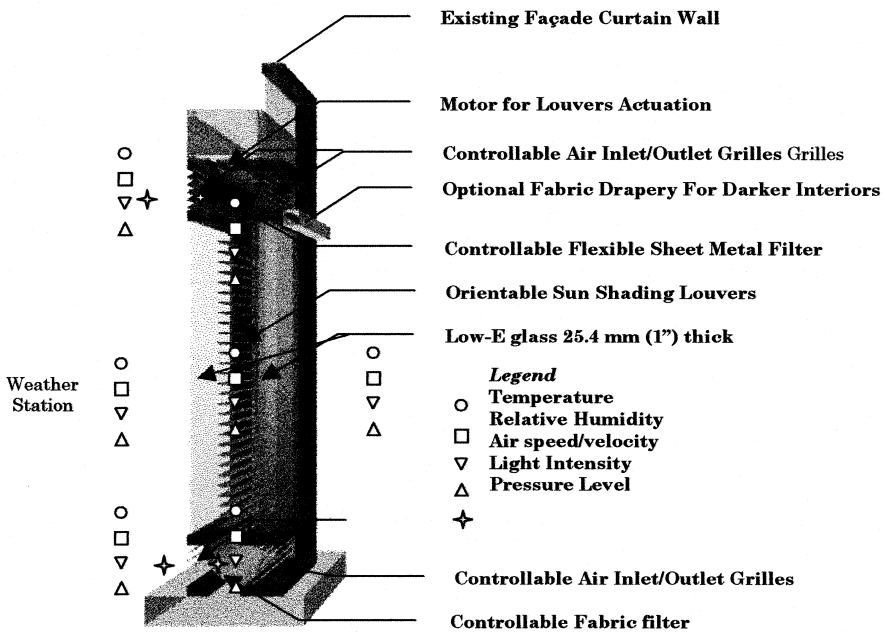


Figure 4 *Deployment of unit in the south facade of a university campus building.*

the flow interruption of the louvered fins that are widely used in a variety of applications, for instance, automotive radiator, air conditioner, refrigerator, and so on (Lee and Selkowitz 1986; Wang et al. 1999).

SFDU Prototype Reproduction for Remote Demonstration of Energy Performance

This smart facade demonstration unit (SFDU) has been designed to allow rapid in situ deployment with the purpose to demonstrate the capabilities of such a system to a client. The unit is, for the time being, limited to multiple glazing elements (easily exchangeable) with movable louvers in the cavity and operable in/out vents for airflow.

The unit is designed to fit in existing commercial window wall frames in case the original glass element can be removed (e.g., if external air inlets are required). In other cases, the unit will be placed against the existing glazing element that will remain intact and serve as an integral part of the unit.

The demonstration targets are threefold: (1) to show the energy-saving potential within the constraints of individual occupant satisfaction requirements, (2) to show the options for manual occupant control and system recovery, and (3) to allow ubiquitous access to the system state and control from any desktop. To reach these objectives, the unit has to be easily configurable and should come with a plug and play sensor and actuator set. The unit developed for these purposes can be snapped to any existing curtain wall and is also easily dismountable to allow testing for a variety of glass types and louvers.

The current unit has been manufactured according to the specifications of the demonstration installation, which demanded a fit of the unit as an integral part of one bay of the curtain wall facade (see Figure 4, showing the unit as replacement of a part of the existing curtain wall). Future units can be "made to order" using the original design, involving only an adjustment of the length of the extruded aluminum parts of the frame and, of course, adjustment of the window pane size. All other components, sensors, and actuators are pre-made and can be easily assembled to meet the specification of the facade opening for application in an existing (or new, for that matter) building. Alternatively, as explained above, the unit can be clamped on to an existing facade. The specification of the clamping system is under development.

THE STATE MONITORING AND CONTROL ARCHITECTURE OF THE UNIT

In order to apply the SFDU in any local setting, a flexible architecture of the monitoring and control system is important. Therefore, special attention has been given to the way the sensors and actuators can be pre-wired in the factory in order to enable a plug and play type of installation on site. An important requirement was that the system provide the opportunity to be monitored and controlled remotely (i.e., "anywhere, any time"). The last requirement is met by equipping the system with a local computer station that is connected to the Internet. The computer runs as a server that can be accessed from anywhere using only a standard web browser. The total architecture is explained in detail below.The main elements of the demonstration unit are shown in Figure 5.

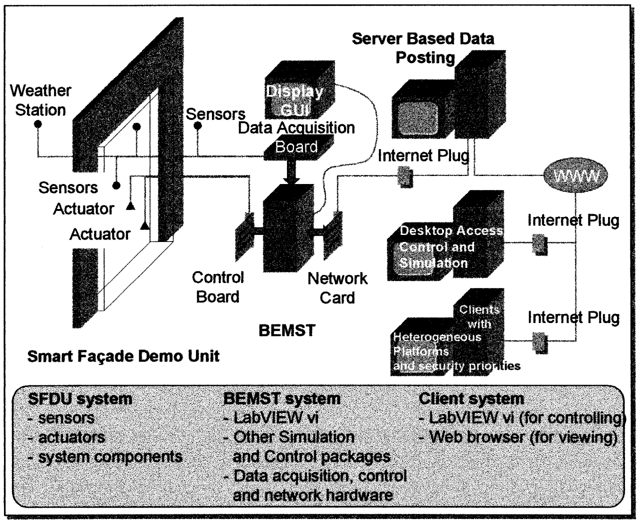


Figure 5 *Architecture of the complete system.*

The physical state of the unit is monitored by a set of factory-installed sensors that measure radiances, mass flows, temperatures, etc. The data are automatically sampled by a local monitoring unit and logged on the local data logging station, the Building Environmental Monitoring Station (BEMST). An important function of the BEMST is to function as a gateway between the data collection and a web hosted server of the data. In the current prototype, these functions are actually combined into one computer that comes as an integral part of the BEMST (Figure 6).

The BEMST is a mobile unit that can be brought on site and can be connected to the smart facade demonstration unit. With an Internet connection, the data recorded by the BEMST are sent to the server.

The BEMST is equipped with a number of sensors hooked up to the outside weather station. The connection boards for the sensors in the SFDU are pre-installed and calibrated and need only to be connected to the unit after installation. The various sensors include those of solar radiation, light levels, humidity, temperature, and wind velocity/direction. The BEMST also has a data acquisition system composed of a CPU, two input/output cards, and the data sampling software. In addition, it contains a variety of probes capable of monitoring, in a time series, the various environmental parameters.

The controllable parts of the SFDU are operated by a set of controllers that actuate the state of the smart devices; each actuator transmits its state to the web server and accepts commands from a local control algorithm. Users with appropriate user privileges can override the local algorithm and manually control the device from anywhere in the building through a standard browser.

A vital part of the data architecture is the web-enabled access to the facade unit. This permits any local or remote user with the correct permissions to monitor sensor readings and

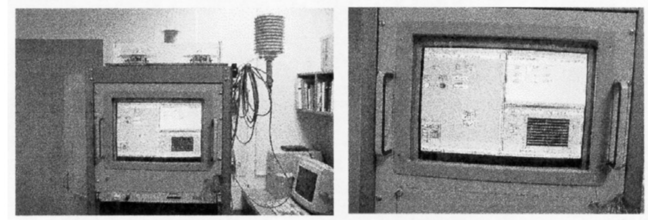


Figure 6 *Front view of the BEMST showing direct data output.*

control actuator values. A server collects the sensor data from the BEMST and serves these data in real time on a web page. The same is accomplished with the control of the unit by giving a user access (through a browser client) to current actuator values and allowing their remote control through a web interface supported on the server. Obviously, the unit must allow user intervention and should thus have an embedded control component that continuously monitors the unit and adjusts the control parameters unless a user takes over and issues an adjustment that overrides the suggestion by the embedded control unit.

The active connection between the unit sensors and actuators is accomplished through the data channeling software running on the BEMST. In the present prototype setup, the monitoring station is a prominent stand-alone component, which in future applications would obviously be integrated in the building energy management system.

BENCHMARK OBJECTIVES AND STRATEGY

The target of benchmarking the SFDU is to create awareness of smart technologies and improve and fine tune the technology based on deployment in real life circumstances and with real occupants. At the same time, it allows a continuous improvement of the underlying simulation models that were developed because extensive calibration will be based on gathered data. Ultimately, the improved model will increase the confidence in the simulation of design improvements, especially in the control strategies that we optimize using these simulation models.

Another major benefit of the benchmark is the verification of the "objective function" (usually called "cost function" in the mathematical formulation) that is used as the target for the optimal control algorithm. The objective function is a weighted mix of different targets (i.e., maximum reduction of heating and cooling demands, optimal natural lighting conditions, maximum reduction of electrical lighting hours, maximum thermal comfort, and maximum view performance of the outside). All of these different targets need a careful inspection and definition. The control algorithm will then use a strategy to issue a control action that maximizes the weighted sum of all of these targets at any time. There is hardly any research available that relates different occupant preferences for these multiple (and usually conflicting) targets to occupant tasks, gender, etc. In the benchmarks, occupants are given two modes of access to influence the control actions, i.e., (1) manual overriding, as explained above, and (2) through the specification of occupant specific preference profiles. All user actions in both categories will be monitored during the benchmark, leading to new data of the type of interaction that occupants prefer. Depending on the type and duration of task performed in the internal space, this will lead to a better understanding of individual preferences and how often they are changed as more experience is gathered with the operation of the smart facade. These occupant-centric issues will be the target of the next stage of the research.

In summary, the benchmark serves the following purposes:

- study the performance of the system under a range of weather conditions and continuously refine the simulation model to accurately predict its behavior
- detect flaws in the design and daily operation of the system
- design an optimal control strategy that can respond to user-defined preferences between multiple and possibly conflicting system and occupant objectives
- simulate local occupant intervention and study ways in which user and control systems interact
- evaluate user satisfaction with the system through post occupancy evaluation (POE)
- showcase the remote access to the unit operation and state inspection and involve the building services engineers in fine-tuning the unit control and operation through this novel interface

CONTROL AND SIMULATION ASPECTS

The behavior of a building envelope results from a complex interaction of its passive and active systems, exposed to changing external and internal boundary conditions and subjected to control actions generated by the autonomous goal searching algorithm of the control system or by nondeterministic user interactions with the system. The complexity is further increased by the fact that the control algorithm has to respond to changing occupant preferences and also has to be able to recover after a manual intervention by the occupant. We are thus confronted with a complex physical system (nonlinear and time variant) with a super imposed control "agent" that has to perform multi-aspect optimization in order to determine the next control action.

This study is carried out using a simulation approach that is adequate to describe complex interrelations and control aspects of interacting building systems. The basic simulation engine of the toolbox is based on a semi-discrete finite element space discretization of the mathematical physical description for each component, resulting in a set of differential/algebraic equations (DAE). The size of the resulting system of equations is dependent on the granularity of the discretization. Each level of discretization contains a set of lumped physical constants to be calibrated based on experimental data. Eventually the system with the lowest granularity (meaning crudest mathematical representation) that still represents reality adequately (after calibration) will be chosen as the model that drives the adaptive control strategy. For this reason, different models with different granularity have been developed and compared. It was found that the lumped model depicted in Figure 7 performed adequately in most circumstances, provided the set of lumped parameters are calibrated from experiments on site (i.e., in the actual local conditions). The lumped system contains five nodes as shown in Figure 7.

All arrows in the system represent a "lumped" physical transport equation for heat and mass, identifiable with a lumped physical parameter. Note that these parameters are not constant but need to be determined as functions of the state (temperature, airflow, and slat angle). Extensive experimentation of the system is taking place leading to the calibration of the lumped model (i.e., its parameters) using a parameter estimation technique. The future deployment of the systems on site will be such that the model will be self-calibrated for each installed unit as part of the online benchmark procedure. This work on a novel self-calibration procedure will be addressed in another publication.

A general formulation of the discretized (or lumped) system in a global set of DAE can be formulated as follows:

$$dx/dt = A(x,t)\cdot x + b(t) + B(t)\cdot u(x,t) \qquad (1)$$

$$y(t) = C\cdot x(t) \qquad (2)$$

where

x = state vector
t = time
A = system state matrix
b = load vector
B = system control matrix
u = control vector
y = observable state (the part of the system state that can be measured)
C = observation matrix

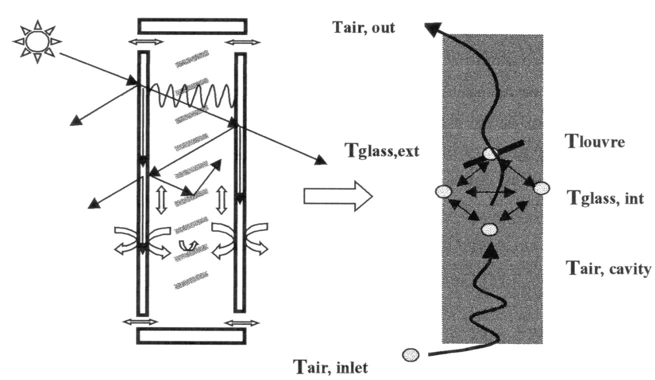


Figure 7 *Lowest order lumped simulation model of ventilated double facade.*

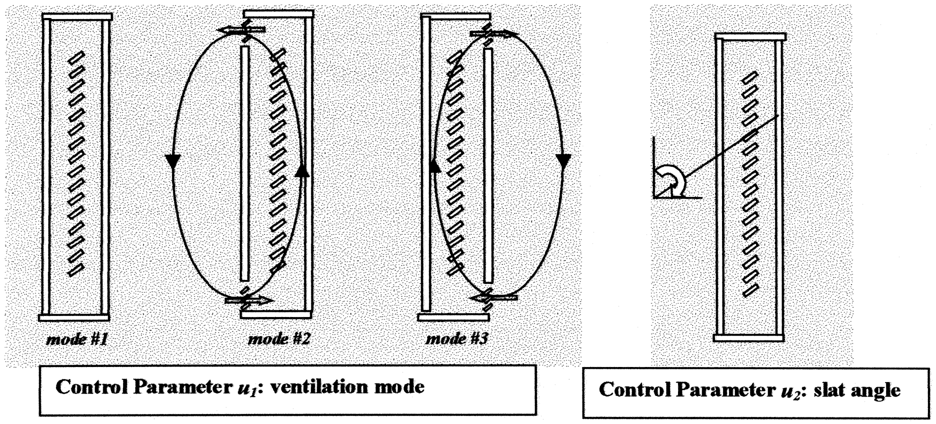


Figure 8 *Control parameters: Ventilation regime and slat angle.*

With initial state at $t = 0$ given as

$$x(t = 0) = x_o \tag{3}$$

the system of differential algebraic formulae (DAE) in Equation 1 can be solved discreetly in time using an adequate DAE solver. In this stage of the research, the MATLAB toolbox is used for this purpose. The control vector u is determined, either as the outcome of a predefined set of control rules or as the result of an adaptive control algorithm that tries to satisfy a given set of objectives.

The elements of A represent the field equations in each component as well as the physical interactions between components, such as longwave radiation exchange between glazing surfaces, louver slats, and external objects and convective heat transfer between cavity and glazing surfaces and louver slats. The corresponding rows in A contain calibrated system parameters for the radiative and convective heat transfer coefficients. In the lumped system (Figure 7) one row in A represents the mass balance of the cavity air, equating buoyancy forces to the friction losses in the cavity and at inlet and outlet.

The control vector u represents the control actions activated by the system itself (through a deterministic control rule or procedure) or through human intervention. The observation matrix C translates sensor output (the system state information) to an observed state y for human inspection. Typically, the user access to the system will show y and u, and, in override mode, the user will be allowed to change certain components of u within certain ranges.

Based on the global system equations, the following studies have been performed:

1. Identification of the (minimal) set of suitable control parameters and the way the user should be given access to them (i.e., based on what subset of the observable state vector and based on what feedback to the user). This set consists of two main control variables—ventilation regime ($u1$) and slat angle ($u2$), depicted in Figure 8.
2. Stability and sensitivity tests of the system aimed at studying the response of the system to user interactions. This has led to a number of restrictions of the allowed user interactions and the frequency with which they may occur. This study is being continued for the current on-site deployment of the unit.
3. Design of the most suitable control strategies of the system (i.e., in what way the occupant will be given access to select a model-based control strategy and override parameters of that strategy).
4. Assessment of overall energy efficiency of the system under different control strategies. A recent study by our research team shows that gains, as a result from optimal control versus an uncontrolled system for a standard winter and summer day, can be substantial. Overall efficiency increases from 0.5 to 0.7 in winter and an increase from 0.64 to 0.82 in spring and fall in the average Atlanta climate (Park 2001).

One of the priorities of the ongoing research is to verify that the predicted energy efficiencies can indeed be obtained in real situations to identify the negative impact that occupant interactions may have and to verify user satisfaction. Therefore, it is not sufficient to predefine control strategies. Rather, the system model needs to be part of a web-based "control center" so that, based on predictive state simulations, advice can be given to the user, informing whether the system is in near optimal state or needs adjustments. The next section provides an overview of these ongoing developments. The following section concentrates on the implementation of these interactions.

MODEL-BASED CONTROL AND INSPECTION

As indicated above, the control unit is an important component of the system. Smart systems save energy by imposing a control strategy that is devised to be the most optimal in the given conditions. Such strategy could either be predefined in a set of fixed rules or could be determined at every time. The latter typically involves performing simulations on an embedded model of the unit, leading to a choice of the next action based on the model predictions. This type of control is called model-based adaptive control.

In the current phase of the research, different control strategies have been designed for testing in the on-site deployment. They are either based on predetermined conditional rules or are model based. Once the most efficient strategies have been determined and verified in practice, it must be determined whether such strategy can be embedded in simple controllers (e.g., as a set of simple conditional statements in a PLC) or that a model-based strategy outperforms traditional controllers at all times. One of the premises of the research is that the occupant may take over at any time, and the control design must allow for this and be able to recover from such occupant interventions and take the system back to the optimal state as soon as possible. Early trials with different strategies have shown that it will be too complex to capture an optimal recovery mode in a simple set of rules. On the other hand, if only a small number of occupant interventions occur, the need for optimal recovery reduces considerably.

In the current setup of the system architecture, the controller function is performed on the server by a software component. This component can either be a representation of a rule-based controller or a full-blown decision component driven by simulation predictions. Preliminary studies on predictive control have shown that the derivation of simple control rules is promising, but more tests and on-site verification need to take place.

During the in-situ benchmarks, access to the state of the system and control parameters is accomplished in a straightforward manner. The BEMST data-logging component stores the data in a database that is accessible through a web interface. The screen output can be either tabulated or shown as a graph as in Figure 10. Moreover, both measured as well as simulated data can be shown in the same graph. This is very useful in the calibration stages when the comparison of actual and calculated data is to verify the correctness of the model in the current external conditions. In the benchmark stages, it will also be helpful to have direct access to the model representation in order to track the way that the different components behave and the way that certain control rules are invoked. Figure 9 shows a particular implementation of a web-based model inspection. It shows a representation of the lumped model that was developed, whereas Figure 10 shows an output window of a running simulation.

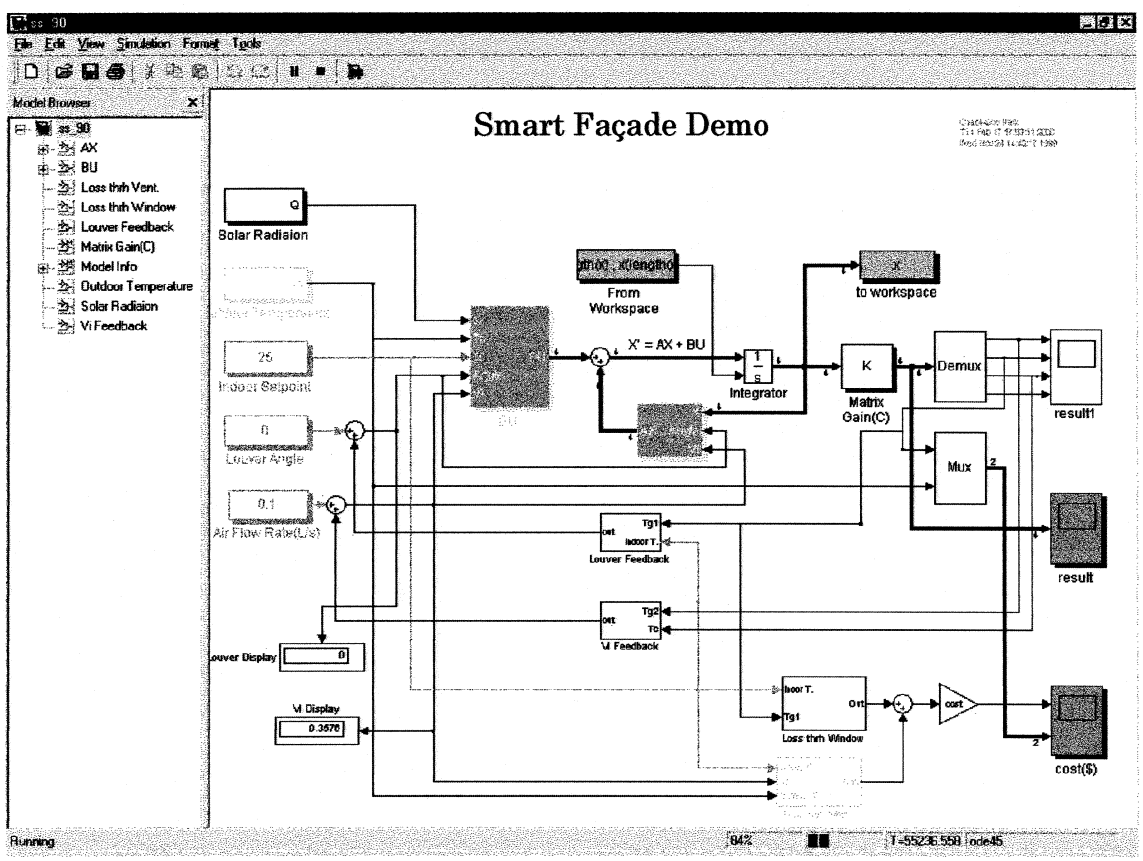


Figure 9 *Simulink model architecture.*

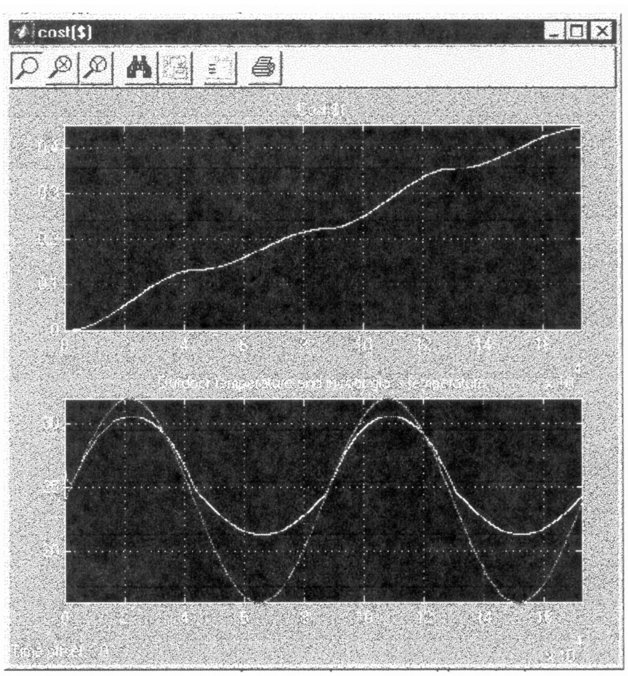


Figure 10 *Typical Simulink output.*

Both figures are shown here only to give a general impression of the type of interaction with the system simulation and state. Figure 9 shows the logical flow of the simple lumped model (Figure 7), which is simulated by connecting inputs and state variables to the differential equations and connecting state variable outputs to certain view windows, as the one in Figure 10. The main box in Figure 9 represents the time integrator of the set of ordinary differential equations with state variable vector x and control vector u. The other boxes serve to calculate the physical variables in the system (sometimes as functions of the state, which explains a lot of the feedback loops).

With appropriately chosen physical parameters, external conditions, and control settings, the model simulates the state and control actions of the actual system in the measured external conditions. In the early stages of the benchmark, the model serves as an easy way for the developers to (remotely) detect anomalies in the system behavior and communicate these with the benchmark service engineers on-site.

The purpose of the model is thus threefold:

1. To underpin model studies and test feasibility of smart components in some climate zones.
2. To design a base control mode to operate the unit.
3. To serve as back end simulation engine to determine control actions during operation.

It is a crucial aspect of the research deliverables that the web-hosted access to the simulation as well as to the physical SFDU allows remote monitoring, control, and calibration. Note that this approach to calibration does not require the control of external or internal conditions, which means that the use of a climate chamber is not required in the development of a new unit. The facade element is simply monitored in its natural environment (i.e., subjected to random conditions and operating modes). The use of a sophisticated parameters estimation technique, such as described in Augenbroe and Tumbuan (1995), based on genetic search algorithms, is robust enough to calibrate the model in any varying conditions.

CONCLUSION AND FUTURE WORK

The main conclusion of the project is that the calibration and testing of a smart facade component can be performed on site through rapid deployment of a configurable test unit that is built from a kit of parts and pre-wired with sensors and actuators. The unit is delivered "Internet ready," which allows immediate testing to be controlled remotely. This approach enables a unique opportunity for manufacturers to undertake design refinements in parallel with actual on-site testing, circumventing expensive climate chamber experimentation. This is believed to be a big plus for the rapid introduction of experimental facade technologies on the American market.

The introduced prototype unit is currently being tested in in-situ experiments. The experimental data are used to calibrate the model and determine the physical parameters, using robust parameter estimation techniques. In a future extension, a procedure will be developed to enable self-calibration. In a typical installation, the calibrated model will subsequently be used to design adequate control strategies and deploy the system in the architecture of Figure 5.

The immediate next step in the research project is the deployment of the unit in an actual project where the technology is considered as part of the refurbishment.

Future research will address the scalability of the technology, dealing with such issues as

1. The miniaturization of the BEMST and web server and their integration in ordinary online building management systems.
2. The integration into the hierarchical nature of control systems and determination of optimal controls on whole building scale together with the reduction of the complexity of control strategies such that they can be programmed in a simple PLC.
3. The group dynamics of user interaction with smart facade systems in typical office settings (this deals with group dynamics and occupant specific preference profiles).

The impact of controllability of the local indoor environment in relation to worker satisfaction, retention, and health issues is another long-term research issue.

ACKNOWLEDGMENTS

The authors appreciate the support from Kawneer Inc. for the construction and installation of the smart facade demonstration unit. Likewise, they wish to thank Ruskin and Marietta Draperies and Coverings for respectively providing the airflow dampers and the motorized shading louvers.

REFERENCES

Andersen, K.T. 1995. Theoretical considerations on natural ventilation by thermal buoyancy. *ASHRAE Transactions* 101 (2): 1103-1117.

Augenbroe, G., and E. Tumbuan. 1995. Simulation of moisture transport to assess durability aspects of composite walls. *4th international IBPSA conference, Building Simulation '95, Madison*, pp. 7-13.

Baker, P., D. Saelens, M. Grace, and T. Inoue. 2000. Advanced envelopes: Methodology, evaluation and design tools. *Final report IEA Annex 32 (IBEPA), Leuven, Belgium.*

Barakat, S.A. 1987. Thermal performance of a supply-air window. *12th Passive Solar Conference Proceedings*, D.A. Andrejko and J. Hayes, eds., pp.159-165.

Bilgen, E. 1984. Experimental study of thermal performance of automated venetian blind window systems. *Solar Energy* 52 (1): 3-7, Pergamon Press.

Brandle, K., and R.F. Boehm. 1982. Airflow windows: Performance and applications. *Thermal Performance of the Exterior Envelopes II*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

COMIS-TRNSYS. 2001. Application example, air quality and thermal comfort in a naturally ventilated school building with glazed double facade. http://www.empa.ch/englisch/erg/sim_expl/ztl_df/ztl_df.htm.

Compagno, A. 1995. *Intelligent glass facades—Material, practice, design*. Verlag, Basel.

Cho, S., K. Shin, and M. Zaheer-Uddin. 1995. The effect of slat angle of windows with venetian blinds on heating and cooling loads of buildings in South Korea. *Energy* 20 (12): pp. 1225-1236.

Faist, A.P. 1998. Double-skin walls. Solar Energy and Building Physics Laboratory of the Institute for Building Technology.

Haddad, K.H., and A.H. Elmahdy. 1998. Comparison of the monthly thermal performance of a conventional window and a supply-air window. *ASHRAE Transactions* 104: 1261-1270.

Haddad, K.H., and A.H. Elmahdy. 1999. Comparison of the thermal performance of an exhaust-air window and a supply-air window. *ASHRAE Transactions* 105 (2): pp. 918-926.

Holmes, M.J. 2000. Optimisation of the thermal performance of mechanically and naturally ventilated glazed facades. *Renewable Energy* 5 (2): pp. 1091-1098, Elsevier Science Ltd., UK.

Jones, J., and T. Messadi. 2000. Experimental study of the cooling season performance of ventilated double-glass envelope cavities. *International Building Physics Conference, Eindhoven, the Netherlands.*

Kitchen, P., and R.D. Moore. 1978. New concept in louver blade design reduces energy losses. *Proceedings of the 5th Annual UMR-DNR Conference on Energy, University of Missouri-Rolla, Missouri Department of Natural Resources.*

Lee, S.E., and S. Selkowitz. 1998. Integrated envelope and lighting systems for commercial buildings: A retrospective. *Proceedings of ACEEE 98, Asilomar, Pacific Grove, CA.*

Li Y., and A. Delsante A. 2001. Natural ventilation induced by combined wind and thermal forces. *Building and Environment*, 36: 59-71.

Mueller, H.F.O. 1984. Exhaust-air ventilated windows in office buildings. *ASHRAE Transactions* 90 (1B): pp. 932-947.

Park, C.S. 2001. *Optimal predictive control for smart façade systems*. Ph.D. qualifying paper. Atlanta: Georgia Institute of Technology, College of Architecture.

Pfrommer, P., K.J. Lomas, and C. Kupke. 1996. Solar radiation transport through slat-type blinds: A new model and its application for thermal simulation of buildings. *Solar Energy* 57 (2): pp. 77-91.

Rheault, S., and E. Bilgen. 1987. Heat transfer optimization of an automated venetian blind window system. *12th Passive Solar Conference Proceedings*, pp.152-158.

Ripatti, H. 1984. Airflow window system—Making fenestration the solution rather than the problem in energy use. *ASHRAE Transactions* 90 (1B): pp. 917-931.

Saelens, D., and H. Hens. 2001. Experimental evaluation of airflow in naturally ventilated active envelopes, *Journal of Thermal Envelope & Building Science*. Ottawa, Canada, Ed. Mark Bomberg.

Talmatamar, T., M. Alhabori, Y. Sfaxi, and C. Awanto. 1995. Analysis of solar radiation for sunlit glass shaded by vertical adjustable flat slats. *Renewable Energy* 7 (7): pp. 663-671.

Todorovic, B., and B. Maric. 2001. *The influence of double facades on building heat losses and cooling loads*. http://www.rcub.bg.ac.yu/~todorom/tutorials/rad31.html.

van Paassen, D., and M. van der Voorden. 2000. Development of simplified tools for evaluation energy performance of double facades. *Proceedings of International Building Physics Conference, Tools for Design and Engineering of Buildings, Eindhoven, The Netherlands*, pp.347-355.

Wigginton, M., and B. McCarthy. 2000. Environmental second skin system. http://www.battlemccarthy.demon.co.uk/research/doubleskin/doubleskinhomepage.html.

Wang, C.C., C.J. Lee, C.T. Chang, and S.P. Lin. 1999. Heat transfer and friction correlation for compact louvered fin-and-tube heat exchangers. *International Journal of Heat and Mass Transfer* 42: 1945-1956.

Walton, G.N. 1989. Airflow network models for element-based building airflow modeling. *ASHRAE Transactions* 95 (2).

Yakubu, G.S., and S. Sharples. 1991. Airflow through modulated louvre systems. *Building Services Engineering Research Technology* 12 (4): pp. 151-155.

Zhang J.S., K. A. Janni, and L. D. Jacobson. 1989. Modelling natural ventilation induced by combined thermal buoyancy and wind. *Transactions of the ASAE* 32(b): 2165-2174.

Yakubu, G.S., and S. Sharples. 1991. Airflow through modulated louvre systems. *Building Services Engineering Research Technology* 12 (4): pp. 151-155.

Zhang J.S., K. A. Janni, and L. D. Jacobson. 1989. Modelling natural ventilation induced by combined thermal buoyancy and wind. *Transactions of the ASAE* 32(b): 2165-2174.