SIMULATION OF DOUBLE-SKIN FACADES FOR HOT AMD HUMID CLIMATE

Matthias Haase*and Alex Amato
Dept of Architecture, The University of Hong Kong (HKU)
Pokfulam Road, HKSAR, China
Tel (852) 2241 5839 Fax (852) 2559 6484
*Corresponding author e-mail mathaase@hkusua.hku.hk

ABSTRACT

Thermal building simulations (TRNSYS) were linked to nodal airflow network simulations (COMIS) for airflow window and solar chimney performance calculation and overall energy consumption for office building facades. Especially interesting was the attempt to reduce the high peak cooling loads during the summer period by controlling the exhaust airflow using a climate sensitive regulator. It could be shown that up to 30% reduction of peak loads can be achieved. This results in significant energy conservations and a reduction in systems cooling size.

INTRODUCTION

There is a world-wide need for a sustainable development (Behling 1996). Looking at examples in European countries a strong emphasis on energy efficiency can be noticed (Baker 2002.; European Commission 1992.; Goulding et al. 1992; Krishan 2001.; Lee et al. 1998).

Energy and Buildings

The build environment in Hong Kong has a great potential for improving its sustainable development (Hui 2000). 52% of the total energy in Hong Kong is used by buildings. Office and commercial buildings are using 37% total energy (emsd 2003). Thus it is important to develop buildings that consume less operational energy during its life cycle.

Buildings and Climate

Especially in moderate to cold climate like Europe new concepts were tested. They took into account the outdoor conditions and tried to create a climatic responsive building (Givoni 1992; Szokolay 1980b; Wigginton 1996). Especially for the top-end market sector of office buildings advanced façade technologies were developed (Wigginton 2002). They tried to integrate more and more building services into the façade system. This has the advantage of reducing the space needed inside the building and reducing initial overall costs. One promising development of advanced façade systems is the double-skin façade (DSF).

Climate in Hong Kong

However, little work has been done on the behaviour of double-skin façades in hot and humid climates (Haase and Amato 2005; Rajapaksha et al. 2003). This is particularly interesting since the building types and the climate are very different in Hong Kong (Lam 1995; Lam 1999; Li and Lam 2000) with an urban environment that is dense and high-rise with usually 40 floors and above (Close 1996).

The seasonal and daily climate in respect to mean temperature, humidity and wind speed distribution in Hong Kong is different to the moderate climate in Europe (Lam and Li 1996; Li and Lam 2000; Li et al. 2004). A new approach for double-skin facades (DSFs) has to take the climatic factors into account to find out if a double-skin façade can help to reduce the energy consumption in buildings in a hot and humid climate.

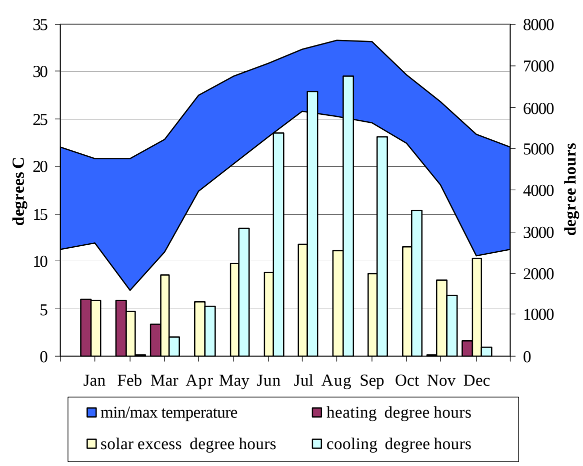


Figure 1. Hong Kong climate

DOUBLE-SKIN FAÇADE TECHNOLOGY

In the following chapters a classification of DSFs and some advantages of this technology is given.

Classification of DSFs

Many types of DSFs have been developed since the first double layer was used in the building envelope (Wigginton). It is helpful to agree on a consolidated classification of DSFs (Parkin 2004). Figure 2 gives an overview of the main characteristics often used when describing the various features of DSFs.

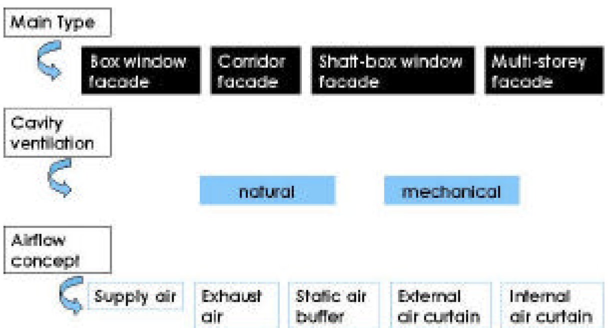


Figure 2. Classification of DSFs

Airflow concepts

When looking at the various airflow concepts it is important to note that all main types of DSFs can be combined with both types of ventilation and all types of airflow concepts. This results in a great variety of DSFs.

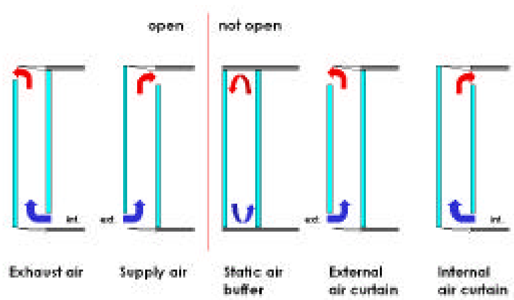


Figure 3. Airflow concepts of DSFs

Figure 3 shows the different airflow concepts that can be applied to DSFs. They can be devided into open systems that allow an exchange of air through the envelope from inside to outside or vice versa and not open concepts that consist of sealed envelopes which do not provide this possibility. More recently, DSF have been developed that act as climate responsive elements with hybrid ventilation (natural and mechanical) concepts with a possibility to change the airflow concept due to different weather conditions in different seasons (Heiselberg 2002).

Advantages of DSFs

The development of DSF technology involves several advantages by improving the thermal, visual and acoustic comfort (Oesterle 2001). In moderate climates the air layer helps to insulate the building and thus reduce the energy consumption for heating. This is more significant in cool climates with strong winter periods (Balocco 2002; Park 2003). Furthermore the buoyancy flow in the cavity itself may reduce solar heat gain and additionally it can support the HVAC-system (heating, ventilation and air-conditioning) and it can help to minimize the size of the system and consequently the energy consumption of the building (Allocca et al. 2003; Andersen 2003; Gratia and De Herde 2004a; Gratia and De Herde 2004b; Hensen 2002; Hensen 1993; Saelens et al. 2003; Stec and Paassen 2001; Stec and Paassen 2004).

Then, it creates a space for advanced sunshading devices. Positioned into the cavity of the DSF it seems to reduce heat gain (von Grabe 2002). In addition, natural daylight filtered into a building for lighting appears to reduce the heat load for artificial lighting on air conditioning (Garcia-Hansen et al. 2002; Grimme 1999). Finally, DSFs provide an additional layer that helps to reduce the acoustic impact into the building (Oesterle 2001).

DSF SIMULATION

The heat transfer through the buildings envelope depends on various factors as shown in Figure 4. It illustrates the window physics, showing the complexity and impact of solar radiation, conduction and convection on the airflow through the double-skin gap. The temperatures and airflows result from many simultaneous thermal, optical and fluid flow processes which interact and are highly dynamic (Chen and Van Der Kooi 1990; Garde-Bentaleb et al. 2002; Prianto and Depecker 2002; Qingyan and Weiran 1998; Xu and Chen 2001a; Xu and Chen 2001b; Zhang and Chen 2000). 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 (Hensen 2002). The temperature inside the offices, the ambient temperature, wind speed, wind direction, transmitted and absorbed solar radiation and angles of incidence govern the main driving forces (Manz 2003; Reichrath and Davies 2002; Zhai and (Yan) Chen).

Several possible calculation models have been developed to simulate the thermal behaviour of DSF (Saelens et al. 2003, Stec and Paassen 2004, Manz 2003). But only few take the dynamic wind pressure on the façade into account (Flamant et al. 2004). The most detailed model recently developed is the model used by Sealens (2002). Saelens studied different DSFs and compared heating and cooling load for temperate climate of Belgium. The results are however not easy to transfer to a hot and humid climate and he simulated only single-storey DSFs.

For Hong Kong thermal comfort improvements of natural ventilation are 20% for the whole year and 10% during the three hottest months June, July, and August (Haase and Amato 2005a). Accordingly, a special focus was to analyze the cooling load and its reduction during the hottest month and the hottest three months.

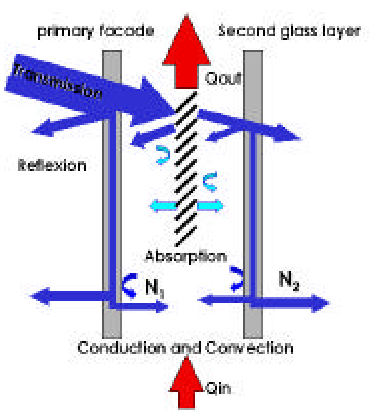


Figure 4. Physics of DSFs

For this study a combined thermal and airflow simulation was chosen. TRNSYS and TRNFLOW (coupled with COMIS) was used to model an office room with DSF (Trnsys 2004; Dorer 2001).

A simple DSF can be described either as external or internal air curtains (EAC or IAC) as shown in Figure 3. Both DSF do not require a control strategy. For simulation purposes the two DSF were modeled as shown in Figure 5 where Figure 5a) describes the EAC model and Figure 5b) the IAC model. Then a switch has been tested by opening windows to allow for supply air and exhaust air. The switch must be controlled by a climate sensitive regulator which allows controlling the exhaust airflow. The aim is together with the optimisation of the shading device to reduce solar heat gain and thus reducing the peak cooling load of the building.

Control strategy

There are several control strategies in respect to DSFs. The first is to control the shading system. The second strategy is to control the airflow direction (from internal to external or vice versa).

Both strategies involve climatic indicators. In the first case a sensor is used to detect the amount of solar radiation on the façade and to shade the window accordingly. In this work the shading device closed (80%) at 200 W/sqm and opened at 150 W/sqm.

The second strategy is more complex. In temperate climates where natural ventilation is a cooling strategy the internal façade consists of open able windows. This allows the occupant to control airflow according to individual comfort (Saelens et al. 2003).

The third strategy is to control the HVAC system. The setpoint temperature determines the room temperature at which the HVAC system starts cooling and is very sensitive to changes (Lam et al. 1996). Here, a setpoint temperature of 26°C was chosen with infinite cooling power. A heating system was not used.

For the DSF with EAC a comparison between room enthalpy and cavity enthalpy was done. The window was opened when the room enthalpy was higher then in the cavity. For the DSF with IAC the window was opened when the cavity enthalpy was higher then outside in order to exhaust the air. Special focus was put on the pressure distribution that has to allow exhaust of air.

Urban context

In order to test the performance of a DSF and its dependence on the airflow in the cavity which is influenced by the pressure coefficients on the envelope simulations were run with different pressure coefficients Cp. The dense and high rise Hong Kong building situation has been simulated in order to derive Cp values for the façade (Grosso 1995). Here a plan area density (PAD) of 35% was used together with 120m building height. The basic building was assumed to be 35m wide and 35m long. The cp values for different orientations have been used in TRNFLOW as an input for three different scenarios as shown in Table 1. The first scenario used cp values determined by Orme et al. (1998). These have been determined for low-rise buildings and should not be used for high-rise application. The second scenario used the calculated Cp values for 18m reference height. The third scenario used the calculated Cp values for 54m reference height and the forth scenario used Cp values for 90m height.

Table 1: List of cp values used in DSF simulation

Orien tation	CpRef. (13m) DSF2-1	Cp1 (18m) DSF2-2	Cp2 (54m) DSF2-3	Cp3 (90m) DSF2-4
0	-0.7	0.016	0.006	-0.002
45	-0.8	0.0169	0.0064	-0.0017
90	-0.5	0.0352	0.0132	-0.0048
135	0.25	0.0024	0.0036	-0.0022
180	0.5	0.0074	0.0114	-0.002
225	0.25	0.0024	0.0036	-0.0022
270	-0.5	0.0352	0.0132	-0.0048
315	-0.8	0.0169	0.006	-0.0017
roof	-0.7	-0.05	-0.05	-0.05

Modelling

Three models were used to compare their performance. The first model is a curtain wall system which acts as a base case for comparison. The second model is a natural ventilated external air curtain. An internal shading device was positioned in the 600mm deep cavity. The third model is a mechanical ventilated internal air curtain with a cavity depth of 240mm. The model room was simulated with 6.6m width and 8m depth. The façade was facing South and a schedule was used to simulate the office use (working hours from 8am to 5pm on weekdays). The window to wall ratio is 44%.

Base Case Curtain Wall

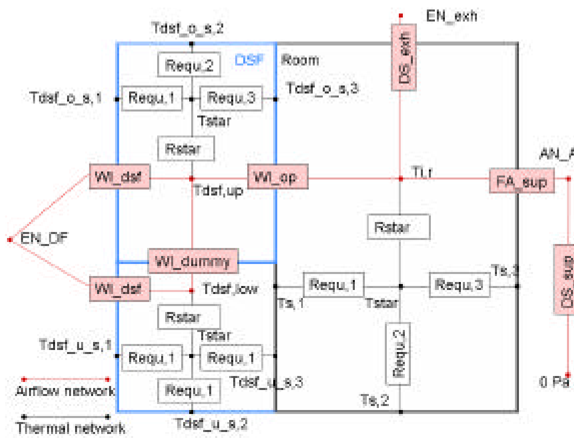
The model consists of a single glazed curtain wall (CW) system. The glass layer consists of a 10mm clear glass with internal shading device. A comparison of the performance of different other glass types has been reported elsewhere (Haase and Amato 2006).

External Air Curtain

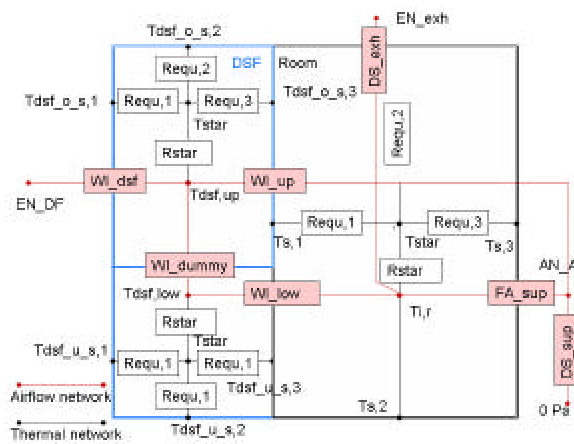
The design proposal includes a DSF with 600mm cavity with one-storey double-skin façade. Both glass layers were selected as single clear glass (10mm).The DSF is open on bottom and top to the outside allowing a naturally ventilated cavity. A shading device is positioned in the cavity and solar controlled (DSF1). A regulator indicates the times of the year when the enthalpy of the air in the window gap is exceeding the enthalpy of the outside air (DSF2). The regulator will then exhaust the air which is expected to result in energy savings.

Internal Air Curtain

The windows are connected to an additional second layer of glazing placed on the inside of the window to create a DSF. The mullion's depth of around 240mm is needed for structural purposes and leaves space for the shading device which can be opened and closed automatically. At the same time the mullion can be used to introduce a second glass layer on the inside. It is open to the room at the bottom and has a ventilation slot on the top of the window. Air is vented through the airflow window from the room back to the MVAC system (AFW1). A control opens the cavity of the double-skin to the exterior, allowing used air from the room to be exhausted. The purpose of this design is to improve the thermal performance of the airflow window (AFW2).



a)



b)

Figure 5. Thermal and airflow simulation DSF (a) and AFW (b)

RESULTS

The performance of a DSF depends on the airflow in the cavity which is influenced by the pressure coefficients on the envelope. Fig 6 shows the results for the DSF with different Cp values as listed in Table 1.

The results indicate that the annual performance of a DSF works in different heights of a high-rise building. It can also be seen that it does not vary much over the height of the building. The DSF1 saves 11% annually, while a peak reduction of 19%. With enthalpy control strategy (DSF2) the annual cooling load reduction ranges between 11% and 12%. The cooling reduction for the hottest month is between 19% and 20%.

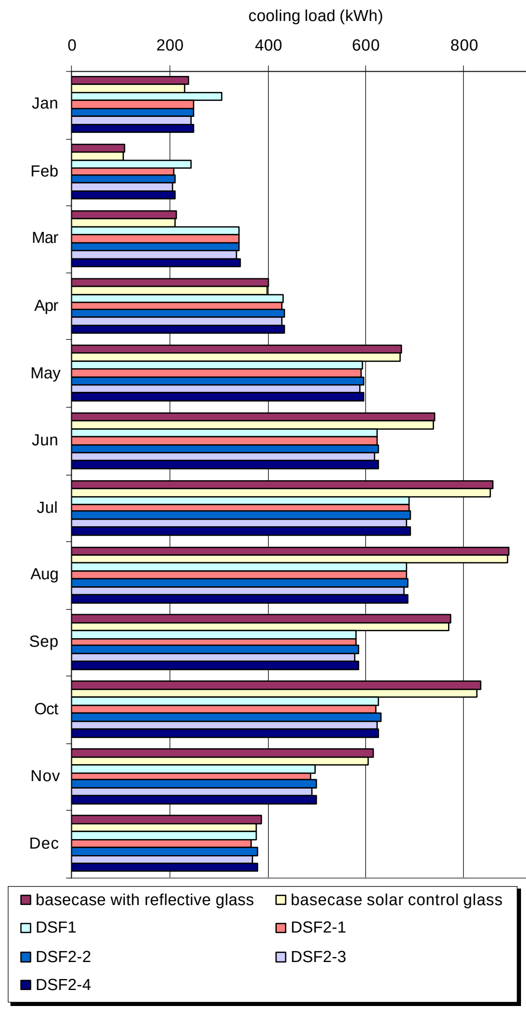


Figure 6. Results for simulation of DSF at different heights

Figure 7 shows the simulation results for DSF and AFW simulation. The DSF saves 11% annually, while a peak reduction of 23%. The enthalpy control strategy results in a further peak reduction of 26% and the annual savings are 12%. The airflow window without control strategy (AFW1) increases the annual cooling load by 5%. This is due to clear glass as outside layer compared to reflective glass layer in the base case. The heat gain in the cavity is in the building and adds to the cooling load. With enthalpy control strategy (AFW2) annual cooling load reduction is 22%. The cooling reduction for the hottest month is 30% and 28% for the hottest four months.

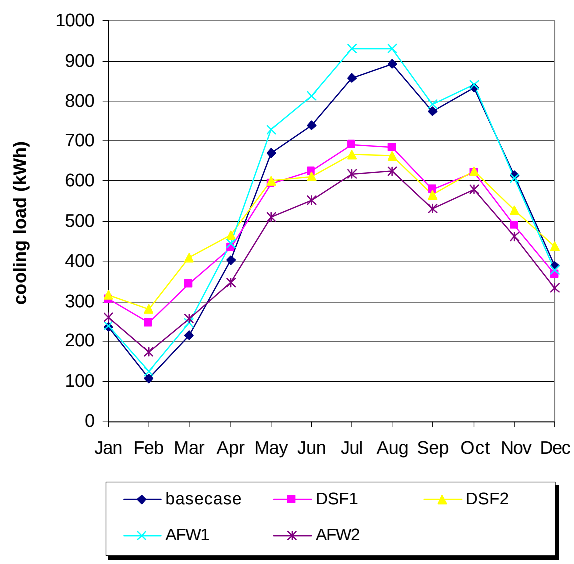


Figure 7. Simulation results for DSF and AFW

CONCLUSION

It is possible to design an energy efficient DSF system. The amount of heat gain through the buildings envelope can be reduced significantly by designing a ventilated DSF that is optimised in respect to heat transfer.

The EAC uses natural ventilation in the cavity to reject heat gain. Wind pressure on the building envelope was taken into consideration. The system provides a possibility to reduce annual cooling loads as well as peak cooling loads of an office room. The results can be slightly better for the EAC with a climatic control especially the reduction of cooling loads in the hot summer period.

The IAC does not reduce the cooling load of the office room. The system depends on an enthalpy based control that extracts air in order reduce the cooling load of an office room. This system gives the best results.

The results have to be validated against measured data from different facade types. This will be done in the near future.

While a reduction of radiation is met by using controlled solar shading devices, there are constraints from maximizing the use of daylight. Further research is planned to optimize the amount of daylight and thus reduce internal heat gain.

For the DSF with EAC the change of the cp-values of the facade shows very small difference in cooling load. In this study pressure coefficients for different building heights were used. For the AFW with IAC the same cp-values were used. The results indicate that a control of exhaust air is important. It could also be demonstrated that the exhaust of the AWF works.

Ongoing research will estimate cp-values for different building shapes and heights. Then different airflow rates and its influence on the energy savings potential will be investigated. This will allow testing the robustness of the system for high-rise application.

While a reduction of radiation is met by using solar shading devices, there are constraints from maximizing the use of daylight. Further, it is important to enhance the use of natural daylighting (Bodart 2002; Lam and Li 1998; Lam and Li 1999). This provides not only energy saving potential but also acknowledges the growing awareness for natural daylight and its effects on a healthy environment (Li and Lam 2001). Further studies are needed and will be conducted in the near future.

REFERENCES

Allocca, C., Chen, Q. Y., and Glicksman, L. R. (2003). "Design analysis of single-sided natural ventilation." *Energy and Buildings*, 35(8), 785-795.

Amato, A., Wong, F., and Humphrey, S. (2005). "A Case Study of Sustainable Refurbishment in Hong Kong: An Energy-Efficiency Assessment of the Parkside Apartments Refurbishment Carried Out for Swire Properties." *International Workshop on Integrated Life-Cycle Management of Infrastructures*, HKUST.

Baker, N. (2002). *Daylight design of buildings*, James & James,, London.

Balocco, C. (2002). "A simple model to study ventilated facades energy performance." *Energy and Buildings*, 34(5), 469-475.

Behling, S. (1996). *Sol power: the evolution of solar architecture*, Prestel, Munich.

Bodart, M. a. D. H., A. (2002). "Global energy savings in offices by the use of daylight." *Energy and Buildings*, 34(5), 421-429.

Chen, Q., and Van Der Kooi, J. (1990). "A methodology for indoor airflow computations and energy analysis for a displacement ventilation system." *Energy and Buildings*, 14(4), 259-271.

Chen, Z. D., Bandopadhayay, P., Halldorsson, J., Byrjalsen, C., Heiselberg, P., and Li, Y. (2003). "An experimental investigation of a solar chimney model with uniform wall heat flux." *Building and Environment*, 38(7), 893-906.

Close, J. (1996). "Optimising daylighting in high-rise commercial developments in SE Asia and the use of computer programmes as a design tool." *Renewable Energy*, 8(1-5), 206-209.

Close, J., Haase, M., and Pang, H. (2004). "Added value" for a PV-stack." *World Renewable Energy Congress (WREC-VII)*, Denver, USA.

Dorer, V. (2001) Users Guide of COMIS 3.1.

European Commission (1992). *Energy in architecture : the European passive solar handbook*, B.T. Batsford, London.

emsd. (2003). "Hong Kong Energy End-use data (1991-2001)." EMSD, Hong Kong.

Flamant, G., Heijmans, N., and Guiot, E. (2004). “Determination of the energy performance of ventilated double-skin facades by the use of simulation integrating the control aspects.” Final Report of the Ministry of Economic Affairs project Ventilated double facades, Belgian Building Research Institute (BBRI), Department Building Physics, Indoor Climate and Building Services.

Garcia-Hansen, V., Esteves, A., and Pattini, A. (2002). "Passive solar systems for heating, daylighting and ventilation for rooms without an equator-facing facade." *Renewable Energy*, 26(1), 91-111.

Garde-Bentaleb, F., Miranville, F., Boyer, H., and Depecker, P. (2002). "Bringing scientific knowledge from research to the professional fields: the case of the thermal and airflow design of buildings in tropical climates." *Energy and Buildings*, 34(5), 511-521.

Givoni, B. (1992). "Comfort, Climate Analysis and Building Design Guidelines." *Energy and Buildings*, 18(1), 11-23.

Goulding, J. R., Lewis, J. O., and Steemers, T. C.(eds) (1992). *Energy conscious design : a primer for architects*, Commission of the European Communities,, London.

Gratia, E., and De Herde, A. (2004a). "Natural ventilation in a double-skin facade." *Energy and Buildings*, 36(2), 137-146.

Gratia, E., and De Herde, A. (2004b). "Optimal operation of a south double-skin facade." *Energy and Buildings*, 36(1), 41-60.

Grimme, F.-W. a. L., M. (1999). "Energy Efficiency in Tropical Office Buildings. Latest Developments in Daylight Guidance Systems. Modern Glazings - Efficient for Cooling and Daylighting. Development of Energy Efficiency Policy for Buildings and Research Activities after 1970 in the field of Low Energy." *Conferencia Internacional de Energía Renovable y Educación Energética*, Havanna, Kuba.

Grosso, M. (1995) CPCALC+, Calculation of wind pressure coefficients on buildings, Software from Polytechnic University of Turin

Haase, M., and Amato, A. (2006). "Double-skin facades in Hong Kong." *SABE*, HKIS to be published in June 2006.

Haase, M., and Amato, A. (2005b). "Development of a double-skin façade system that combines airflow windows with solar chimneys." *Sustainable Building (SB05)*, September 2005, Tokyo, Japan.

Haase, M., and Amato, A. (2005a). "Fundamentals for climate responsive envelopes." *Glass in Buildings 2*, April 2005, Bath, UK.

Haase, M., Close, J., and Pang, H. (2004a). "Enhanced ventilation with solar chimneys." *Joint Symposium 2004 Servicing dense built environments*, Nov 2004, Hong Kong, China.

Haase, M., Close, J., and Pang, H. (2004b). "Natural ventilation with solar chimneys." *2nd CIB Student Chapters International Symposium, Sustainability and Innovation in Construction and Real Estate*, Oct 2004, Tsinghua University, Beijing, China.

Haase, M., Wong, F., and Amato, A. (2004). "Double-skin facades for Hong Kong." *International Conference on Building Envelope Systems & Technology*, April 2004, Sydney, Australia.

Heiselberg, P. (ed.) (2002). "HybVent - Hybrid ventilation." IEA-ECBCS Annex35 Hybvent. http://hybvent.civil.auc.dk/

Hensen, J., Bartak, M., Drkal, F. (2002). "Modeling and simulation of a double-skin facade system / Discussion." *ASHRAE Transactions*, 108, 1251.

Hensen, J. L. M. (1993). "Towards an integral approach of building and HVAC system." *Energy and Buildings*, 19(4), 297-302.

Hensen, J. L. M., and Nakahara, N. (2001). "Building and Environmental Performance Simulation: Current State and Future Issues." *Building and Environment*, 36(6), 671-672.

Hui, S. C. M. (2000). "Solar Hong Kong - present applications and future prospects." *Renewable Energy World*, 3(1), 76-83.

Krishan, A. (ed.) (2001). *Climate responsive architecture : a design handbook for energy efficient buildings*, Tata McGraw-Hill,, New Delhi.

Lam, J. C. (1995). "Building envelope loads and commercial sector electricity use in Hong Kong." *Energy*, 20(3), 189-194.

Lam, J. C. (1999). "Climatic influences on the energy performance of air-conditioned buildings." *Energy Conversion and Management*, 40(1), 39-49.

Lam, J. C. (2000). "Energy analysis of commercial buildings in subtropical climates." *Building and Environment*, 35(1), 19-26.

Lam, J. C., Hui, S. C. M., and Chan, A. L. S. (1997). "Regression analysis of high-rise fully air-conditioned office buildings." *Energy and Buildings*, 26(2), 189-197.

Lam, J. C., and Li, D. H. W. (1996). "Study of solar radiation data for Hong Kong." *Energy Conversion and Management*, 37(3), 343-351.

Lam, J. C., and Li, D. H. W. (1998). "Daylighting and energy analysis for air-conditioned office buildings." *Energy*, 23(2), 79-89.

Lam, J. C., and Li, D. H. W. (1999). "An analysis of daylighting and solar heat for cooling-dominated office buildings." *Solar Energy*, 65(4), 251-262.

Lee, E. S., DiBartolomeo, D. L., and Selkowitz, S. (1998). "Thermal and Daylighting performance of an automated venetian blind and lighting system in a full-scale private office." *Energy and Buildings*, 29(1), 47-63.

Li, D. H. W., and Lam, J. C. (2000). "Solar heat gain factors and the implications to building designs in subtropical regions." *Energy and Buildings*, 32(1), 47-55.

Li, D. H. W., and Lam, J. C. (2001). "Evaluation of lighting performance in office buildings with daylighting controls." *Energy and Buildings*, 33(8), 793-803.

Li, D. H. W., Wong, S.L., and Lam, J. C. (2003). " Climatic effects on cooling load determination in subtropical regions." *Energy Conversion and Management* 44, 1831 –1843

Li, D. H. W., Lau, C. C. S., and Lam, J. C. (2004). "Overcast sky conditions and luminance distribution in Hong Kong." *Building and Environment*, 39(1), 101-108.

Manz, H. (2003). "Numerical simulation of heat transfer by natural convection in cavities of facade elements." *Energy and Buildings*, 35(3), 305-311.

Oesterle, E., Lieb, R.-D., Lutz, G., Heusler, B. (2001). *Double-skin facades : integrated planning : building physics, construction, aerophysics, air-conditioning, economic viability*, Prestel,, Munich.

Orme, Liddament M., Wilson A. (1998) Numerical Data for Air Infiltration & Natural Ventilation Calculations, Air Infiltration and Ventilation Centre (AIVC), Coventry GB

Park, C.-S. (2003). "Occupant-Responsive optimal control of smart facade systems," PhD thesis. Georgia Institute of Technology.

Parkin, S. (2004). "A description of a ventilated double-skin façade classification." *International Conference on Building Envelope Systems & Technology*, Sydney, Australia.

Prianto, E., and Depecker, P. (2002). "Characteristic of airflow as the effect of balcony, opening design and internal division on indoor velocity - A case study of traditional dwelling in urban living quarter in tropical humid region." *Energy and Buildings*, 34(4), 401-409.

Qingyan, C., and Weiran, X. (1998). "A zero-equation turbulence model for indoor airflow simulation." *Energy and Buildings*, 28(2), 137-144.

Rajapaksha, I., Nagai, H., and Okumiya, M. (2003). "A ventilated courtyard as a passive cooling strategy in the warm humid tropics." *Renewable Energy*, 28(11), 1755-1778.

Reichrath, S., and Davies, T. W. (2002). "Using CFD to model the internal climate of greenhouses: past, present and future." *Agronomie*, 22(1), 3-19.

Saelens, D., Carmeliet, J., and Hens, H. (2003). "Energy performance assessment of multiple skin facades." *International Journal of HVAC&Research*, 9(2), 167-186.

Saelens, D. (2002), Energy Performance Assessment of Single Storey Multiple-Skin Facades, PhD thesis, Katholieke Universiteit Leuven, Belgium

Stec, W., van Paassen, A. H. C. (2001). "Controlled double facades and HVAC." *7th Clima 2000 World Congress*, Napoli (I).

Stec, W. J., and Paassen, A. H. C. v. (2005). "Symbiosis of the double skin facade with the HVAC system." *Energy and Buildings*, 37(5), 461-469

Szokolay, S. V. S. V. (1980a). *Environmental science handbook for architects and builders*, Construction Press,, Lancaster.

Szokolay, S. V. S. V. (1980b). *World solar architecture*, Architectural Press, London.

TRNSYS16 (2004), User manual, Solar Energy Laboratory, University of Wisconsin-Madison, http://sel.me.wisc.edu/trnsys

von Grabe, J. (2002). "A prediction tool for the temperature field of double facades." *Energy and Buildings*, 34(9), 891-899.

Watson, D. (ed.) (1993). *The Energy design handbook*, American Institute of Architects Press,, Washington, D.C.

Wigginton, M. and Battle McCarthy (2000). "Environmental Second Skin Systems." Interet resource, accessed Aug 2004. http://www.battlemccarthy.demon.co.uk/research/doubleskin/mainpage.htm

Wigginton, M. (1996). *Glass in architecture*, Phaidon Press,, London

Wigginton, M. (2002.). *Intelligent skins*, Butterworth-Heinemann, Oxford.

Xu, W., and Chen, Q. (2001a). "A two-layer turbulence model for simulating indoor airflow: Part I. Model development." *Energy and Buildings*, 33(6), 613-625.

Xu, W., and Chen, Q. (2001b). "A two-layer turbulence model for simulating indoor airflow: Part II. Applications." *Energy and Buildings*, 33(6), 627-639.

Zhai, Z., and (Yan) Chen, Q. (2004). "Numerical determination and treatment of convective heat transfer coefficient in the coupled building energy and CFD simulation." *Building and Environment*, 39(8), 1001-1009.

Zhang, W., and Chen, Q. (2000). "Large eddy simulation of indoor airflow with a filtered dynamic subgrid scale model." *International Journal of Heat and Mass Transfer*, 43(17), 3219-3231.