Gosselin, J.R. and Chen, Q. 2008. "A dual airflow window for indoor air quality improvement and energy conservation in buildings," *HVAC&R Research*, 14(3), 359-372.

A Dual Airflow Window for Indoor Air Quality Improvement and Energy Conservation in Buildings

J.R. Gosselin Q. Chen*
Fellow ASHRAE

ABSTRACT

This paper proposes a novel dual airflow window for use in residential buildings that tempers outdoor air with exhausted indoor air. The energy needed to condition outdoor air is reduced because of the counterflow heat exchange between the two flow streams. Experimentally validated computational fluid dynamics (CFD) simulations have been used to optimize the window design and to estimate the benefits of the window system. The results show that a small flow rate of 10 L/s and a small cavity width of 9 mm result in the best window performance. The heat recovery efficiency of the window varies from 20 to 56% under the conditions studied in this paper. Within this range, the utilization of trapped solar energy can account for up to a 20% improvement in efficiency during winter conditions. The performance of the dual window is better than that of the existing single airflow window. Although the study shows risk of condensation under humid conditions, the dual airflow window has a great potential for conserving energy and improving indoor air quality.

INTRODUCTION

Buildings in the United States account for one-third of the total primary energy consumption and two-thirds of the electricity consumption (Hawken et al., 1999). Since infiltration and ventilation in dwellings accounts for one-third to one-half of the energy used for heating and cooling (Sherman and Matson, 1997), the construction of the building envelope has become increasingly tighter. This effort has the tendency to decrease ventilation and its associated energy penalty at the possible expense of adequate indoor air quality (Sherman and Matson, 1997). Indoor air quality (IAQ) is important since up to 90% of a typical American's time is spent indoors (EPA, 2001), and poor IAQ has been linked to respiratory illness, allergies, asthma, and sick building syndrome. Reduction in energy consumption for heating and cooling buildings should therefore not be achieved at the expense of IAQ but with the use of innovative design.

For commercial buildings IAQ can be regulated by the HVAC system that mixes fresh outdoor air with return air for the air supplied to the indoor space. In residential buildings, however, outdoor air typically enters the space through doors, operable windows and infiltration. During the heating and cooling seasons, ventilation is usually limited to infiltration as air systems typically use 100% recirculated air or hydronic systems heat air through convection with

* Jenn R. Gosselin was a graduate research assistant and Qingyan Chen is a professor at School of Mechanical Engineering, Purdue University, West Lafayette, Indiana. Gosselin is now with Vanderweil Engineers, Mass.

no direct air exchange. The Environmental Protection Agency (EPA) (2006) reports that, "Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home." Among the different measures for providing adequate fresh air in residential buildings, airflow windows seem most promising. This investigation has thus further explored the potential for airflow windows by improving their design.

PRINCIPLES OF EXISTING AIRFLOW WINDOW DESIGNS

The main difference between a conventional window and an airflow window is the existence of free or forced convection between two layers of glass called airflow cavities. There are four main modes of operation for airflow windows: supply, exhaust, indoor air curtain and outdoor air curtain (Figure 1). A supply air window draws air from the outside to the inside space; an exhaust air window extracts air from the inside to the outside space. The indoor and outdoor air curtains have airflow paths from inside to inside and outside to outside, respectively. Airflow is driven by natural, mixed or forced effects.

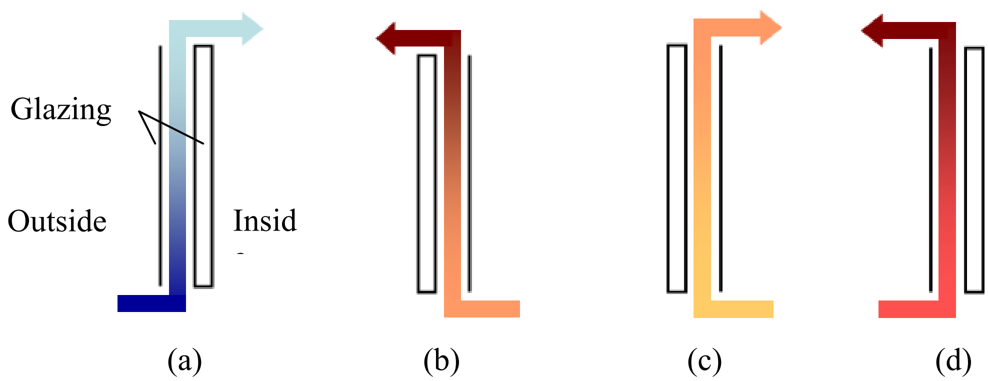


Figure 1. Existing airflow window types: (a) supply mode, (b) exhaust mode, (c) indoor air curtain and (d) outdoor air curtain.

Entrained solar heat is captured by airflow and directed indoors or outdoors depending on the operating mode. This reclaimed solar energy is used to preheat outdoor air in the supply mode and reheat indoor air in the indoor air curtain mode during the heating season. Airflow in the exhaust window and outdoor air curtain is used to remove solar energy by convecting away the excess heat during the cooling season.

As compared to a conventional window, the exhaust air window can also improve thermal comfort conditions, because the surface temperature of the interior glass pane becomes closer to the room air temperature. The decrease in temperature difference between the occupant and the inner window surface during the heating season decreases radiation exchange and improves thermal comfort.

Although the air curtain cannot be used to improve IAQ or meet ventilation requirements, it offers benefits related to energy consumption and thermal comfort. The outdoor air curtain is most beneficial on a sunny day during the cooling season. Outdoor air is driven upward in the outer airflow cavity, keeping the middle glass pane from overheating and thus reducing heat conduction to the indoors. The indoor air curtain reclaims solar energy in the inside cavity and convects it to the indoor space during the heating season.

REVIEW OF PREVIOUS RESEARCH

The first supply air windows were developed in the 1940's and further research and implementation was mainly conducted during the 1970's and 80's in Europe and North America (Tomory, 1983; Müller, 1983; Ferguson and Wright, 1984; Inoue et al., 1985; Wright, 1986; and Yuill, 1987). The first airflow window patent was filed in Sweden in 1956 (Brandle and Boehm, 1982). White (1975) filed a patent for a "Heat Exchanger Window" in the United States in 1975. More recent studies have been conducted by Haddad and Elmahdy (1998 and 1999), Southall and McEvoy (2000), McEvoy and Southall (2000), McEvoy et al. (2003) and Baker et al. (2003). Table 1 summarizes the studies for each mode of operation.

Table 1. Summary of airflow window publications.

Mode of Operation	**Publication**
Supply	Brandle and Boehm (1982) Barakat (1987) Southall and McEvoy (2000) McEvoy and Southall (2000) McEvoy et al. (2003)
Exhaust	Müller (1983) Tomory (1983) Inoue et al. (1985) Haddad and Elmahdy (1998, 1999)
Indoor Air Curtain	Sodergren and Bostrom (1971) Tomory (1983) Brandle and Boehm (1987) Onur et al. (1996)
Indoor / Outdoor Air Curtain	Etzion and Erell (2003) Leal et al. (2003) Leal et al. (2004) Erell et al. (2004)

The researchers conducted simulations and/or experimental tests for the windows with simulations being used more frequently. For instance, Wright (1986) and Haddad and Elmahdy (1998, 1999) used the VISION computer program to study the windows. A detailed overview of the VISION program development is provided by Haddad and Elmahdy (1998). McEvoy and Southall (2000) and McEvoy et al. (2003) used both a nodal network analysis and computational fluid dynamics (CFD) in their studies. Safer et al. (2004, 2005) used two-dimensional CFD simulations to study a double façade that operates in a way similar to the supply air window.

Previous research efforts have focused on the potential energy savings that can be achieved when an airflow window is used during the heating and cooling seasons. Emphasis was also placed on improving or maintaining the thermal comfort of the building occupants. However, with modern construction practices focusing on improving IAQ, airflow windows that involve the transfer of air between the inside and outside of a building can improve IAQ and reduce heating/cooling loads. The added benefit of satisfying ventilation requirements for an indoor space with the supply air window has been studied by Haddad and Elmahdy (1999), McEvoy and Southall (2000), and Southall and McEvoy (2000).

Current airflow window designs have several limitations. For instance, only the supply air mode offers the potential for improving IAQ because outdoor air can be transferred to the indoor space. Several limitations to the implementation of the airflow window also arise from the airflow cavity design in terms of cleaning outdoor air. Since airflow through the cavity is driven by buoyancy generated from the solar heat, the use of filters can hinder the effectiveness of natural ventilation. Without filtering, however, it may be difficult to keep the window clean. This research work will attempt to address the limitations of airflow windows with respect to the fresh outdoor air and overcome the flow resistance due to filtering.

PROPOSED NOVEL AIRFLOW WINDOW DESIGN

This investigation proposed an airflow window system that consists of a triple glazed unit with forced airflow between each glass layer and two modes of operation, supply and exhaust, as shown in Figure 2. Glazing surfaces are uncoated and the glass is of clear construction. The airflow schematic shows that the outlet and inlet of the airflow are positioned at the same location. Since the exhaust and intake are located at the same height, the width of the window was equally split between inlet and outlet at the top and bottom of the window to avoid short-circuiting tempered fresh air into the indoor air stream. Due to this positioning of the inlets/outlets, the window system works like a crossflow heat exchanger with solar energy recovery. Exhausted indoor air is used to temper outdoor air, thus reducing heating/cooling demands. Indoor air is exhausted through the inner airflow cavity of the window system. In this way, the temperature of the interior window surface is close to the room air temperature and thermal comfort can be improved. Additionally, this window introduces conditioned outdoor air to the interior space through the outer cavity for the improvement of IAQ.

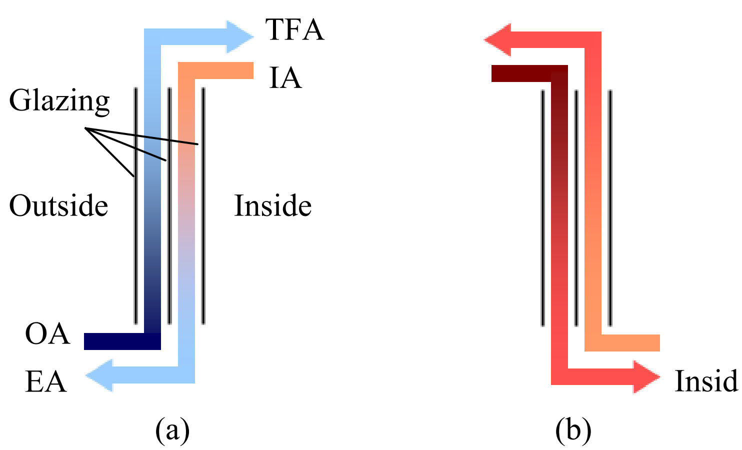


Figure 2. Two operating modes: (a) supply and (b) exhaust; note that TFA = tempered fresh air, IA = indoor air, OA = outdoor air and EA = exhaust air.

This design uses two small fans to drive air through the cavities. By using the fans, filters can be placed at the inlets to clean the air that flows through the cavities. Additionally, while airflow in windows with a single air stream and can be promoted by positively or negatively pressurizing the indoor space, a window with a dual air stream cannot use this method. Thus, the use of fans can make the window maintenance much easier and the flow rate very stable.

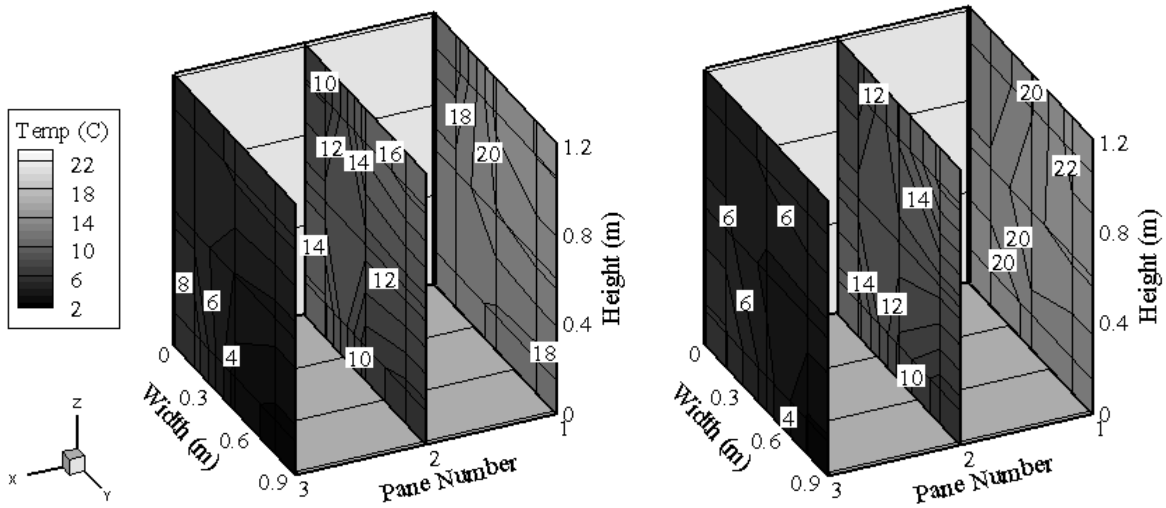
The overall motivations for using an airflow window are the potential benefits that result from reducing energy consumption for heating/cooling, improving the thermal comfort, and/or improving IAQ. The goal of this research is to develop a novel airflow window for use in residential buildings. By utilizing solar energy and heat recovery between the indoor air and exhaust air streams, the airflow window can help reduce added energy costs associated with providing adequate IAQ.

RESEARCH METHOD

The objective of this research is to optimize the proposed dual airflow window design. Should this be carried out experimentally, tens of experimental tests must be conducted. The experimental approach would be very expensive and time consuming. Computational tools offer an alternative to an experimental parametric study. Among the computational tools, the two-dimensional simulation tools such as VISION are insufficient for study the dual airflow window design. Due to the crossflow heat exchange present in the proposed window system, there exists no plane of symmetry about which the problem could be reduced to two dimensions. According to our literature review, CFD is the most promising three-dimensional modeling tool. Safer et al. (2004, 2005) successfully utilized a commercial CFD software Fluent to study a ventilated cavity with incident solar radiation. Thus, Fluent was selected as the computational tool for optimizing the proposed dual airflow window design.

However, it was challenging to calculate radiation through semi-transparent media, such as glazing, by Fluent or other CFD software. This investigation had to account for the heat sources and sinks in the glass due to surface-to-surface radiation and absorbed solar radiation. Fluent was only used to calculate conduction and convection within the window system and radiation from the inner and outer surfaces of the window system. The CFD model uses the Re-Normalization Group (RNG) k-ε turbulence model and a second order numerical scheme. In order to accurately model convective heat transfer across the window surface, the mesh must be fine enough to capture boundary layer effects. Additionally, the aspect ratio of each cell in the grid must be small enough to reduce numerical diffusion. With a cell aspect ratio less than 7, this study used 464,158 cells for the 15 mm cavity width.

As compared with experimental data, the simulated results obtained by using the combined CFD and hand calculation method are rather accurate. Figure 3 compares the results for the case under winter conditions with a flow rate of 10 L/s and an interior temperature of 22°C. The flow rate is needed for one person in order to meet the ASHRAE IAQ standard (ASHRAE, 2003a). Our experiment measured mainly air and surface temperature and airflow rates through the panels. Although there was no solar radiation present in the experiment, radiation effects from surface-to-surface radiation proved to be important. If the radiation model is added, it is unlikely the accuracy will be worse. Thus, the CFD model is regarded as validated and can be used for the study presented in the next section.



(a) (b)

Figure 3. Comparison of (a) simulated results with (b) experimental data under winter conditions with a 10 L/s airflow rate and 12 mm cavity width; pane 1 is the inner pane.

PARAMETRIC STUDY

The validated research method was then used to conduct a parametric analysis to optimize such a dual airflow window system for various climate conditions and design parameters. The parameters studied include mode of operation (supply/exhaust), weather conditions (winter/summer, sunny/cloudy, and windy/calm), airflow rate (10, 15 and 20 L/s), and airflow cavity thickness (9, 12 and 15 mm). Table 2 presents details for each of the parameters studied. Performance was measured using heat recovery efficiency. A comparison was then made between the final dual airflow supply window configuration and a similar single airflow supply window. Note that all analyses were conducted for a triple pane construction with clear, clear, clear glazing with no coatings. The spectral properties used for the radiation calculations were from ASHRAE Handbook (ASHRAE 2005). Our design did not include the impact of the window frame because the study did not deal with cross-window heat transfer.

The overall performance of the window system can be quantified by evaluating the efficiency of the heat exchange (ε):

$$\varepsilon = \left| \frac{T_{out} - T_{o,i}}{T_{out} - T_{in}} \right| \qquad (1)$$

where T_{out} is the outside room temperature, $T_{o,i}$ is the inside outlet temperature (TFA in Figure 2), and T_{in} is the inside room temperature.

Table 2. Overview of the parameters studied.

Parameter		Variation	Details
Mode of Operation		Supply	See Figure 2 for detailed schematic
		Exhaust	
Weather Conditions	*Season*	Winter	2°C outdoor and 22°C indoor temperatures
		Summer	37°C outdoor and 24°C indoor temperatures
	Solar	No Solar	0 W/m^2 direct / 0 W/m^2 diffuse
		Sunny	800 W/m^2 direct / 200 W/m^2 diffuse
		Cloudy	0 W/m^2 direct / 200 W/m^2 diffuse
	Wind	Windy	6.7 m/s outdoor wind speed
		Calm	0.2 m/s outdoor wind speed
Airflow Rate		Varied	10, 15 and 20 L/s
Airflow Cavity Thickness		Varied	9, 12 and 15 mm

Effect of Mode of Operation

The optimal airflow window configuration ought to depend on the mode of operation and the weather conditions. For example, the supply mode may be most effective during winter months, while the exhaust mode may be the most effective during summer months. Such operating modes could make use of buoyancy effects to drive airflow in the window cavity so that fan energy consumption could be reduced.

Figure 4 shows the exit temperature for the supply and exhaust modes. Results are presented for summer and winter conditions with a sunny or cloudy sky. The most desirable mode of operation would provide the highest exit temperature to the indoors during the winter and the lowest exit temperature to the indoors during the summer. For a flow rate of 10 L/s, the supply mode was slightly better during the winter and the exhaust mode slightly better during the summer. Since this difference is a mere 1°C or less, mode of operation is not important when fans were used to drive the flow. For the range of flow rates studied, the ratio of the largest Grashof number to the square of the smallest Reynolds number was 3.8×10^{-3}. Since this value is much less than one, forced convection effects are dominant in the fan driven airflow setup. As a result the following analysis will be limited to a study of the supply air window configuration.

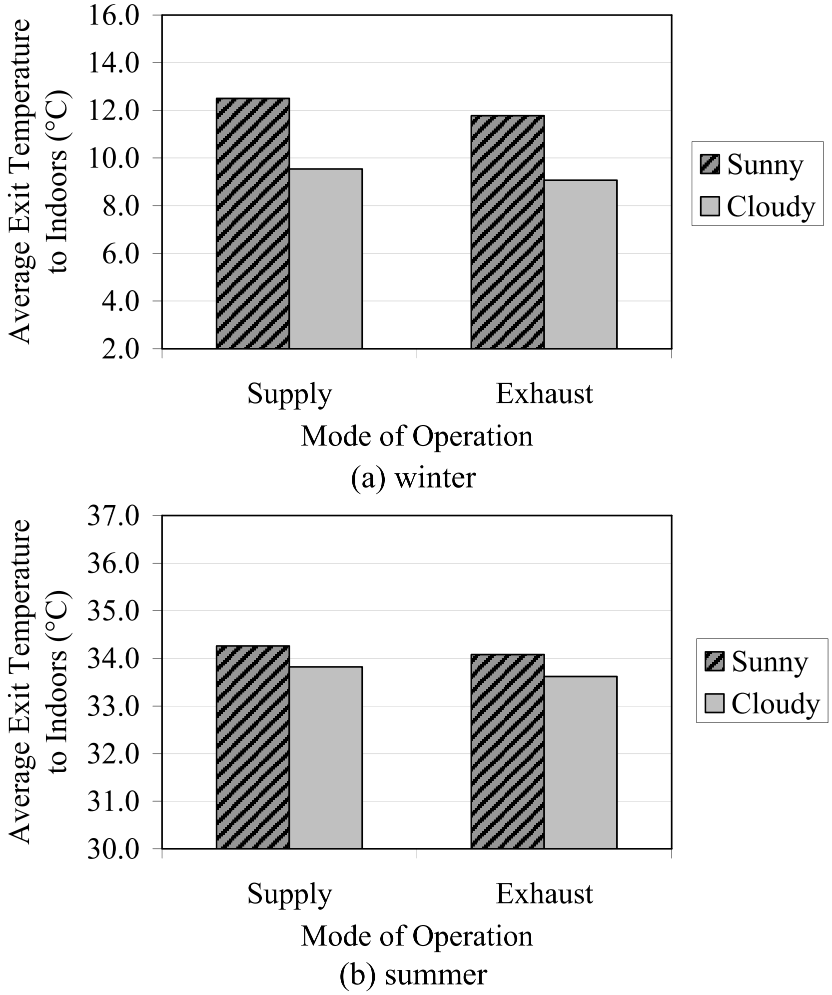
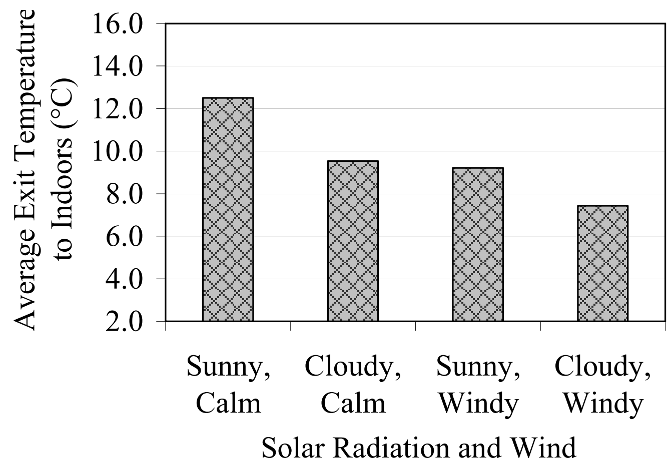


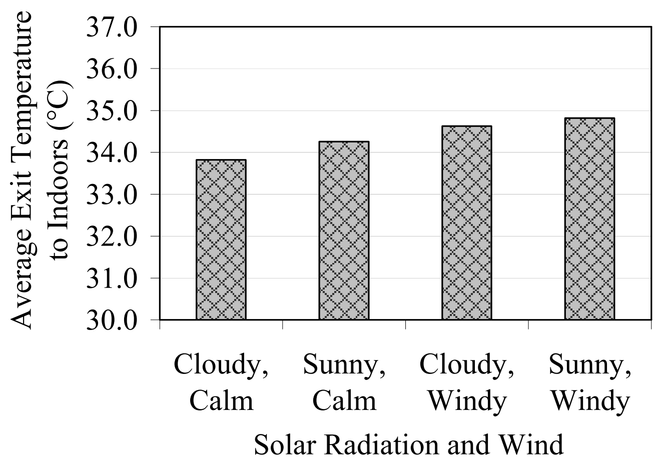
Figure 4. Impact of supply and exhaust modes on exit air temperature to indoors with 10 L/s airflow rate and 12 mm cavity width.

Effect of Solar Radiation and Wind

Figure 5 shows the exit temperature to the indoors for four combinations of weather conditions. The results are presented in descending order from best to worst performance. During winter conditions, the exit temperature to the indoors was the highest under sunny and calm conditions. On the other hand, during summer conditions, the exit temperature to the indoors was the lowest under cloudy and calm conditions. Solar radiation added heat to cavity air so it is desirable in the winter but not in the summer. Calm wind conditions are favorable for less convective heat losses during the winter and less convective heat gains during the summer.



(a) winter



(b) summer

Figure 5. Effect of weather conditions on exit air temperature to indoors with 10 L/s airflow rate and 12 mm cavity width.

A further analysis of the effect of solar radiation on the average exit air temperature to the indoors was also conducted with no solar radiation, cloudy conditions and sunny conditions. As anticipated, it was found that solar radiation resulted in an increase in the average exit temperature to the indoors. During the winter, sunny versus no solar radiation conditions result in a 20% increase in heat transfer efficiency as shown in Table 3. Conversely, during summer months, sunny versus no solar radiation conditions result in about a 7% decrease in window performance. Note that there was uncertainty inherent in the experimentally measured glass temperatures that were used as input values in the CFD model. These values were used to calculate radiation exchange between the panes of glass and the window with its surroundings. The T-type thermocouples were used to make the measurements and were accurate to the nearest 0.01°C.

Table 3. Summary of efficiencies for various solar radiation conditions.

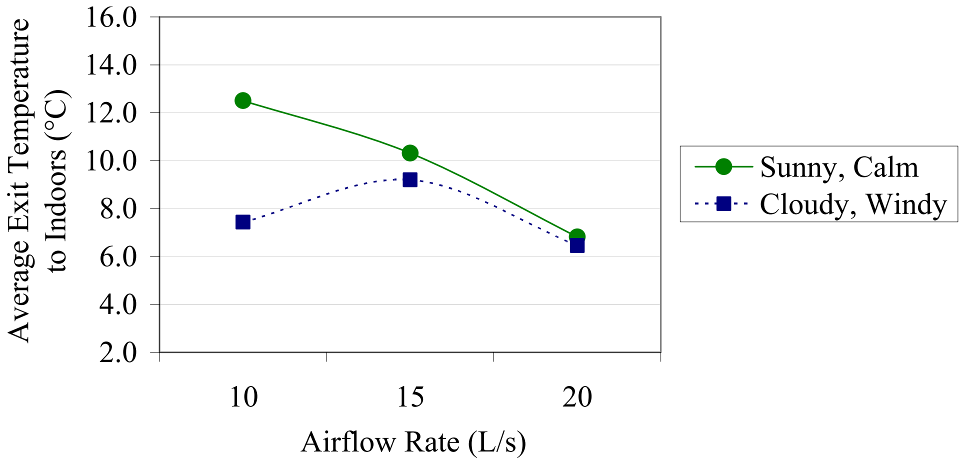
	Winter		Summer	
	Temperature (°C)	**Efficiency (-)**	**Temperature (°C)**	**Efficiency (-)**
No Solar	8.5	32.5	32.7	19.4
Cloudy	9.5	37.7	33.8	14.5
Sunny	12.5	52.5	34.3	12.5

Effect of Airflow Rate

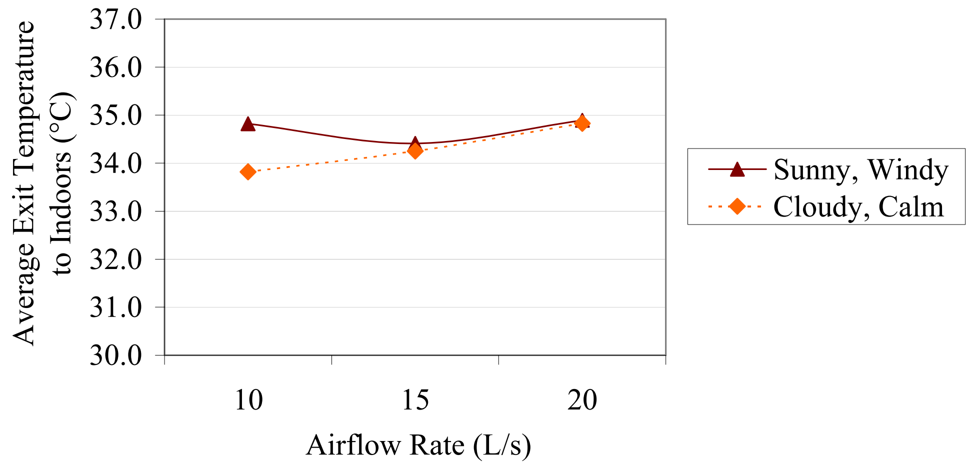
The effect of airflow rate on the exit temperature to the indoors during winter and summer conditions is shown in Figure 6. Results are shown for the best and worst solar/wind combinations. The effect of airflow rate varies significantly depending on the weather conditions.

During sunny, winter conditions, the largest increase in exit temperature to the indoors was achieved with the smallest flow rate of 10 L/s. However, during cloudy, winter conditions, the greatest exit temperature was achieved with a flow rate of 15 L/s. Opposite performance trends were found for the cloudy and sunny summer conditions. Clearly, the effect of flow rate on window performance is not linear, although a smaller flow rate seems desirable. At a flow rate of 20 L/s, the heat transfer is dominated by convection effects. However, the airflow rate is too large for the maximum amount of heat to be transferred between the glass surfaces and the air. A flow rate between 10 and 15 L/s is thus recommended.

For the lowest flow rate studied, the following trends can be observed. Under sunny conditions, the heat absorbed by the window panes results in an increase in the temperature of the air delivered to the indoor space. Under cloudy conditions, the exit temperature is closer to the outermost pane temperatures and therefore closer to the outdoor air temperature.



(a) winter



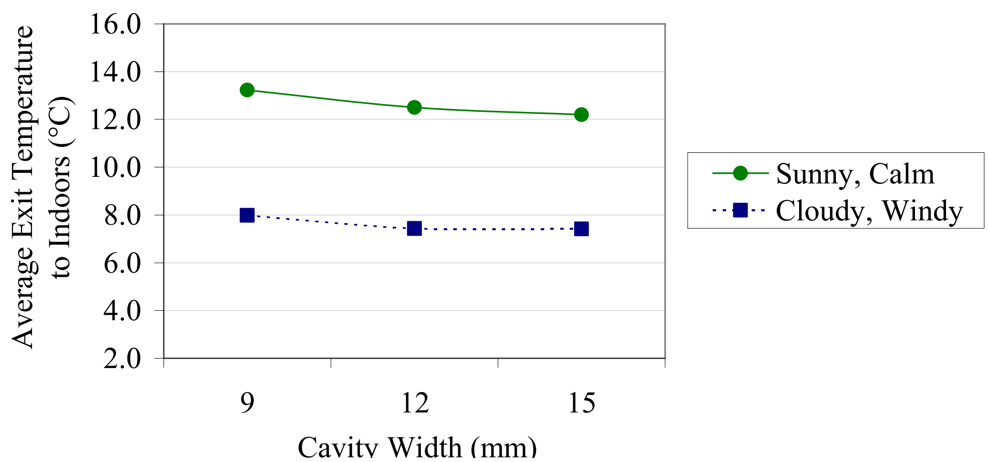
(b) summer

Figure 6. Effect of airflow rate on exit temperature to indoors with a 12 mm cavity width.

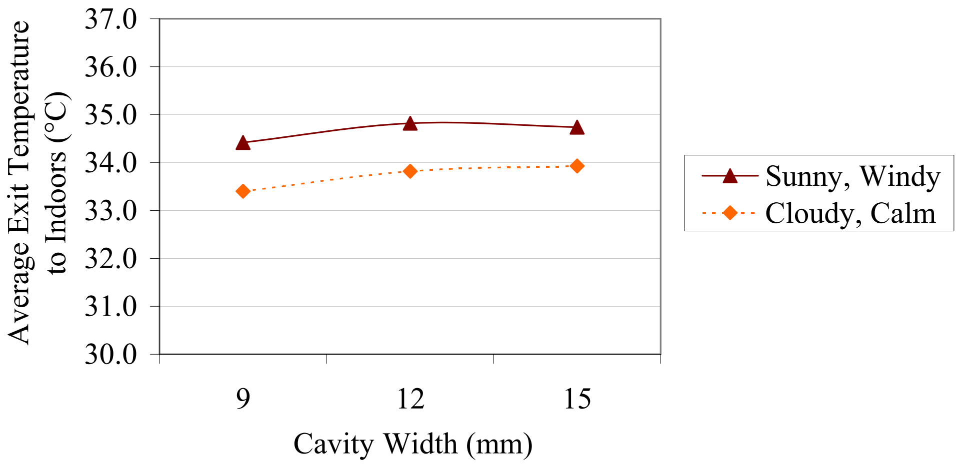
Effect of Cavity Width

The final parameter studied in this investigation was cavity width. Figure 7 shows its effect on exit temperature to the indoors. In general, smaller cavity widths showed better window performance. Unlike airflow rate, cavity width has a small impact on exit temperature during the winter. The impact of cavity width on exit temperature for both winter and summer conditions is about 1 K over the range of 9 to 15 mm.

Results suggest that the smaller the cavity width, the greater the heat transfer. However, small cavity widths may cause maintenance problems. Small cavity widths may prevent the inner glass surfaces from being accessible if the window construction does not allow for the window to be opened for cleaning. In the case that the inner window surfaces are accessible, small cavity widths may lead to the need for more frequent cleaning of the window surface. Also, as the cavity width decreases, the air velocity and flow resistance increase. This may lead to the potential for acoustic problems and an increase in fan energy. Therefore, cavity widths smaller than 9 mm were not considered for use in this airflow window.



(a) winter



(b) summer

Figure 7. Effect of cavity width on exit temperature to indoors with a 10 L/s airflow rate.

Optimal Design and Comparison with a Single Airflow Window

The above analysis suggests that the optimal dual airflow window should have an airflow rate of 10 L/s and a cavity width of 9 mm, based on the window material properties used in this investigation. With such a design, the maximum heat exchange efficiency is 56.2% for a sunny and calm winter day and 27.7% for a cloudy and calm summer day. The minimum heat exchange efficiency is 29.9% for a cloudy and windy winter day and 19.8% for a sunny and windy summer day.

This study has further compared the optimal dual airflow window design to the supply air window with a single airflow path as shown in Figure 1a. Sunny and calm conditions were used for a winter day, while cloudy and calm conditions for a summer day. The single airflow window has Argon as the gas fill in the cavity of the insulated unit. Although the single airflow configuration results in a more uniform temperature distribution across the inner pane, the average pane temperature is about 1.5°C lower than that in the dual airflow configuration during winter conditions. Additionally, the average exit temperature to the indoors is 1.5 to 1.0°C warmer for the dual airflow configuration over the range of 10 to 20 L/s, respectively. On the other hand, the average pane temperature is about 2°C greater for the single airflow configuration when compared to the dual airflow configuration during the summer conditions. The average exit temperature to the indoors is also 2.1°C cooler for the dual airflow configuration over the range of 10 to 20 L/s, respectively.

DISCUSSION

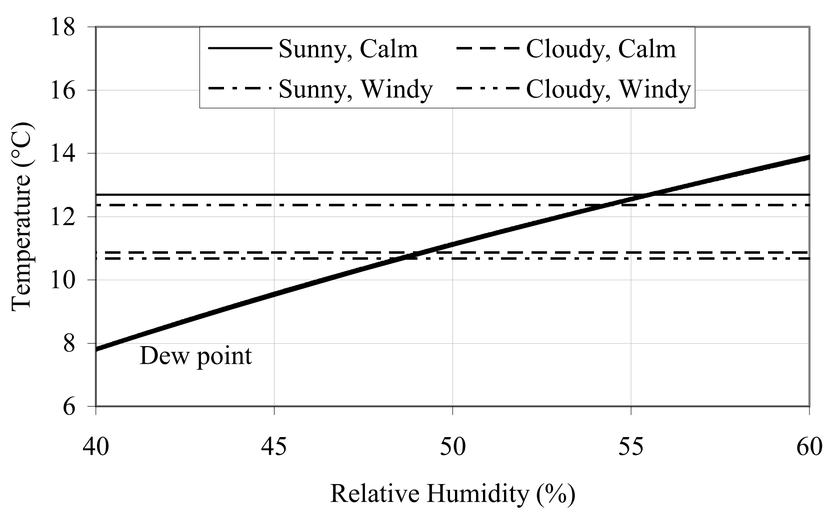
The low pane temperature for the dual airflow window may indicate the risk for condensation, which occurs when the glass temperature falls below the dew point of the surrounding air. Depending on the season, condensation may occur at different locations in the window system. Under winter conditions, the greatest risk occurs when the warm indoor air flows past the colder middle glass pane; under summer conditions, the greatest risk occurs when the hot, humid outdoor air flows past the colder middle glass pane. Therefore, to study the condensation resistance of the window system, the lowest temperature of the middle glass pane and the dew point temperature of the indoor air during winter conditions and outdoor air during summer conditions were tracked.

Figure 8a presents results from the condensation analysis during winter conditions. The bold, solid line indicates the dew point temperature of indoor air at 22°C over a range of relative humidity values. The four horizontal lines track the lowest temperature of the middle glass pane under various solar and wind conditions. The intersection of the dew point line and the pane temperatures indicates the minimum temperature before which condensation begins to occur in the window system. The results show that under winter conditions with an outdoor temperature of 2°C, the indoor humidity must not exceed 48.5% if condensation is to be avoided. If the indoor humidity is low as found in most winter cases, the condensation problem may not occur even at below freezing temperature. We have tested the window with a relative humidity of 30% at 22^{o}C, no condensation appears when the temperature drops to -15^{o}C

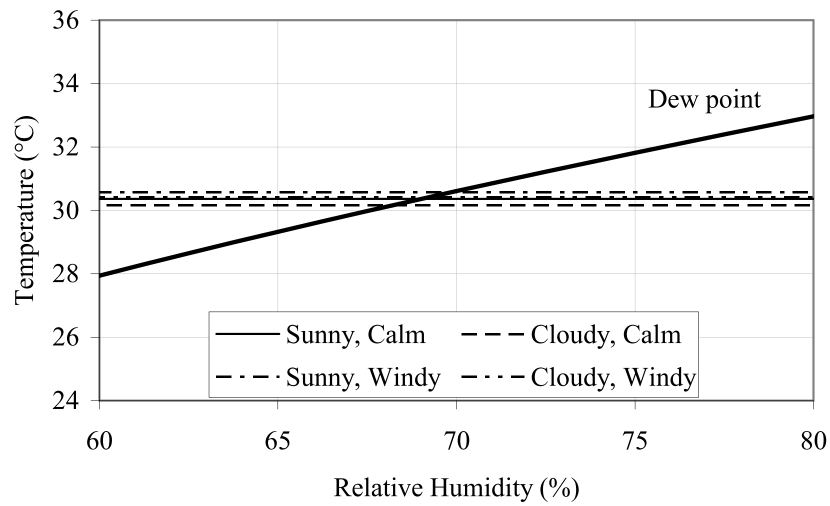
Similarly, Figure 8b presents results from the condensation analysis during summer conditions. The dew point temperature line is plotted for outdoor air at 37°C over a range of relative humidity values. With an indoor temperature of 24°C, condensation may occur when outdoor humidity levels exceed 68.1%.

The energy use by the fans at 20 L/s is around 10 W/fan. If the supply air temperature is tempered by 1 K, the energy conserved is 20 W. Thus, the energy used by the fans is minimal, compared with the energy conserved.

Note that one of the key points of the conventional airflow window designs (supply and exhaust windows, etc.) uses a ventilated air cavity with movable solar absorption layer (blinds). In some airflow window designs it is possible to choose to use or expel the heated air of the cavity depending on heating or cooling requirements of the house. This paper presents a 'window heat exchanger' concentrating on the heat transfer between inside air and outside air. It also deals with solar radiation but only the absorbed energy of the glass layers. No blinds or curtains were considered at present which key elements are in the conventional systems. This will be a subject of further study.



(a) winter



(b) summer

Figure 8. Condensation analysis on the dual airflow window system with 10 L/s flow rate and 9 mm cavity width.

CONCLUSIONS

This paper proposed a novel dual airflow window for the improvement of indoor air quality (IAQ) and conservation of energy for heating and cooling in residential buildings. A research method that used both computational fluid dynamics (CFD) for heat conduction and convection and hand calculations for heat radiation was developed and validated against experimental data. The validated research method was then used to conduct a parametric study of the proposed window system. Airflow rate, cavity width, solar radiation, wind, outdoor temperature and humidity were considered. The following conclusions were obtained.

1. The dual airflow window can conserve energy by using the window panes as a heat exchanger. The window can also improve IAQ by supplying fresh outdoor air to the indoors. The window can also improve thermal comfort because the interior surface temperature is closer to the room air temperature, when compared to a single airflow window.
2. By using fans to supply and extract air through the window cavity, forced convection effects dominate. This leads to a nearly identical thermal performance for the supply and exhaust air windows. The window performed better for sunny and calm conditions in the winter and cloudy and calm conditions in the summer. The airflow rate should be low and the cavity width should be small to improve performance.
3. With the optimal design of 10 L/s flow rate and 9 mm cavity width, the heat exchange efficiency of the dual airflow window varies from 29.9% for a cloudy and windy winter day to 56.2% for a sunny and calm winter day, and from 19.8% for a sunny and windy summer day to 27.7% for a cloudy and calm summer day. Solar radiation increases efficiency by up to 20% under winter conditions.
4. Condensation risk exists on the middle glass pane. During winter conditions, exhausted indoor air may condense if the indoor air humidity exceeds 48.5% at 22°C; during summer conditions, the outdoor air may condense if the humidity exceeds 68.1% at 37°C.

ACKNOWLEDGMENTS

The work presented in this paper was partially supported by a Graduate Fellowship from the National Science Foundation (NSF) and a Grant-in-Aid from the American Society of Heating, Ventilating and Air Conditioning Engineers (ASHRAE).

REFERENCES

ASHRAE. 2005. *ASHRAE Handbook - Fundamentals*. Chapter 30, Atlanta: American Society of Heating, Ventilating and Air Conditioning Engineers, Inc.

ASHRAE. 2003. *ASHRAE Handbook - Applications*. Chapter 33, Atlanta: American Society of Heating, Ventilating and Air Conditioning Engineers, Inc.

ASHRAE. 2003a. *ASHRAE Standard 62.2-2003 Ventilation for Acceptable Indoor Air Quality*, Atlanta: American Society of Heating, Ventilating and Air Conditioning Engineers, Inc.

Baker, P.H., M.E. McEvoy and R. Southall. 2003. Improving air quality in homes with supply air windows. BRE Information Paper, BRE Bookshop.

Barakat, S.A. 1987. Thermal performance of a supply-air window. *Proceedings of the 12th Annual Passive Solar Conference* 12: 152-158, Portland, OR.

Brandle, K. and R.F. Boehm. 1982. Airflow windows: performance and applications. ASHRAE/DOE Conference, *Proceedings of Thermal Performance of the Exterior Envelopes of Buildings II.* Las Vegas, NV.

EPA, 2001. Healthy Buildings, Healthy People: A Vision for the 21st Century, EPA report #402-K-01-003. Washington: Environmental Protection Agency.

EPA, 2006. An introduction to indoor air quality. http://www.epa.gov/iaq/ia-intro.html, Environmental Protection Agency.

Etzion, Y. and E. Erell. 2003. Controlling the transmission of radiant energy through windows: a novel ventilated reversible glazing system. *Building and Environment*. 35(5): 433-444.

Erell E., Y. Etzion, N. Carlstrom, M. Sandberg, J. Molina, I. Maestre, E. Maldonado, V. Leal and O. Gutschker. 2004. 'SOLVENT': Development of a reversible solar-screen glazing system. *Energy and Buildings*. 36(5): 467-480.

Ferguson, J.E. and J.L. Wright. 1984. VISION: A computer program to evaluate the thermal performance of super windows. Report No. Passive-10, Ottawa: National Research Council Canada.

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(1B):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):918-926.

Hawken, P., A. Lovins, and L.H. Lovins. 2000. *Natural Capitalism*. Boston: Little, Brown and Co.

Inoue, T., Y. Matsuo, and T. Ibamoto. 1985. Study on the thermal performance of ventilation window. *Proceedings of International Symposium on Thermal Application of Solar Energy*. pp. 221-226.

Leal, V., E. Maldonado, E. Erell, and Y. Etzion. 2003. Modeling a reversible ventilated window for simulation within ESP-R – the SOLVENT case. *Proceedings of Building Simulation 2003*, Eindhoven, The Netherlands.

Leal, V., M. Sandberg, E. Maldonado, and E. Erell. 2004. An analytical model for the airflow in a ventilated window with known surface temperatures. *Proceedings of Roomvent 2004*, Coimbra, Portugal.

McEvoy, M. and R.G. Southall. 2000. Validation of a computational fluid dynamics simulation of a supply air 'ventilated' window. *CISBE Conference*. Dublin, Ireland.

McEvoy, M.E., R.G. Southall, and P.H. Baker. 2003. Test cell evaluation of supply air windows to characterize their optimum performance and its verification by the se of modeling techniques. *Energy and Buildings*. 35: 1009-1020.

Müller, H. 1983. Exhaust-air ventilated windows in office buildings. *Proceedings of the 18th Intersociety Energy Conversion Conference* Vol. 5, pp. 2015-2018.

NREL. 1995. Typical meteorological year data (TMY2). http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2, National Renewable Energy Laboratory.

Onur, N., M. Sivrioglu, and O. Turgut. 1996. An experimental study on air window collector having a vertical blind for active solar heating. *Solar Energy*. 57(5): 375-380.

Safer, N., M. Woloszyn, G. Rusaouen and J.J. Roux. 2004. Influence of solar radiation on heat and air flow transfers in double skin façades with Venetian blinds. *Proceedings of Roomvent 2004*, Coimbra, Portugal.

Safer, N., M. Woloszyn, J.J. Roux, G. Rusaouen, and F. Kuznik. 2005. Modeling of the double-skin facades for building energy simulations: radiative and convective heat transfer. *Proceedings of Building Simulation 2005*, pp. 1067-1074, Montreal, Canada.

Sherman, M.H. and N. Matson. 1997. Residential ventilation and energy characteristics. LBNL 39036. http://epb.lbl.gov/ventilation/resventw.fm5.pdf, Berkeley: Lawrence Berkeley National Laboratory.

Sodergren, D. and T. Bostrom. 1971. Ventilating with the exhaust-air window. *ASHRAE Journal*. 13(4):51-57.

Southall, R.G. and M. McEvoy. 2000. Results from a validated CFD simulation of a supply air 'ventilated' window. *Proceedings of Roomvent 2000*, Stockholm, Sweden.

Tomory, T. 1983. Extract-air window. *Proceedings of 9th CIB Congress*. Stockholm, Sweden.

White, W.S. 1975. United States Patent for a Heat Exchanger Window. Patent Number: 3,925,945.

Wright, J.L. 1986. Effective U-values and shading coefficients of preheat/supply air glazing systems. *Proceedings of Renewable Energy Conference '86*. Ottawa, Canada.

Yuill, G.K. 1987. Laminar air flow super window. Prepared for Renewable Energy Branch, Energy Mines and Resources, Ottawa, Canada, File Number 6179, DD#71.