THE SOLAR DYNAMIC BUFFER ZONE (SDBZ) CURTAIN WALL: THEORY AND SIMULATION

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Given the increases in both the environmental and economic costs of energy, there is a need to design and build more sustainable and low-energy building systems now. Curtain wall assemblies are engineered wall assemblies that are used widely in both high-rise as well as low-rise construction. These assemblies show great promise – they can be built better now. Often ignored, spandrel panels that comprise a part of curtain wall assemblies can be natural solar collectors. By using a simple, low cost method such as a Solar Dynamic Buffer Zone (SDBZ), solar energy can be efficiently gathered using the movement of air. This paper will discuss the theory behind an innovative, energy efficient new curtain wall system. Using an experimentally validated numerical model, a SDBZ curtain wall system will be shown to be a more sustainable option in terms of energy performance for traditional curtain wall assemblies in Toronto, ON.

1. INTRODUCTION

In 2003, building energy use accounted for approximately 19% of all energy use in Canada (Cuddihy *et al* 2005). Since 2003, this number continues to increase. Given these percentages and the increasing trend, it seems logical to focus on reducing this consumption.

There are many reasons to reduce energy use – all equally valid. Environmentalists believe it is important to reduce the impact of humans on the environment. In contrast, many building owners adopt a purely economic point of view: reduce energy use to save money. As the cost of heating and cooling continues to dramatically increase, energy costs may soon become increasingly more important to homeowners. Given the world growth in the demand for energy relative to the supply of energy, such price increases are expected to continue long into the future. Building owners may soon realize that, in addition to the initial capital cost of a home, operational costs are important. The opportunity to collect solar energy that would otherwise be lost to the exterior presents itself on most buildings. The Solar Dynamic Buffer Zone (SDBZ) curtain wall is but one simple approach to harness this energy and reduce energy consumption for buildings.

This paper reviews the conceptual layout of an SDBZ curtain wall system designed, developed and tested at the Building Science Laboratory (Department of Civil Engineering) at the University of Toronto, Toronto, Canada. An experimentally

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validated numerical model is then used to simulate design day, seasonal and building case study performance.

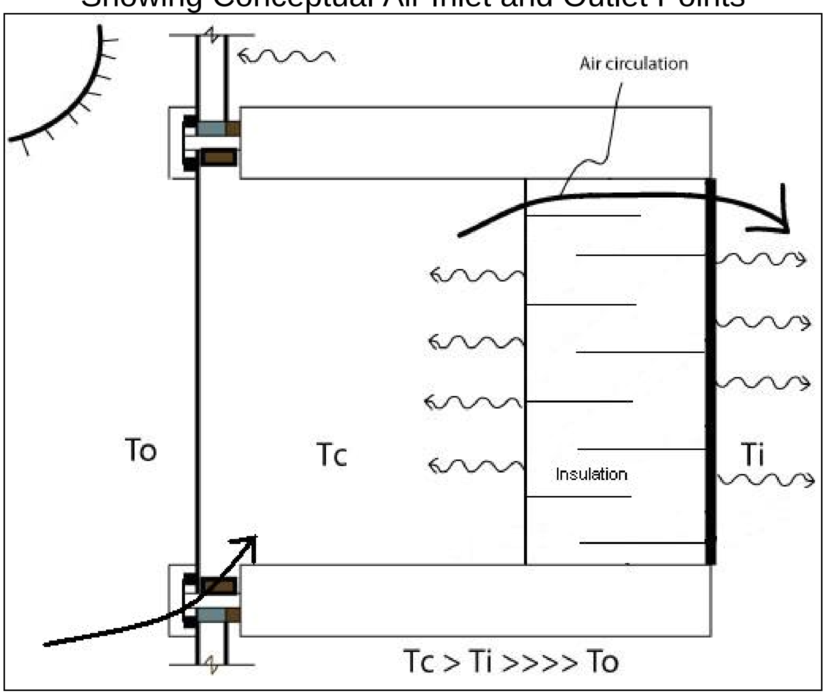
2. THE SDBZ PROTOTYPE

2.1. Conceptual Design

A preliminary investigation (Richman 2008) suggested that the solar gain within a curtain wall spandrel panel may be large enough to significantly contribute to reducing a building's energy requirements. The next step was to take the theoretical concept of the SDBZ and meld it into a workable, constructible system.

Once captured, the solar heat must be brought into the building. Ordinarily the spandrel insulation greatly reduces this heat gain component. One simple way of bringing in this captured solar heat is by drawing air through the spandrel cavity components. Based on the preliminary results (Richman 2008), it was decided to further develop the SDBZ as a fresh air pre-heater of exterior air during the daytime. Figure 1 shows a schematic of the final conceptual SDBZ Curtain Wall design and how air can be used to transport the captured solar energy.

FIGURE 1: Final Conceptual SDBZ Curtain Wall Design
Showing Conceptual Air Inlet and Outlet Points



In a module-based SDBZ curtain wall system, the transfer of the preheated cavity air can be controlled by a system of small fans. As such, the SDBZ can be a module-based, nearly passive system, that can employ the use of relatively simple, low-cost fans or a larger district approach.

It may be more desirable to link the SDBZ to the building's air handling system as part of its fresh-air intake circulation loop. By doing this, it is expected that no additional energy is required to transport the SDBZ air. An efficient design has the potential to minimize the overall energy used for a building's fresh-air intake.

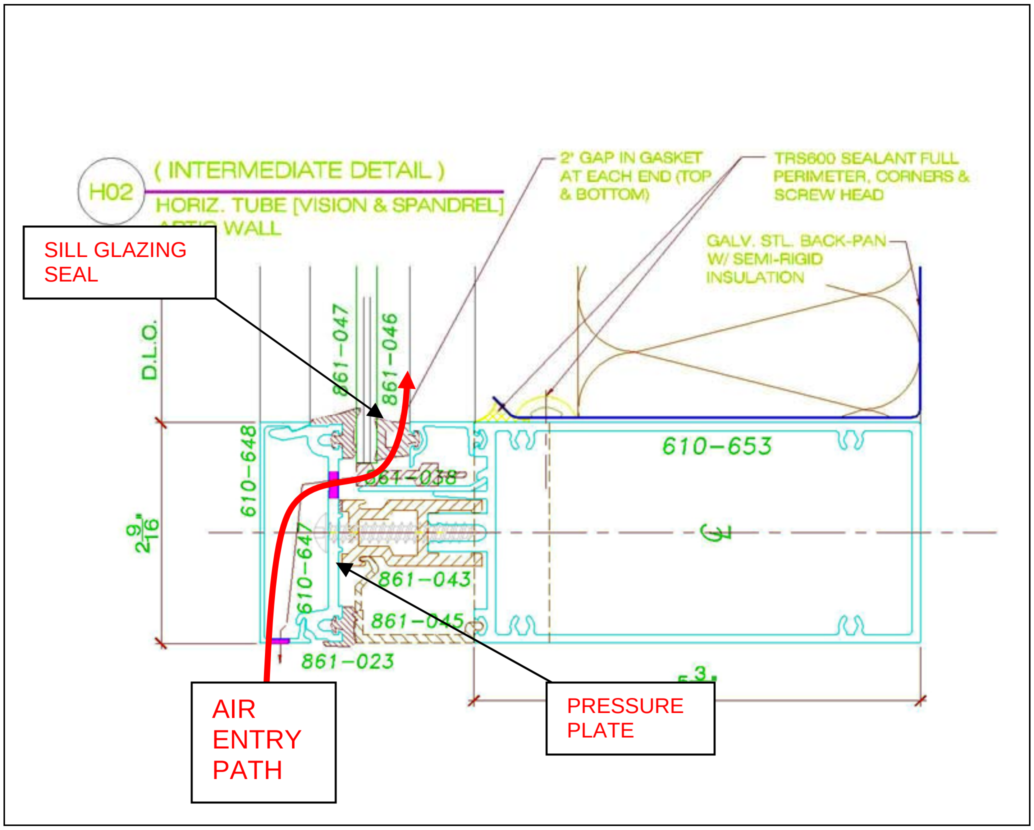
To maximize the performance as a solar absorber, the collecting surface (i.e. typically semi-rigid mineral wool insulation) can be painted or otherwise colored black. At this stage of the design, the SDBZ construction included standard 2" mineral wool batt insulation (U-value = 0.54 $W/m^2 \bullet K$) with a 6 mm clear spandrel glass light.

2.2. Inlet/Outlet Design

The first challenge during modification of an off-the-shelf curtain wall specimen as the SDBZ prototype was how exterior air could enter the cavity. Based on preliminary investigation (Richman 2008), it was concluded that exterior air should enter at the bottom of the cavity and exit at the top of the cavity. This design consideration was finalized in this manner so as to have flow in-line with buoyancy effects associated with natural convection. Since warm air rises, introducing a flow opposite to this would require additional fan energy, effectively reducing the overall efficiency of the SDBZ.

Following a detailed inspection of the lower spandrel transom of the original curtain wall sample, it was decided that the drainage ports in the pressure plates provided a natural entry path for exterior air into the cavity. Figure 2 shows how air enters the cavity through a flow path crossing the snap-on-caps, pressure plate and glazing cavity. To accommodate this flow path, openings were made in the snap-on-cap and pressure plate and the majority of the spandrel sill glazing seal was removed in order to provide a continuous path between the exterior and cavity interior.

FIGURE 2: Cross Sectional View of Air Entry Path

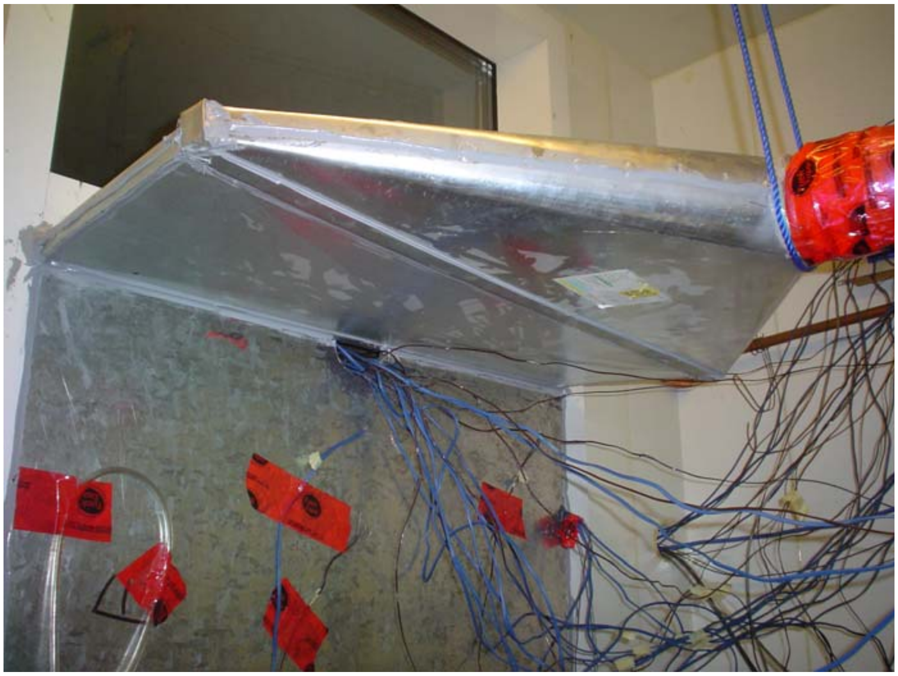


Following several experimental regimens investigating various outlet geometries such as circular and square (Richman 2008), the final SDBZ employs a continuous 25 mm manifold duct at the top of the spandrel cavity as shown in Figure 3 below. It was theorized that this type of outlet geometry would promote accurate analysis of the SDBZ by applying the numerical model presented in the next section.

To summarize, the final SDBZ prototype comprised the following:

- Inlet openings in the spandrel sill snap-on-cap (0.0123 m^2/m^2)
- Inlet openings in the pressure plate (0.0123 m^2/m^2)
- Areas of the glazing seal removed and an inlet opening between the spandrel glass and glazing neck (0.0123 m^2/m^2)
- Outlet opening 25mm manifold duct across the full cavity width (0.0421 m^2/m^2)

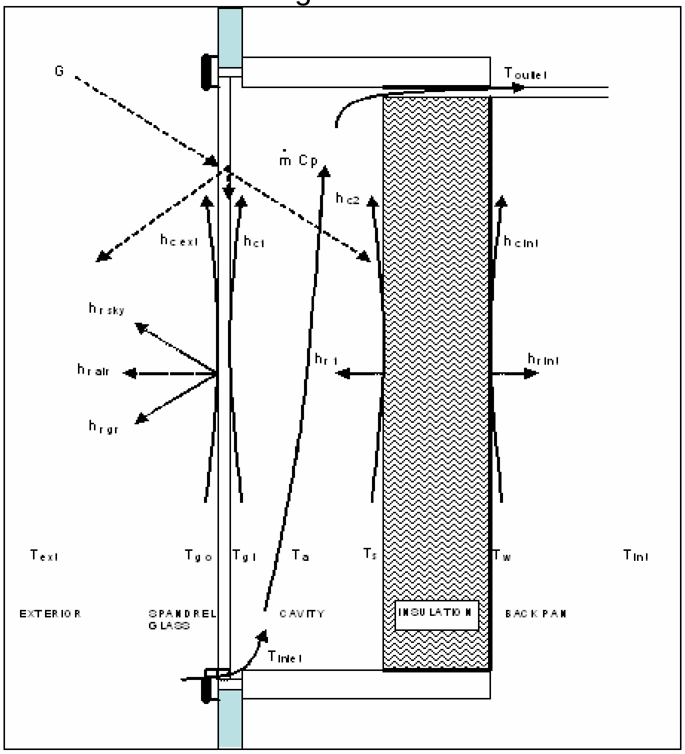
FIGURE 3: Bottom View of Manifold Duct Installation



3. NUMERICAL MODEL

Based on the finalized prototype model of the SDBZ curtain wall outlined in the previous section, Figure 4 presents the thermal characteristics of the model. Shown here is the radiative, convective and conductive heat transfer mechanisms involved in the near passive collection, via. the spandrel cavity air stream, of incoming solar energy.

FIGURE 4: Schematic of SDBZ Experimental
Model Showing Thermal Behaviour



Based on the thermal characteristics shown in Figure 4 and the design concepts discussed in Section 2, the governing heat balance equations were developed using the following assumptions:

i. Steady state conditions
ii. Thermal storage by the SDBZ components was negligible
iii. Minimal, non-linear, stratification of surface temperatures. As such, average surface temperatures were utilized
iv. The heat flow to the sides is negligible
v. The glass layer is opaque to infrared radiation
vi. The inlet temperature is equal to the ambient air temperature
vii. The short wave radiation absorbed in a glass layer can be apportioned equally to the two surfaces
viii. The heat flux is taken to be unidirectional in the system (i.e. perpendicular to the direction of air flow)
ix. The sky temperature is approximated by the Bliss correlation (Berger *et al*, 1984).
x. The ground temperature is equal to the ambient air temperature.

These assumptions are discussed and justified by the author elsewhere (Richman 2008, Richman and Pressnail 2008). A discussion of how the heat transfer coefficients are obtained and model validation is also presented by Richman (2008). Keeping the notation of heat in (left side of equation) and heat out (right side) for each element, the governing heat balance equations are then as follows:

<u>Glass Cover – Exterior</u>

$$\frac{GA_g\alpha_g}{2} + h_{k1}A_g(T_{g_i} - T_{g_o}) = h_{r,gr}A_g(T_{g_o} - T_{gr}) + h_{r,sky}A_g(T_{g_o} - T_{sky}) + \quad (1)$$

$$h_{r,air}A_g(T_{g_o} - T_{ext}) + h_{c,ext}A_g(T_{g_o} - T_{ext})$$

Glass Cover – Interior

$$\frac{GA_g\alpha_g}{2} + h_{r1}A_s(T_s - T_{g_i}) + h_{c1}A_g(T_a - T_{g_i}) = h_{k1}A_g(T_{g_i} - T_{g_o}) \quad (2)$$

Cavity Air

$$h_{c2}A_s(T_s - T_a) = \dot{m}C_p(T_{outlet} - T_{inlet}) + h_{c1}A_g(T_a - T_{g_i}) \quad (3)$$

Collector Surface

$$GA_s\tau_g\alpha_s = h_{c2}A_s(T_s - T_a) + h_{r1}A_s(T_s - T_{g_i}) + U_1A_w(T_s - T_w) \quad (4)$$

Metal Back Pan Surface – Interior

$$U_1A_w(T_s - T_w) = h_{r,\text{int}}A_w(T_w - T_{\text{int}}) + h_{c,\text{int}}A_w(T_w - T_{\text{int}}) \quad (5)$$

Knowing T_{ext} and T_{int} as boundary conditions for a simulation, the above equations can be reduced to a system of five equations with five unknowns which in conjunction with Equations 6 and 7 below and solved using a standard Newton-Rhapson method.

Relationship Between Inlet, Outlet and Cavity Air Temperatures

$$T_a = 0.75T_{outlet} + 0.25T_{inlet} \quad (6)$$

Equation for Sky Temperature (Bliss 1961)

$$T_{sky} = (T_{ext} - 273)\left[0.8004 + 0.00396(T_d - 273)\right]^{0.25} + 273 \quad (7)$$

4. SIMULATION RESULTS AND DISCUSSION

Using the numerical model described above, two separate simulations and a building case study were conducted to analyze the performance of the SDBZ curtain wall: (i) a January design day, (ii) a typical heating season, both for Toronto, ON, Canada and (iii) an institutional building in Toronto, ON. A brief description of boundary conditions and input sources follow.

Based on values from the literature (Eicker, 2003) for average flows in fresh-air preheating systems and the experimental results presented above, the design flow used during the simulations was 110 m^3/m^2•h. Results presented published by the author show the numerical model adequately predicts performance at this design flow (Richman 2008).

4.1. January Design Day

The boundary conditions for the Toronto January design day are outlined below. Figures 5 and 6present the performance of the system.

- Solar radiation values for January 21 (43° latitude) assuming bright, sunny conditions.
- Exterior ambient air temperature of -20°C.
- Exterior relative humidity of 80%.
- Interior ambient air temperature of 21°C.
- Interior relative humidity of 25%.

An overall efficiency of 21.9% is promising with an average collected energy of 200 W·h/m^2 of spandrel area throughout the day.

FIGURE 5: January Design Day Performance Predicted Using the Numerical Model

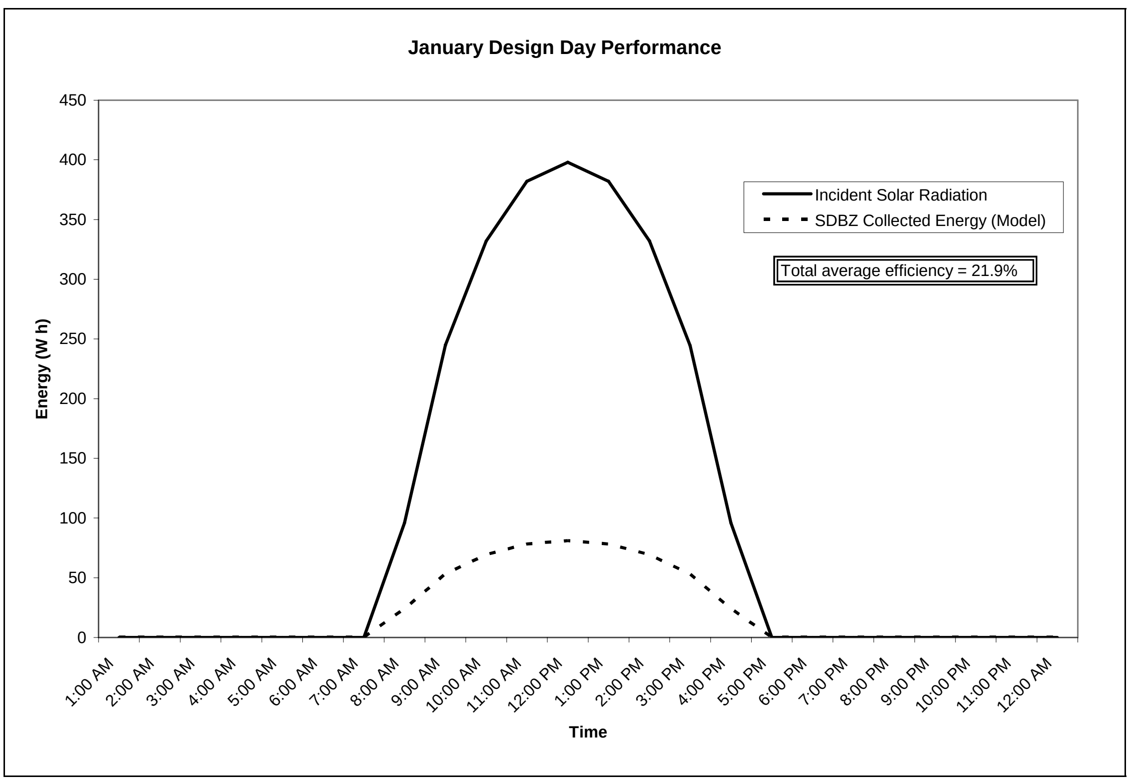
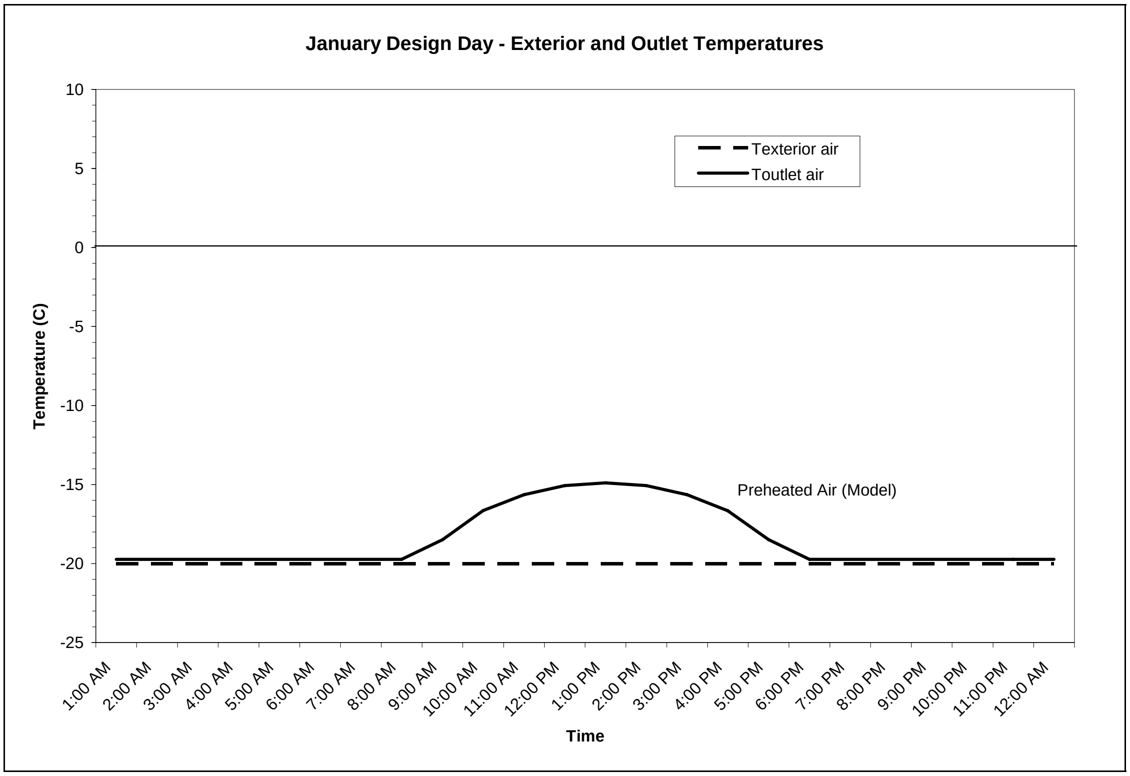


FIGURE 6: Simulated Outlet Temperatures Using the Numerical Model

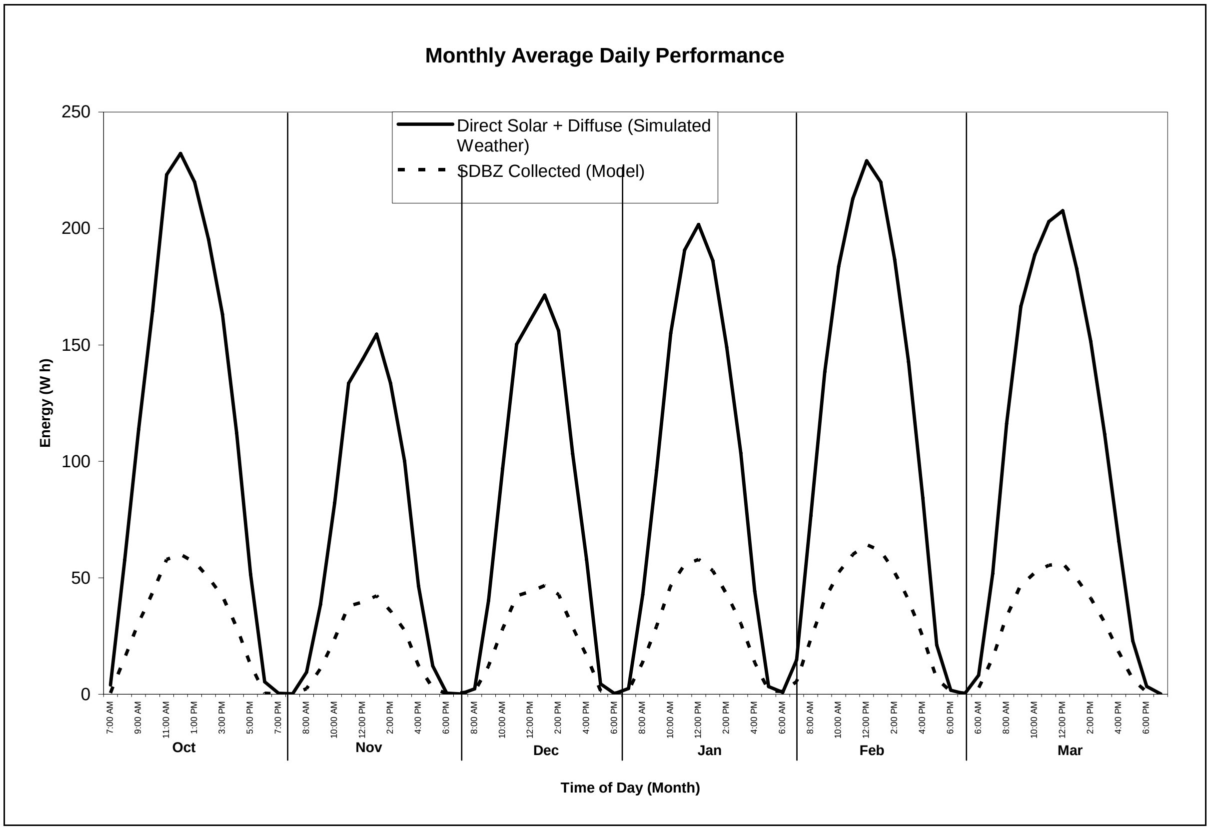


4.2. Toronto Heating Season

To gain a better understanding of the actual performance of the SDBZ, the numerical model was simulated using weather data from an average heating season for Toronto, ON. Weather data was obtained from a standard CWEC weather file and manipulated to satisfy the required input of the numerical model. Based on values reported in the Canadian Climate Normals (Canadian Climate Normals, 2006), the typical heating season for Toronto was found to be between September 21 and April 21.

Figure 7 presents the performance of the SDBZ over most of the heating season. In this period from October 1 to March 31, the average overall seasonal energy efficiency based on the model was found to be 28%.

FIGURE 7: Seasonal Simulated Performance



4.3. Case Study: Leslie Dan Pharmacy Building

The numerical model was used to predict the expected savings of a real building in downtown Toronto, ON. The Leslie Dan Pharmacy Building is located on the north west corner of University Avenue and College Street West. It is home to the University of Toronto's Faculty of Pharmacy and is best described as an institutional building with office, lab and teaching spaces. Figure 8 shows a general elevation of the building. Construction of the Leslie Dan building was completed in 2006. The building comprises twelve floors with two basement levels and a mechanical penthouse. A large atrium towards the north elevation separates the offices (north third) from the southern two-thirds containing lab and teaching spaces. The building façade consists primarily of a unitized curtain wall, with large spandrel areas on the south, east and west elevations. This makes it an excellent candidate for application of the SDBZ. The five levels above grade generally comprised a large atrium along the east and south elevations.

FIGURE 8: Cut-away Elevation of Leslie Dan Pharmacy Building
(Source: Foster Architects.com)

The building is primarily heated with steam provided from the University of Toronto steam loop. Using data supplied by the University of Toronto, the average energy consumption for heating the entire building was calculated for operation during the winter of 2006 to be 25,579 mmBTU or approximately 7,498,000 kWh.

To simulate the predicted benefits of applying an SDBZ system to the building, focus was maintained on the sixth floor and above (including the mechanical penthouse level). The building contained three different spandrel panel geometries: 0.7m x 3.2m, 1.0m x 3.2m and 1.4m x 3.2m. To complete the case study, it was assumed that each panel would be working independent of one another and all air flow could be collected by a series of ducts built into the existing air-handling system. Using the process outlined in section 6.5, the numerical model was calibrated for the various flow lengths associated with the spandrel areas on the building. As such, the numerical model was run to simulate performance of each spandrel panel geometry for the south, east and west elevations. The total collected energy was then calculated by knowing the performance for each panel geometry and the total number of panels on a particular elevation. Table 1 summarizes the case study simulation performance and shows an annual savings of 352,237 kWh. Using the price of steam paid by U of T in 2006 (U of T, 2007), this amounts to an annual monetary savings of approximately $25,000.

TABLE 1: Summary of Case Study Simulation –
Leslie Dan Pharmacy Building, Toronto

Panel Type (m x m)	# of Panels	Total Area (m^2)	Air Flow (m^3/m^2h)	Simulated Collected	Total Collected

				Energy (kWh/panel)	Energy (kWh)
		South Elevation			
0.7 X 3.2	26	58	96	412.2	10,717
1.0 X 3.2	234	749	67	540.8	126,547
1.4 X 3.2	81	363	48	692.9	56,125
		East Elevation			
0.7 X 3.2	22	49	96	215.9	4,750
1.0 X 3.2	173.5	555	67	284.3	49,326
1.4 X 3.2	53.5	240	48	365.6	19,560
		East Elevation			
0.7 X 3.2	22	49	96	250.2.9	5,504
1.0 X 3.2	173.5	555	67	329.1	57,099
1.4 X 3.2	53.5	240	48	422.6	22,609
Total		**2,858**			**352,237**

Based on values provided by Building Services at the university, an estimate of the average fresh-air requirements for the upper flours in the building is presented in Table 2. Fans 1, 2, 6, 7 and 8 are variable flow fans that operate at various percentages of maximum flow depending on the exterior air temperature. Fans 4, 5 and 6 are continually run at 100% capacity. Based on these values, the SDBZ could provide 82% of the average fresh-air requirement during the heating season using a cavity flows of approximately 50 to 100 $m^3/m^2{\cdot}h$ as shown in Table 6-2. The simulation is limited to these flows based on the predictive capacity of the numerical model outlined in previous studies (Richman 2008).

TABLE 2: Summary of Fresh-air Delivery for
Upper Floors of Leslie Dan Pharmacy Building

		Air Handlers			
Area	**Air Handler #**	**Max Flow (cfm)**	**Type**	**Avg. Exterior Temp (from simulation)**	**Operating Flow (cfm)**
Office 4-12	1	9,900	variable	1.7	7,104
Office 4-12	2	15,500	variable	1.7	11,122
Upper Lab 12-9	3	29,000	100%		29,000
Upper Lab 12-9	4	19,000	100%		19,000
Upper Lab 12-9	5	25,000	100%		25,000
Office 4-12	6	16,000	variable	1.7	11,481
Office 4-12	7	18,500	variable	1.7	13,274

Office 4-12	8	19,000	variable	1.7	13,633
				Total	**129,614**

Based on this simulation, the SDBZ curtain wall could reduce the overall heating load for the Leslie Dan Pharmacy Building by approximately 4.7%. Although this seems low, this value demands further discussion.

Firstly, this simulation was run using the numerical model created in this research. Since this model is limited in its predictability, the optimum operating conditions could not be simulated. With a more robust numerical model, the SDBZ could be analyzed to provide 100% fresh air requirements for the entire building. This would result in a 76% increase in operating flow. As such, the expected energy savings would increase as well. Based on the existing spandrel panel configurations, the optimum flow regime for the façade could be determined using the model and an iterative process.

Secondly, the Leslie Dan Pharmacy Building is energy in-efficient. The building used the second most energy per square metre of floor area on the University of Toronto campus (U of T, 2007). In this context, a 4.7% energy savings has a considerable financial benefit. Once again, when considering this energy as otherwise lost to the exterior, the results are promising.

Figures 5 through 7 graphically show that the SDBZ concept is feasible. With average efficiencies of approximately 28%, this system outperforms many standard passive solar collecting systems with published efficiencies ranging between 20% and 40% (Yeh et al, 2005). During an average Toronto heating season, the SDBZ numerical model predicts energy savings of 205 kWh/m^2. This value places the SDBZ in the upper range of published energy savings (150 kWh/m^2 to 210 kWh/m^2) for fresh air pre-heating solar air collectors (Eicker, 2003). These results in addition to the case study provides further evidence supporting the SDBZ curtain wall as a more sustainable alternative to traditional curtain wall assemblies a means to reduce a building's heating cost.

5. CONCLUSIONS

The SDBZ curtain wall is an innovative system coupling the concepts of dynamic buffer zone and solar architecture. This approach has not been documented to date and represents state-of-the-art technology in the field of façade engineering. Through simple modifications during the manufacturing stage, an SDBZ curtain wall can act to transport pre-heated fresh-air to a building's air handling system. Simulations have shown that 100% of the fresh-air requirements can be delivered via the SDBZ curtain wall, eliminating the need for most, if not all, of the extraneous fresh-air handling equipment typically found on roof tops and intermediate mechanical floors within buildings.

What's more, the SDBZ curtain wall can be applied in new construction and as a retro-fit option. This research has shown that simple modifications to the glazing sill and head of the back-pan allow air to pass into and through the spandrel cavity. As such, a conventional curtain wall can be transformed into a SDBZ assembly by simple modifications in the field during a routine glazing replacement program. If the decision to employ an SDBZ curtain wall is known in the design stage, a partnership between the curtain wall manufacturer, building envelope and mechanical engineers will promote the seamless inclusion of this assembly into the building design.

6. NOMENCLATURE

A_g	area of the glass surface, m^2
A_s	effective area of the receiving surface, m^2
A_w	cross-sectional area of the wall components (i.e. insulation and metal back pan), m^2
C_p	specific heat of air, kJ/kg•°C
G	incoming radiation normal to the glass, W/m^2
h_{c1}	convective heat transfer coefficient between interior glass surface and cavity air, W/m^2•K
h_{c2}	convective heat transfer coefficient between collector surface and cavity air, W/m^2•K
$h_{c,ext}$	convective heat transfer coefficient between exterior glass surface and exterior environment, W/m^2•K
$h_{c,\mathrm{int}}$	convective heat transfer coefficient between interior metal back pan surface and interior, W/m^2•K
h_{k1}	conductive heat transfer coefficient between the interior and exterior glass surfaces, W/m^2•K
h_{r1}	radiative heat transfer coefficient between collector surface and interior glass surface, W/m^2•K
$h_{r,air}$	radiative heat transfer coefficient between exterior glass and exterior air, W/m^2•K
$h_{r,\mathrm{int}}$	radiative heat transfer coefficient between interior metal back pan surface and interior, W/m^2•K
$h_{r,gr}$	radiative heat transfer coefficient between exterior glass and ground, W/m^2•K
$h_{r,sky}$	radiative heat transfer coefficient between exterior glass and sky, W/m^2•K
$\dot{m}$	mass flow rate of cavity air, kg/s
T_a	temperature of cavity air, K
T_{ext}	temperature of exterior, K
T_{g_i}	temperature of interior glass surface, K
T_{g_o}	temperature of exterior glass surface, K
T_{inlet}	temperature of the air at the inlet opening, K
T_{int}	temperature of the interior, K
T_{outlet}	temperature of the air at the outlet opening, K
T_s	temperature of the collecting surface, K
T_w	temperature of the interior metal back pan surface, K
U_1	conductive heat transfer coefficient between the collector surface and the interior metal back pan, W/m^2•K
α_g	absorptance of the glass
α_s	absorptance of the collector surface
τ_g	transmittance of the glass

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