ENERGY SIMULATION OF A DOUBLE SKIN FAÇADE: A PROCESS USING CFD AND ENERGYPLUS

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ABSTRACT

This research presents a validated modeling process for analyzing the thermal performance of a naturally ventilated double skin façade (DSF) using an annual building energy simulation program (BESP) such as EnergyPlus along with a computational fluid dynamics (CFD) package. The model is used to develop correlations that can be implemented in a BESP, allowing users to take advantage of the accuracy gained from the CFD simulations without the required computation time. Correlations were developed for airflow rate through the cavity, average cavity air temperature, and interior convection coefficient. The correlations were used to identify deficiencies of EnergyPlus for this application in both its mixed air zone air temperature calculation and in its available correlations for interior convection coefficient. The correlations also served to validate the ability of the COMIS link to predict an accurate airflow rate through the cavity.

INTRODUCTION

As energy conservation is gaining importance in the building industry, the double skin façade has become one strategy designers are considering to reduce the energy consumption of a building over its lifetime. Some designers and researchers propose that a double skin will improve the energy performance of a typical glazed façade, and therefore lower the building's heating and cooling loads.

Current literature on the energy performance of a DSF is conflicting in its conclusions, in part as a result of deficiencies in modeling tools for this application. Depending on the modeling tools used, the configuration of the DSF, the base for comparison, and the intent of the research, conclusions ranging from 50% annual energy savings to negative energy savings resulting from a DSF have been stated in recent papers. One recent study showing cooling energy savings from a DSF was carried out by W.N. Hien et al. They found cooling energy savings resulting from the façade's ability to shield the building from solar gains and extract heat with natural airflow even on east and west facades (Hien et al., 2005). Dr. Karl Gertis, director of the Fraunhofer Institute of Building Physics in Stuttgart, Germany, is an expert on double skin facades. He claims that existing DSF simulations cannot be trusted, and that DSF's are generally unsuitable for the German climate, and much too expensive to justify. While cooling energy savings are often predicted due to natural airflow through the cavity, he says, in reality the cavity air temperature is often increased over the summer outdoor air temperature thereby increasing the cooling load (Gertis, 1999). Questions remain about whether or not cooling energy savings can be realized from a DSF with no operable windows.

A naturally ventilated double skin facade presents an intricate energy modeling problem, dependent on accurate analyses of wind and buoyancy-driven airflow through the cavity, incident solar radiation, and radiative, conductive, and convective heat transfer through the glazed façades and into the adjacent space. Accuracy in existing energy simulation tools for this modeling task depends on CFD simulation, which makes an annual analysis impossible due to the required computation time. Conversely, most CFD packages do not have the ability to analyze angular dependant radiation through glazing with the accuracy provided by an annual building energy simulation program, and cannot simulate building heating and cooling loads or predict building energy consumption.

In this research, an iterative modeling process is developed using the PHOENICS CFD package and EnergyPlus Version 1.2.1 to assess the thermal performance of a DSF with buoyancy-driven airflow and no operable windows. The configuration of the DSF analyzed is similar to that studied by Dirk Saelens at the Vliet Test Cell in Leuven Belgium, whose data was used to validate the model (Saelens, 2002). It is a single-story high cavity with openings at the top and bottom of the exterior façade to allow outdoor air to flow through the cavity. The CFD-EnergyPlus modeling process is able to accurately predict airflow rate through the cavity, along with cavity air and surface temperatures in order to accurately predict heat transfer between the cavity and interior zone for use in an annual building energy analysis.

MODELING PROCESS

EnergyPlus is capable of a detailed analysis of heat transfer through the exterior and interior glazed facades resulting from solar radiation, radiative transfer within the cavity, convective heat transfer due to airflow through the cavity, and conduction through materials. This tool was used to determine cavity surface temperatures and heat flux at a given solar radiation, outdoor air temperature, and cavity airflow rate. To extract the required values, an annual simulation of EnergyPlus was run using 15 minute time steps, and values were used from time steps that had external conditions exactly matching those of the DSF being analyzed. These values were then used in the CFD model as boundary conditions of cavity surfaces and heat flux from the internal shading device. The CFD model was used for a detailed analysis of quasi-steady-state airflow and heat transfer through the cavity. The airflow rate and temperature stratification found from with CFD were then entered into the EnergyPlus model by altering the opening size to force the desired airflow rate through the cavity at the desired ΔT. These new conditions produced slightly different surface temperatures in EnergyPlus, and the CFD model was altered accordingly and re-run. This iterative process was used to converge on sufficient accuracy in both surface temperatures and airflow rates. The process is illustrated in Figure 1.

No more than five iterations were ever needed for values to converge, or vary by less than 5% from the previous iteration. As more and more models were run with this process, it was found that altering the EnergyPlus opening size by a known factor at the start of the process would reliably result in convergence with only two iterations. This finding greatly sped up the process for later models.

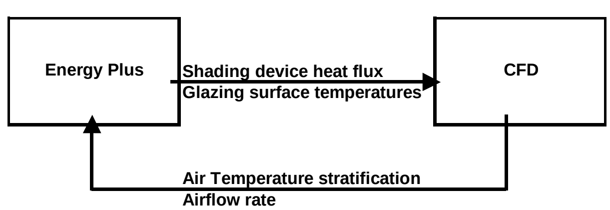


Figure 1 Iterative Modeling Process

The DSF cavity model analyzed consists of an interior double pane insulating glazing and an exterior single pane clear glazing. There are rectangular openings at the bottom and top of the exterior glazing that allow outdoor air to flow up through the cavity. A roller shading device extends the width of the cavity. The PHOENICS CFD model uses the RNG-derived k-ε turbulence model, which has been found to have an error of 7.6% in predicting airflow rate through a DSF cavity compared to measured data (Chiu et al., 2001). The average grid cell size in the cavity is 3.75 x 10^{-5} m^3, with cells smaller near surfaces than in the center of the cavity. This model resulted in an airflow prediction error of 10% compared to the value calculated for a hypothetical model with infinite grid cells. The interior glazing is an external plate at the domain boundary with an initial temperature as determined with EnergyPlus; the model is able to determine heat transfer through this plate as a function of surface temperature, air temperature, and detailed airflow patterns near the surface. The domain is large enough beyond the cavity openings so that the boundaries do not affect airflow at the openings. Details of the CFD model are shown in Table 1, with an image of the model's geometry shown in Figure 2.

The EnergyPlus model consists of two zones: one of the DSF cavity and one of an adjacent space maintained with purchased air at 20° C. The COMIS airflow model link within EnergyPlus is used to predict airflow from an exterior node through the cavity zone through an opening in the exterior glazing. The 'detailed' interior and the 'MoWitt' exterior convection coefficient correlations are used (LBNL, 2004).

Table 1 CFD Model Details

DOMAIN	
Domain Size	5.0m high (z) by 5.2m wide (y) by 1.0m deep (x)
Domain Material	Air at 20°C, 1 atm
Reference Pressure	100,000 Pa (atmospheric pressure)
Reference Temp.	273 K
SOURCES	
Buoyancy Model	Boussinesq
Buoyancy Reference Temp.	Outdoor air temperature
Gravitational Acceleration	-9.81 m/s in the z-direction
BOUNDARY CONDITIONS	
Side, top, bottom, & front domain boundary conditions	Openings with 'deduced' air velocities, external temperature = outdoor air temperature at inflow only, external pressure at atmospheric pressure
Back boundary conditions	Adiabatic solids (concrete) with depth = cavity depth

CAVITY DETAILS	
Cavity Size	2.7m high by 1.2m wide by 0.3m deep
Cavity External Façade	Internal plate with surface temperatures on both sides determined by EnergyPlus model
Cavity Internal Façade	External plate with surface temperature determined by EnergyPlus model
Shading Device	Blockage with fixed heat flux determined by EnergyPlus model

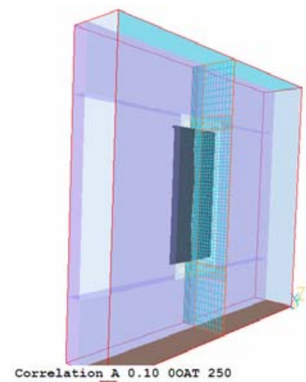


Figure 2 CFD Model

MODEL RESULTS

Temperature stratification results from one model using the process described above are shown in Figure 3. The model shown has an outdoor air temperature of 0º C and an incident solar radiation of 500 watts/m^2. The stratifications in the center of the figure show the air temperature inside of the cavity ranging from 0º to 12º C.

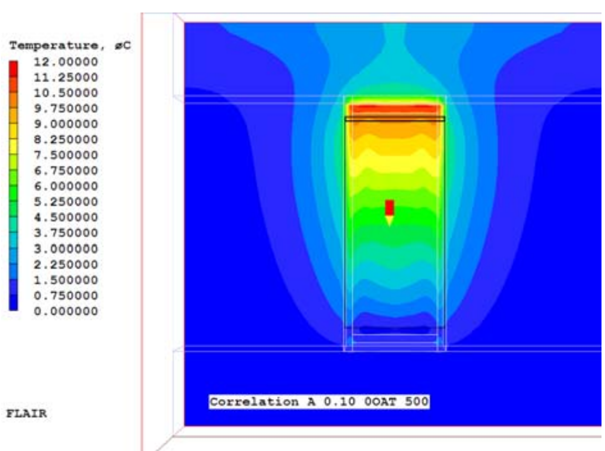


Figure 3 CFD Temperature Stratification Results

The modeling process was validated using measured data taken by Dirk Saelens at the Vliet Test Cell in Leuven, Belgium (Saelens, 2002). The five cases with varying outdoor air temperatures and levels of incident solar radiation used for validation are detailed in Table 2. The final model, calibrated to model the effective pressure loss through the complex louvers on the Vliet Test Cell DSF, has errors calculated with root mean differences for airflow rate of 2.7 m^3/hr or 9%, and 2.0° C or 15% for temperature stratification compared to the measured data. Modeled and measured values for temperature stratification within the cavity and airflow rate, along with net and percent errors for five different cases are detailed in Table 3.

Table 2 Conditions of Model Validation Cases A-E

	INCIDENT SOLAR RADIATION (WATTS/M^2)	OUTDOOR AIR TEMPERATURE (ºC)
A	295	3.6
B	575	9.8
C	579	23.3
D	0	16.2
E	0	3.9

Table 3 Temperature and Airflow Net Errors

	ΔT (PEAK CAVITY AIR TEMP. – OUTDOOR AIR TEMP., ºC)				AIRFLOW RATE THROUGH CAVITY (M^3/HR)			
	Modeled	Measured	Net Error	% Error	Modeled	Measured	Net Error	% Error
A	11.9	15.2	-3.3	-22%	30.5	3 1	-0.5	-2%
B	25.1	25.2	-0.1	0 %	47.5	5 0	-2.5	-5%
C	17.3	20.2	-3.0	-15%	38.5	3 8	0 . 5	1 %
D	1 . 7	1 . 3	0 . 4	33%	10.8	1 3	-2.2	-17%
E	4 . 2	4 . 1	0 . 1	3 %	23.1	1 8	5 . 1	28%

CORRELATIONS

The modeling process described above was used to analyze the performance of a number of double skin façade cavity geometries, each with a range of outdoor environmental conditions. The main goals of the modeling were to determine airflow and temperature stratification profiles as they are affected by varying the cavity geometry, and to develop correlations that can be used to improve the occuracy of a BESP such as EnergyPlus. In this analysis, the only driving force for airflow is buoyancy; the wind pressure is zero in each of the models. This allows for correlations to be developed for buoyancy-driven airflow independently, which can be added to wind effects in an annual simulation.

Fifteen different DSF models were run to analyze the cavity geometry variables of depth (the distance between the two facades), h/d (height/depth) ratio, height, opening size, and shading device (louvers or roller shade). Each of the models was run under a number of different outdoor air temperatures and levels of incident solar radiation: enough to determine trends in the airflow and temperature performance of the cavities.

Airflow Rate

Figure 4 shows plots of airflow rate versus $\Delta T_{average}$ (average cavity air temperature – outdoor air temperature) from three of the DSF cavity models run. The models shown are single story high cavities with depths of 0.30 m and h/d ratios of 10. The data fit exponential curves very well; the lowest regression coefficient (R^2) for any of the curve fits for the 15 models is 0.997.

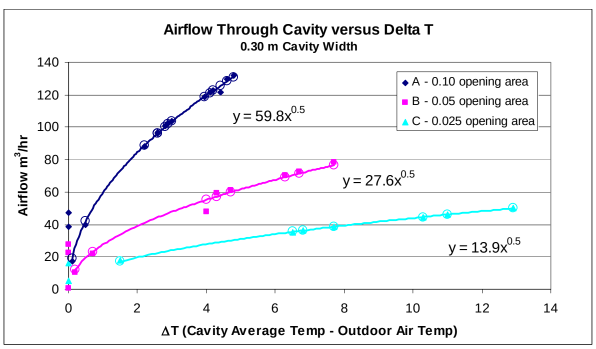


Figure 4 Airflow Rate Correlations

Equation 1, a correlation for airflow rate as a function of opening size and h/d ratio for a single story high cavity with a roller shading device was developed using the model results.

$$V = \left(-6.2 * \frac{h}{d} + 647.5\right) A_{opening} \sqrt{\Delta T}_{Average} \qquad (1)$$

The correlation has a total R^2 of 0.95, and is valid for opening sizes from 0.00 through about 0.15 m^2, h/d ratios from about 1 through 15, and for any range of temperatures seen in a DSF cavity. Louvered blinds were found to reduce the airflow rate by about 6% below the value found with this equation. A number of models were also run with a five-story high cavity. Although there was not enough data to include the cavity height variable in Equation 1, a separate equation, Equation 2, was developed for a five-story (15 m) high cavity.

$$V = 1375 * A_{opening} \sqrt{\Delta T}_{Average} \qquad (2)$$

Equations 1 & 2 can be used to determine the buoyancy-driven airflow rate through a cavity as a function of ΔT, and the cavity geometry at a time step in a BESP.

Saelens also developed a curve fit from his measured data for airflow rate versus ΔT. This curve is compared to values calculated using Equation 1 in Figure 5. To generate this curve, Equation 6 (described below) was first used to calculate the $\Delta T_{average}$ (average cavity air temperature - outdoor air temperature) from the ΔT_{real} (peak cavity air temperature – outdoor air temperature) and this value was used in Equation 1 to calculate airflow rate. The values used in Equation 1 to describe the Vliet Test Cell are: h = 2.7 m, d = 0.3 m, and $A_{opening}$ = 0.026 m^2. The results from the correlation developed in this research (labeled Pappas in the figure) match those plotted by Saelens from measured data quite well for ΔT values between 0°C and 25°C. The regression coefficient between the two sets of data is 0.997.

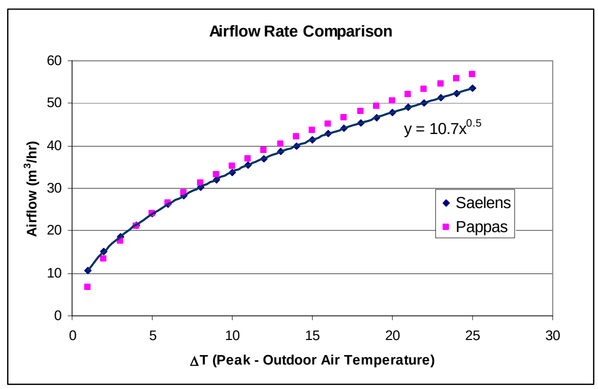


Figure 5 Airflow Rate Correlation Compared to Measured Data

Cavity Air Temperature

The following correlations for average cavity air temperature were also developed from the model results. They are valid for any cavity height, depth, or opening size, and for any range of temperatures seen in a DSF cavity. The lowest R^2 value for any of the temperature correlations is 0.92.

$$T_{AverageCavityAir} = 1.05 * T_{EPlusZoneAir} - 2.97 \qquad (3)$$

It was found that the mixed air model used in EnergyPlus does not predict a zone air temperature sufficiently accurate to use as the average cavity air temperature for a DSF cavity. Equation 3 relates the actual cavity average air temperature as determined by

CFD to the cavity zone air temperature determined with the mixed air model used by EnergyPlus. If Equations 1 or 2 are used to calculate airflow rate within EnergyPlus (or any simulation tool using a mixed air model), it is necessary to use this equation to first determine the actual cavity air average temperature from the zone air temperature. This correlation uses data from all of the CFD models run, and has a strong regression coefficient independent of cavity height.

$$T_{PeakCavityAir} = 2.43\left(T_{AverageCavityAir}\right)^{0.78} \qquad (4)$$

$$T_{PeakCavityAir} = 3.68\left(T_{AverageCavityAir}\right)^{0.69} \qquad (5)$$

Equations 4 & 5 can be used to calculate the peak cavity air temperature from the average cavity air temperature, both values as determined with CFD. The peak cavity air temperature is the driving force for buoyancy-driven airflow so it is valuable to relate this to the value used in Equations 1 & 2. These correlations are strongest when the data is separated for cavity height, and equations were developed for a single story cavity (Equation 4) and a five-story cavity (Equation 5) separately. Equations 4 & 5 can be used in hand-calcualtions to determine air temperature stratification within the cavity for use in calculating heat transfer or airflow rate.

$$\Delta T_{Real} = 1.87 * \Delta T_{Average} \qquad (6)$$

Equation 6 relates the temperature difference that drives buoyancy-driven airflow (peak cavity temperature – outdoor air temperature), with the ΔT used in the airflow correlations above (average cavity temperature - outdoor air temperature). This correlation has a strong regression coefficient independent of cavity height; data from all of the CFD models run are included in this relationship.

Cavity Pressure

Equation 7 for a single story cavity and Equation 8 for a five-story cavity were developed to relate the (peak cavity air temperature) – (outdoor air temperature) to the (peak cavity pressure) – (outdoor air pressure), in Pascals. These equations can be used to relate cavity air temperature to pressure for a BESP model that uses zone pressures to calculate airflow between zones, such as COMIS.

$$\Delta T_{Real} = 28.44\Delta p + 1.51 \qquad (7)$$

$$\Delta T_{Real} = 5.30\Delta p + 2.69 \qquad (8)$$

Saelens also created a curve fit for Δp versus ΔT from his measured data. This correlation along with that developed in this research (Equation 7) for a single story cavity is shown in Figure 6. The two correlations match very well for ΔT values between 0º and 25º C; the regression coefficient between the two sets of data is 0.996 within this range.

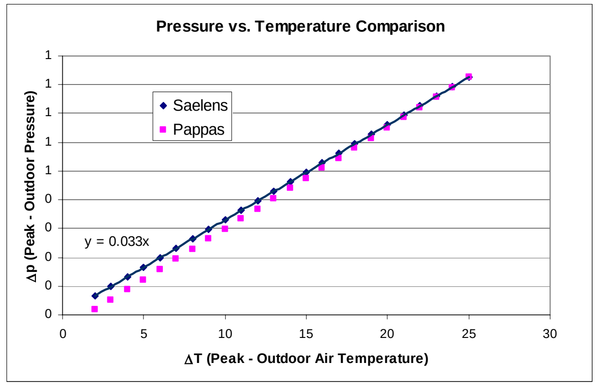


Figure 6: Pressure versus Temperature Correlations

Interior Convection Coefficient

Heat transfer through the interior glazing, the ultimately useful value from these correlations, is largely dependent on convection from airflow at the interior cavity glazing surface. Predicting the rate of heat transfer through the facade, therefore, depends on the accuracy of the convection coefficient used. Figure 7 shows a plot of the convection coefficient calculated from CFD model results using the average air temperature from CFD and the glazing surface temperature. Also plotted is the interior convection coefficient used in EnergyPlus from the 'detailed' correlation (LBNL, 2004). As shown, the EnergyPlus correlation under-predicts the convection coefficient for ΔT values less than ±4º C compared to the CFD results. The average $h_{convection}$ from CFD results is 2.16 w/m^2 °C, shown in the constant curve in the figure. The regression coefficient for all the CFD model values compared to this average is 0.92. This is the strongest correlation found with this resarch for $h_{convection}$ of an interior surface with buoyancy-driven airflow through a double skin façade.

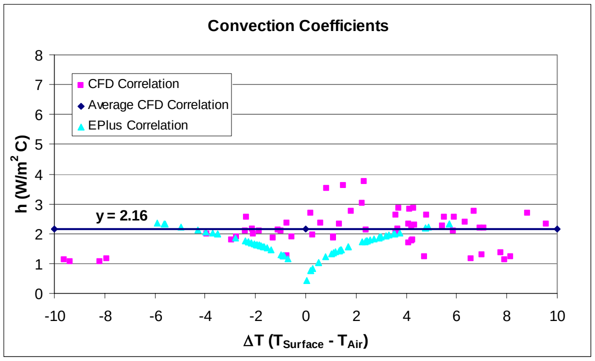


Figure 7 Convection Coefficients

ENERGYPLUS PERFORMANCE ASSESSMENT

The results from the modeling process were also used to assess the ability of EnergyPlus Version 1.2.1 to predict an accurate heat transfer through the interior glazing as the program exists. Annual measured data was not available to assess annual energy results, but components of the simulation can be addressed individually. The EnergyPlus model, as described above, uses COMIS to predict buoyancy-driven airflow from the exterior through a cavity zone. As shown in Figure 8, EnergyPlus consistently predicts heat transfer values much lower than the modeling process developed in this research for the same cavity geometry and outdoor air conditions. The CFD heat transfer prediction is about 1½ times greater than that of EnergyPlus, on average for all models run. The following analysis offers explanations for this difference in results.

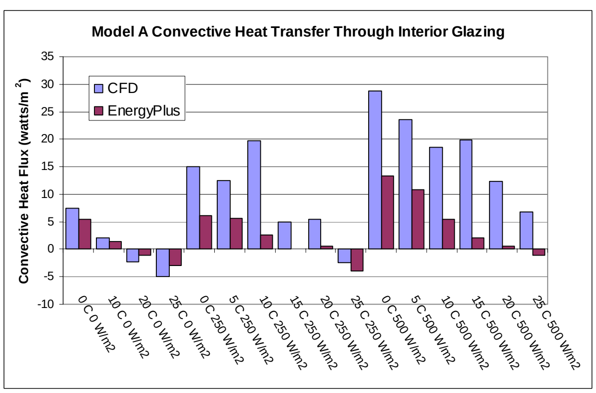
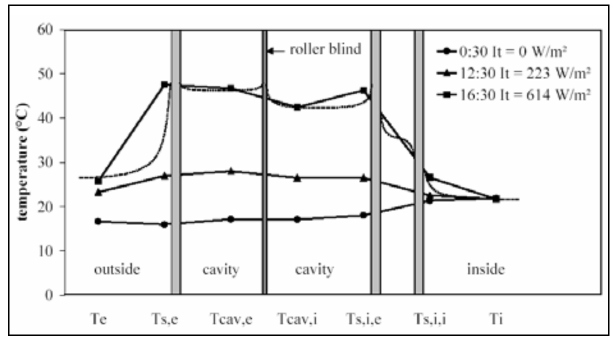


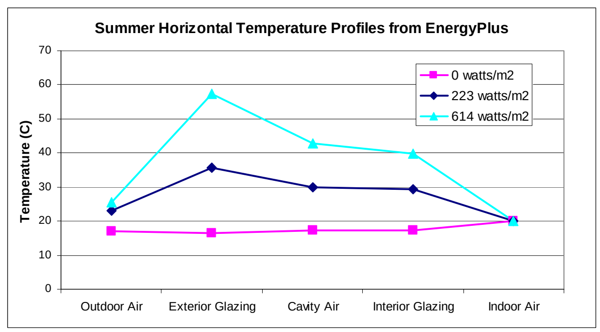
Figure 8 Heat Transfer through Interior Glazing

Surface Temperature Prediction

The glazing surface temperatures predicted by EnergyPlus vary significantly from those from measurements taken by Saelens under the same cavity and exterior conditions. As shown in Figure 9, the exterior glazing temperature from EnergyPlus is much greater than the measured value when there is incident solar radiation. The temperature of the interior glazing, the value used to calculate heat transfer through this surface, is 4%, 13%, and 16% different from the measured values (in order of increasing levels of incident solar radiation) for the three summer conditions shown in these figures.



(a) Saelens Measured Data (Saelens, 2002)



(b) EnergyPlus Results

Figure 9 Summer Cavity Horizontal Temperature Profiles

Airflow Rate

Three different models were run in EnergyPlus to assess the ability of COMIS to predict buoyancy-driven airflow through the cavity. The models are all single story cavities with h/d ratios of 10, roller shading devices, and opening sizes as detailed in Table 4. The Correlations shown in the table were calculated using Equation 1 for each of the models, and the Regression Coefficients compare values from these correlations to EnergyPlus predictions for the same ΔT (zone air temperature – outdoor air temperature in EnergyPlus). As shown, the EnergyPlus values predicted by COMIS are very close to those calculated with the validated correlations. So, although the ΔT value used by EnergyPlus is not accurate because of the mixed air zone air temperature model, COMIS predicts an accurate buoyancy-driven airflow rate for a *given* ΔT.

Table 4 Airflow Rate Correlations Compared to EnergyPlus Results

	OPENING SIZE (M^2)	CORRELATION	R^2
A	0.100	$V = 59.8\sqrt{\Delta T}$	0.972
B	0.050	$V = 27.6\sqrt{\Delta T}$	0.988
C	0.025	$V = 13.9\sqrt{\Delta T}$	0.991

Recommendations and Further Research

The heat transfer through the interior glazing predicted by EnergyPlus is inaccurate compared to results from the validated model. This is in part due to inaccuracies in both cavity air temperatures and the interior convection coefficient correlation. It was found that the zone mixed air model used by EnergyPlus does not provide an accurate cavity air temperature for this modeling task. The zone air temperature from EnergyPlus can be altered with Equation 3 to find the actual average cavity air temperature. Also, there is not a correlation for interior convection coefficient available within EnergyPlus that is accurate for this application. The constant value of 2.16 w/m^2 °C is the most accurate value determined from this research and can be used for a more accurate analysis.

Although building energy results have not been analyzed for any period of time that includes multiple time steps, the two changes mentioned above should provide a more accurate energy analysis of a double skin façade with buoyancy-driven airflow in EnergyPlus. Further research is needed to implement these correlation into an annual simulation program to assess results on a design day or annual basis. Also, the EnergyPlus algorithm for radiative transfer within the cavity was not analyzed. Because the existing algorithm is meant for zones with aspect ratios closer to a typical room, it is likely that some error exists in this calculation as well. This area also requires further research.

CONCLUSIONS

The iterative modeling process developed in this research using CFD and EnergyPlus can be used to analyze the thermal performance of a double skin façade with buoyancy-driven airflow. The model was validated using measured data from Dirk Saelens taken at the Vliet Test Cell in Leuven, Belgium, and errors were calculated with root mean differences for airflow rate prediction of 2.7 m^3/hr (or 9%), and 2.0° C (or 15%) for temperature stratification. The modeling process was used to develop correlations for airflow rate, temperature stratification, and interior convection coefficient that can provide a more accurate energy analysis of a DSF with buoyancy-driven airflow within an annual building energy simulation program than is currently possible.

EnergyPlus 1.2.1 was also analyzed for accuracy as it currently exists. The model was found to predict an accurate buoyancy-driven airflow rate for a given ΔT using the COMIS network airflow model. However, the predictions for cavity surface temperatures are not accurate compared to measured values, and heat transfer through the interior glazing is on average 1½ times less than that predicted by the validated modeling process. Altering the cavity zone air temperature with Equation 3 and providing a more accurate correlation for the interior convection coefficient should allow EnergyPlus to give a more accurate energy analysis for this application.

NOMENCLATURE

V	airflow through cavity (m^3/hr)
d	cavity depth, distance between two facades (m)
h	cavity height (m)
h/d	cavity hight/depth ratio (demensionless)
$A_{opening}$	area of one cavity opening (m^2)
T	temperature (º C)
$T_{EPlus\ zone\ air}$	cavity zone air temperature use by EnergyPlus (º C)
$T_{AverageCavityAir}$	actual average cavity air temperature from CFD model (º C)
$T_{PeakCavityAir}$	actual peak cavity air temperature from CFD model (º C)
$\Delta T_{average}$	average cavity air temperature – outdoor air temperature (Kelvins)
ΔT_{real}	peak cavity air temperature – outdoor air temperature (Kelvins)
Δp	peak cavity air pressure – outdoor air pressure (Pascals)
$h_{convection}$	interior convection coefficient (w/m^2 °C)

ACKNOWLEDGMENTS

Validation of the model with measured data would not have been possible without the data taken from Dirk Saelens' research at the Vliet Test Cell in Leuven, Belgium.

REFERENCES

Chiu, Yin-Hao, MSc & Li Shao, PhD. An Investigation into the Effect of Solar Double Skin Façade with Buoyancy-Driven Natural Ventilation. School of Built Environment, University of Nottingham, UK. 2001.

Gertis, Karl. Sing neuere Fassadenentwicklunger bauphysikalisch sinnvoll? Teil 2: Glas-Doppelfassaden (GDF). Ernst & Sohn Bauphysik 21 (1999), Heft.

Hien, Liping, Chandra, Pandey, & Xiaolin. Effects of Double Glazed Façade on Energy Consumption, Thermal Comfort and Condensation for a Typical Office Building in Singapore. National University of Singapore. 2005.

Lawrence Berkeley National Laboratory with the U.S. Department of Energy. EnergyPlus Manual: Documentation Version 1.2.1. September, 2004.

Saelens, Dirk. Energy Performance Assessment of Single Story Multiple-Skin Facades. Katholieke Universiteit Leuven. September, 2002.