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A computational method for calculating heat transfer and airflow through a dual-airflow window

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Abstract

An airflow window has great potential for conserving energy and improving indoor air quality in residential buildings. Existing airflow windows use a single airflow path, and their energy performance can be studied using several computational models. A dual-airflow window with triple glazing can conserve more energy than a single-airflow window, because the former works like a cross-counterflow heat exchanger. However, no suitable computer programs can be used to evaluate the energy performance of the dual airflow window. This paper proposes a four-step computational method that uses both computational fluid dynamics (CFD) and coded radiation calculations to determine airflow and heat transfer through the window. Experimental tests on a full-scale dual-airflow window system were used to obtain various indoor and outdoor air and window surface temperatures for validating the computer method. The agreement between the computed and measured temperatures is very good.

Keywords: Window, Computational fluid dynamics, Building simulation, Energy analysis

1. Introduction

In recent years, the building community has integrated sustainable design concepts that can improve indoor air quality while conserving energy in buildings (http://www.usgbc.org/). For instance, ventilated building façades are currently being integrated into commercial buildings across Europe [1]. However, this technology has not been utilized as frequently in residential buildings, because it is expensive and multistory facades may not be applicable to residential designs. Airflow windows are not as complicated as ventilated facades, but could improve indoor air quality, enhance daylighting, and conserve energy for heating and cooling [2-3]. The potential for airflow window use in residential construction for the improvement of indoor air quality should therefore be explored.

As the name implies, the main difference between conventional windows and airflow windows is the existence of free or forced convection between two layers of glass

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called airflow cavities. An airflow cavity is usually combined with a double glazed insulated unit, resulting in a triple paned airflow window. However, various combinations of single panes or double glazed insulated units can be used to form an airflow window.

There are four main modes of operation for airflow windows: supply, exhaust, indoor air curtain, and outdoor air curtain as shown in Fig. 1. Note that in each of the cases, the outside is shown as the left side of each window and the inside is shown as the right side of each window. Typically used during the heating season, a supply air window draws air from the outside to the inside space (Fig. 1(a)). Conversely, during the cooling season, an exhaust air window extracts air from the indoor space to the outdoor space (Fig. 1(b)). The indoor and outdoor air curtain windows have airflow paths from inside to inside and outside to outside, respectively, as shown in Figs. 1(c) and (d). In all cases airflow is typically from bottom to top to make use of the thermal buoyancy effects as the air heats up. The exhaust air window may also be used during the heating season with airflow from top to bottom.

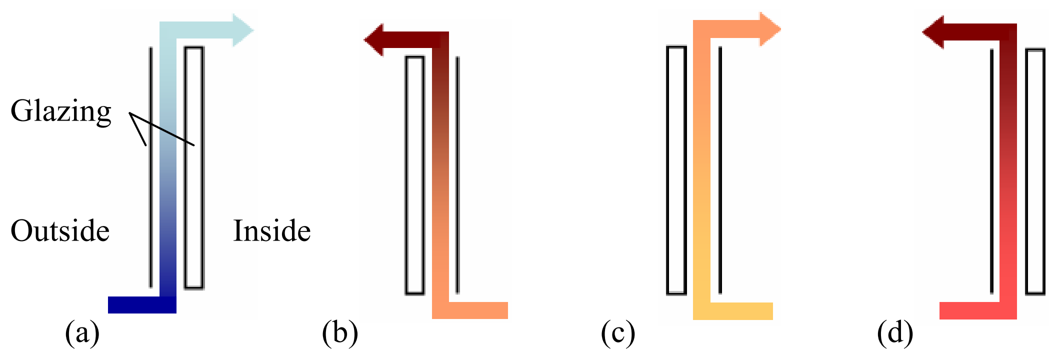


Fig. 1. Existing airflow window types: (a) supply mode, (b) exhaust mode, (c) indoor air curtain, and (d) outdoor air curtain [4].

Recently, the authors have developed a new dual-airflow window as shown in Fig. 2. The dual-airflow window is better than the one shown in Fig. 1(a) because the heat exchange between the two air streams can further conserve energy for cooling and heating [4]. The new airflow window is also better than those shown in Figs. 1(b), (c), and (d) because it can bring fresh outdoor air to the interior space, improving indoor air quality.

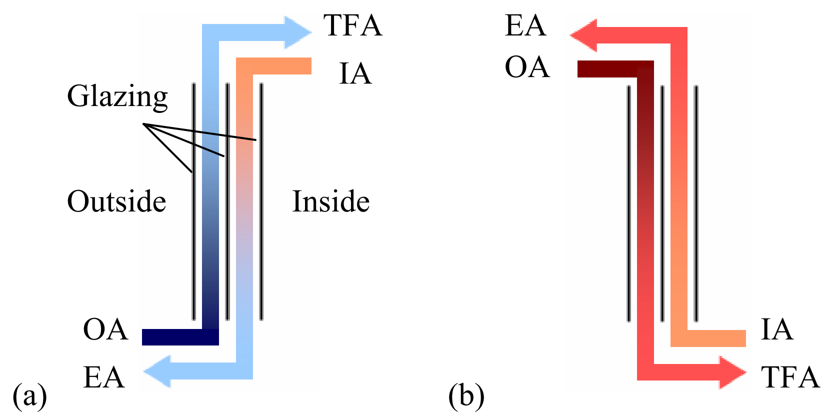


Fig. 2. Two operating modes of the new dual airflow window: (a) supply and (b) exhaust (TFA – tempered fresh air, IA – indoor air, OA – outdoor air, and EA – exhaust air) [4].

In order to evaluate the overall performance of the dual-airflow window, it is essential to develop a computational method that establishes flow and energy balances in the window. The computational method can then be implemented into a building energy analysis program, such as EnergyPlus (http://www.eere.energy.gov/buildings/energyplus/), that determines the annual energy performance of the window for different climate regions. The computational method can also provide accurate airflow information within the window which can be used to assess the window's impact on indoor air quality.

2. Existing computational methods for single-airflow windows

Ferguson and Wright [5] developed a computer program, VISION, to simulate the thermal performance of "superwindows". The windows included two or more layers of glass, a low-e coating on one or more glass surfaces, and/or various gases, such as argon, to fill the insulated glass units. Note that superwindows are not airflow windows. The VISION computer program treated the triple paned window as five nodes, with each of the nodes representing the indoor and outdoor temperatures and the inner, middle, and outer pane temperatures. A set of equations is then used to balance the energy across the window system. Convective heat transfer, longwave radiation exchange between the outdoors and indoors, and source terms to account for absorbed solar radiation were considered. This program assumed that airflow is laminar, hydrodynamically stable, and fully developed. Haddad and Elmahdy [6] provide a detailed overview of the VISION program.

Wright [7] later made modifications to the program to allow for modeling of airflow windows. The modifications assume that heat transfer is two-dimensional and the glass panes are isothermal. Energy calculations account for the heat gains and losses due to convection as air flows vertically over the window surfaces. Calculations also account for radiation exchange between each glass pane and between the window and the inside/outside spaces. The modified model also accounts for the energy present in the supply air as it enters the window system. Eleven configurations of double to quadruple paned supply air windows, each with only one airflow cavity, were studied. Wright used this program to estimate the effective U-values and shading coefficients of both conventional windows and airflow windows. Steady, laminar, and fully developed airflow conditions were also assumed for the heat transfer calculations. In both cases, isothermal glass pane temperatures were assumed. Results from Wright's study are limited to operation of a supply air window at one point in time during the heating season when there is no solar radiation.

Haddad and Elmahdy [6,8] simulated both the supply air and exhaust air windows. Their simulations used a program similar to VISION [5]. Comparisons were made between the supply and exhaust modes as well as between airflow and conventional windows. Their studies are probably the first hourly simulations that spanned one year and studied the effect of orientation on window performance.

The performance of an airflow window can be simulated by considering an energy balance across the window itself (i.e. VISION) or by considering an energy balance between the window and interior space. For instance, Barakat [9] used a simple computer code to study the heat balance across the entire envelope of a room. Several factors, dependent on the space, determine the energy gains and losses. If the room has a mechanical system, then energy transfer from the outdoor and exhaust airflows needs to be considered. Similarly, the use of an airflow window requires energy tracking of the incoming and exhaust airflows. Conductive losses are incurred across the walls, ceiling, floor, and insulated glazing elements. Radiation exchange, including solar radiation through glazed surfaces and radiation exchange between interior and exterior objects is included. Finally, the building envelope and interior objects such as furniture may also act as energy storage elements, which is accounted for in the program.

At present, many energy analysis programs have implemented those methods to calculate heat transfer through the single-airflow windows, such as EnergyPlus. The programs can effectively determine the overall energy performance of the windows.

On the other hand, computational fluid dynamics (CFD) can provide detailed airflow and temperature distributions for an airflow window. CFD studies [10,11] have been conducted to evaluate the performance of the conventional and supply air window configurations. In these studies, CFD models of conventional windows with various constructions were validated by comparing simulated results to comparable conditions reported in the ASHRAE handbooks and experimental measurements with good agreement. CFD has also been used to study ventilated double façades that have very similar heat transfer and flow characteristics as single airflow windows. For instance, Safer et al. [12,13] used CFD to study a double façade with an interior blind. Airflow through the façade is similar to that found in the outdoor air curtain window. This two-dimensional model makes use of the discrete ordinates (DO) radiation model to track incident solar radiation and assumes isothermal pane temperatures on the inside and outside glass layers. Those CFD studies have demonstrated that CFD is very capable program that can accurately calculate airflow though single-airflow window configurations and ventilated facades.

However, it is difficult to couple CFD results with a whole building simulation over the course of one year for varying weather conditions [14]. Research was therefore conducted using a network analysis of airflow windows instead of a CFD simulation. For instance, Leal et al. [14,15] used an airflow network model coupled with an energy balance equation in ESP-r (http://www.esru.strath.ac.uk/Programs/ESP-r.htm) to study an airflow window and its relationship to the whole building heat transfer. Their investigations suggested how many zones the window should be divided and gave insight into the local pressure loss coefficients at the inlet and outlet of the window as well as the values of heat transfer coefficients. The network model has used many approximations and thus the coupled network and energy simulations have errors.

The above review shows that none of the energy simulation programs are capable of handling the new dual-airflow window that has very complicated heat transfer and flow features. Two-dimensional computer programs, such as VISION, are insufficient for the dual airflow window. Due to the crossflow heat exchange present in the dual-airflow window, the simplification of the three-dimensional problem to a two-dimensional one would lead to an unacceptable error. CFD programs can give accurate airflow and heat transfer through the dual-airflow window, although it is not feasible to couple a CFD program with an energy simulation program for hourly energy analysis over a year.

3. A new computational method for the dual-airflow window

This investigation proposes to calculate heat transfer and airflow through the window by dividing weather data into different bins. The CFD simulations should only be conducted for no more than 31 cases if each bin has 2 K that would cover a temperature range from -20^{o}C to 40^{o}C. Then an energy simulation program can use the CFD results for calculating heat transfer through the dual-airflow window to ensure an accurate estimation of hourly heating or cooling load through the window over a year. Thus, our proposed method is not to couple a CFD program with an energy simulation program but to use limited CFD results for hourly energy simulation.

Our study used a commercial CFD program, Fluent (www.fluent.com) to model conduction and convection within the window system and radiation from the inner and outer surfaces of the window system. The CFD program uses the Re-Normalization Group (RNG) k-ε turbulence model and a second order numerical scheme. Hand calculations supplement the CFD window simulations to account for the heat sources and sinks in the glass due to surface-to-surface (S2S) radiation and absorbed solar radiation. This approach reduces computing time and allows for all radiation effects to be accounted for in the CFD model as detailed below.

Although the window geometry is simple, the simultaneous modeling of three-dimensional mixed-mode heat transfer is difficult. This was due to two factors: window aspect ratio and the radiation models used in Fluent. 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 so that accuracy and convergence are not impeded. With a height of 1.22 m and a glass thickness of 3 mm, this can be difficult to achieve while maintaining a reasonable total grid number. Since the temperature gradient across the glass was small due to the relatively high glass conductivity, only one cell was used across the thickness of the glass. This study managed to maintain a cell aspect ratio less than 7 with a total grid number of 464,158 for the 15 mm cavity width.

Three radiation interactions are present in the window system: radiation to the interior space, radiation between each pane of glass, and solar radiation. The S2S radiation model available in Fluent is limited to a single enclosure. Therefore, the multiple enclosures formed by the two airflow cavities and the indoor/outdoor spaces cannot be modeled simultaneously with the S2S radiation model. From the perspective of solar radiation, only the discrete ordinates radiation model is capable of modeling glass, a semi-transparent media. However, computational costs are significantly increased when this model is employed, and surface-to-surface radiation effects are not accurately modeled when no external radiation source is present. Thus, this investigation uses a combination of CFD modeling and coded calculations to account for all radiation effects. Fig. 3 presents a flowchart of the proposed computational method for calculating the three-dimensional airflow and heat transfer through the new dual-airflow window. The Q values used in the figure are defined in Fig. 4. The computational method has the following steps:

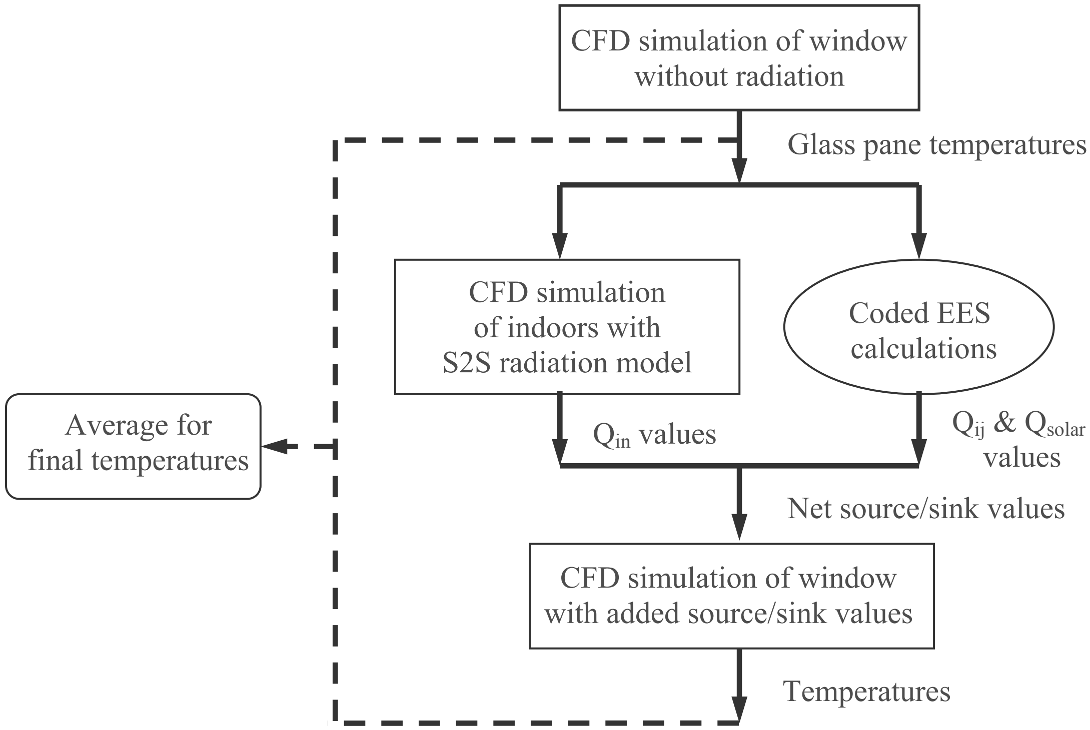


Fig. 3. Flowchart of computational methodology.

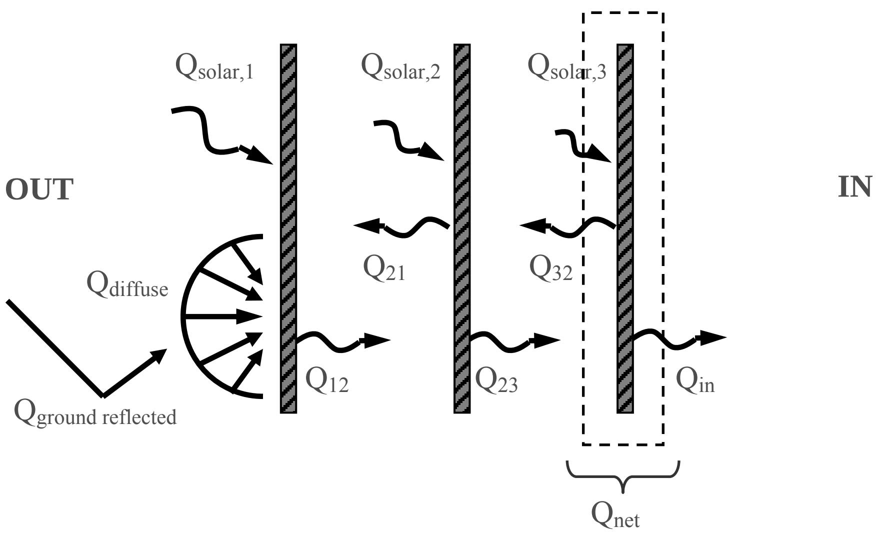


Fig. 4. Overview of net radiation on each subsurface.

Step 1: CFD simulation of window without radiation

CFD simulations of the window system are first conducted to estimate the heat transfer effects due to conduction and convection. Different indoor and outdoor air temperatures (determined by the bin) serve as the model inputs. The CFD model with an active radiation model calculates the glass pane temperatures from these inputs. For the geometry studied, each glass surface was divided into nine isothermal sections (subsurfaces), resulting in a CFD output of nine temperatures per pane of glass.

Step 2 (a): CFD simulation of indoor enclosure with the S2S radiation model

From the resulting interior glass pane temperatures, the S2S radiation energy exchange (Q_{in}) between the window surface and the walls, ceiling, and floor of the interior space can be calculated.

Step 2 (b): Coded EES calculations

The temperatures on each pane of glass are used to estimate the S2S radiation exchange (Q_{ij}) between the window panes through Eq. (1) [16]:

$$Q_{ij} = \frac{A\sigma(T_i^4 - T_j^4)}{\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1} \tag{1}$$

where A is the area of the subsurfaces of the window panes, T is the subsurface pane temperature, ε is the emissivity of each pane, and σ is the Stefan-Boltzman constant. Panes are divided into several sections to enhance the accuracy of calculations made using Eq. (1). These calculations have been coded into Engineering Equation Solver (EES) to simplify repeated calculations.

The energy from solar radiation (Q_{solar}) is estimated for each glass pane. First solar radiation flux is divided into direct radiation, diffusive radiation and ground reflected radiation by using typical meteorological year (TMY2) data (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2). Theoretically, solar radiation should also be divided into different bins as the outdoor air temperature changes. For simplicity, the present study considered the worst case scenarios to evaluate window performance, cloudy on a cold winter day and sunny on a hot summer day. In both cases, solar noon was considered, so the angle of incidence on the window was fixed. An hourly energy analysis of an entire year would require more than one solar value. Furthermore, if this method is to be expanded to study a dual-airflow window design within interior blinds, then more than one solar radiation value is needed and the "bin" method should be definitely employed.

Second the actual incident solar radiation is calculated according to the seasonal angle of the sun and the window orientation. Then the absorptivity of each glass layer can be estimated using data from ASHRAE [17]. For a clear-clear-clear triple glazing unit, about 12% of solar radiation was absorbed by the outer pane, 8% by the middle pane, and 5% by the inner pane. Sky radiation from the window can also be considered as negative radiation. Finally, the total heat source from solar radiation or sink due to sky radiation for each pane can be determined.

Step 3: CFD simulation of window with added source/sink values

With the heat sources and sinks obtained in Steps 2(a) and (b) as additional input, radiation can be accounted for in the CFD model without directly using the computationally expensive discrete ordiantes model. The CFD simulation is used to calculate the glass pane and air temperatures for the dual-airflow window.

Step 4: Averaging temperatures from Steps 1 and 3 to obtain final temperatures

The glass pane and air temperatures obtained in Step 1 did not include radiation. The resulting temperatures used in Step 2 would over-predict in winter / under-predict in summer the radiation from the room enclosure to the window. This is because the calculation in Step 2 is based on temperatures that are higher/lower than the actual final temperatures present in the window system. On the other hand, the calculation in Step 3 would under-predict in winter / over-predict in summer the radiation from the room enclosure to the window for a similar reason. Due to the high nonlinearity present in these calculations, this study proposes to use the average glass pane and air temperatures obtained from Steps 1 and 3 as the final temperatures. Then the final temperatures can be expressed as a function of outdoor air temperature and can be used by an energy simulation program for hourly energy analysis of a building with such dual-airflow windows.

This four-step approach can greatly reduce the computing time compared with a direct coupling of the CFD program with an energy simulation program for hourly energy analysis. The approach can also greatly enhance the accuracy of the simulated results compared with an airflow network model.

4. Validation of the new computational method for dual-airflow window

Note that the new computer method is not purely CFD. The method seems more accurate than an airflow network model but it may not be as good as a pure CFD model. This is because the method involves CFD and coded calculations with some uncertainties. It is therefore essential to validate the new computational method.

This investigation has obtained flow and temperature data to validate the computational method through experimental measurements of a full-scale dual-airflow window. As shown in Fig. 5, the window was installed in an environmental chamber facility that was divided into indoor and outdoor chambers. The temperature and humidity of each chamber was controlled independently.

The measurements were performed for the forced convection (axial fan driven) supply mode under winter and summer conditions without solar radiation. The glazing area was 1.22 m high and 0.92 m wide. The triple layer construction was formed using double strength, clear glass with a thickness of 3 mm. A combination of omnidirectional anemometers and a tracer gas system using sulfur hexafluoride (SF_6) were used to obtain airflow through the two cavities formed between the three layers of glass.

Nine thermocouples were glued on one surface of each of the three panes of glass for a total of 27 surface temperature readings. There were two airflow inlets and two airflow outlets in the window system. Each had three thermocouples for inlet/outlet airflow temperature measurements, for a total of 12 airflow temperature readings.

The experiments were conducted for four different scenarios: winter (2°C outdoor / 22°C indoor temperatures) and summer (37°C outdoor / 24°C indoor temperatures) conditions with a 10 or 15 L/s flow rate through each cavity.

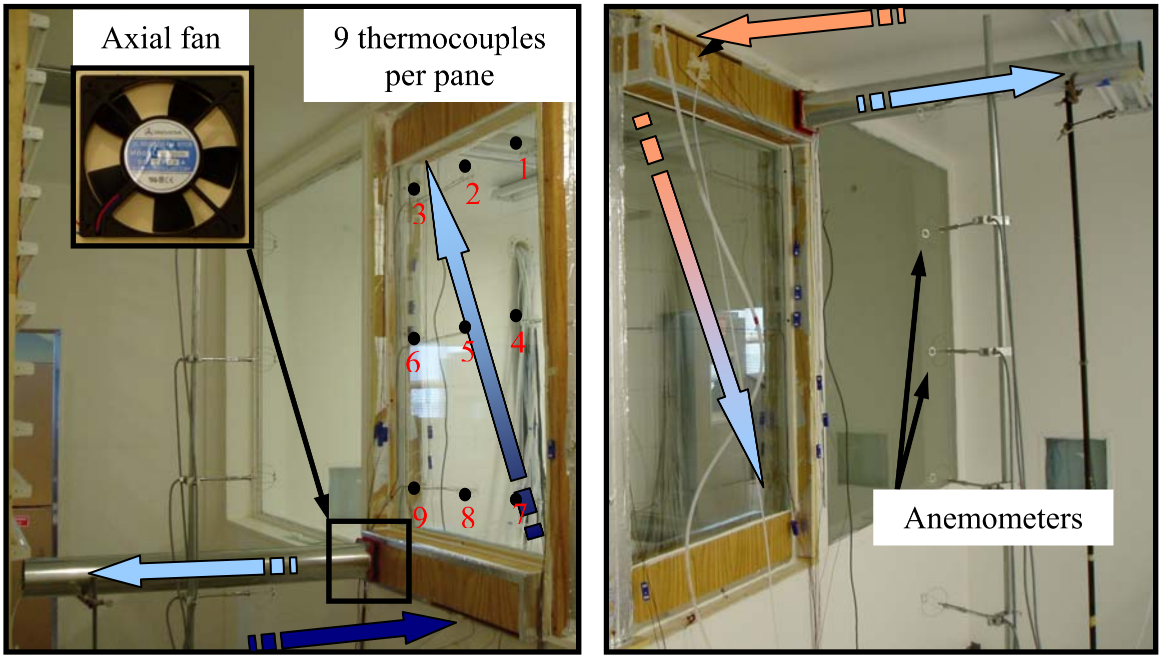


Fig. 5. Outdoor (left) and indoor perspective (right) of the experimental setup.

Fig. 6 shows experimental and simulated results for winter conditions with a flow rate of 15 L/s. The intersection of the vertical and horizontal lines on each pane of glass indicates the location of the thermocouples during experimental testing. Also, Pane 1 is the inner pane closest to the indoor space. The general temperature trends are similar between the experimental and simulated results. The agreement between the measured and computed results is very good. At the indoor and outdoor inlet locations, the glass pane temperatures are the highest and lowest, respectively. The temperature profiles on the inner and outer panes of glass follow the crossflow airflow patterns present in the window systems. The center pane has a more uniform temperature that is close to the average of the two incoming air stream temperatures.

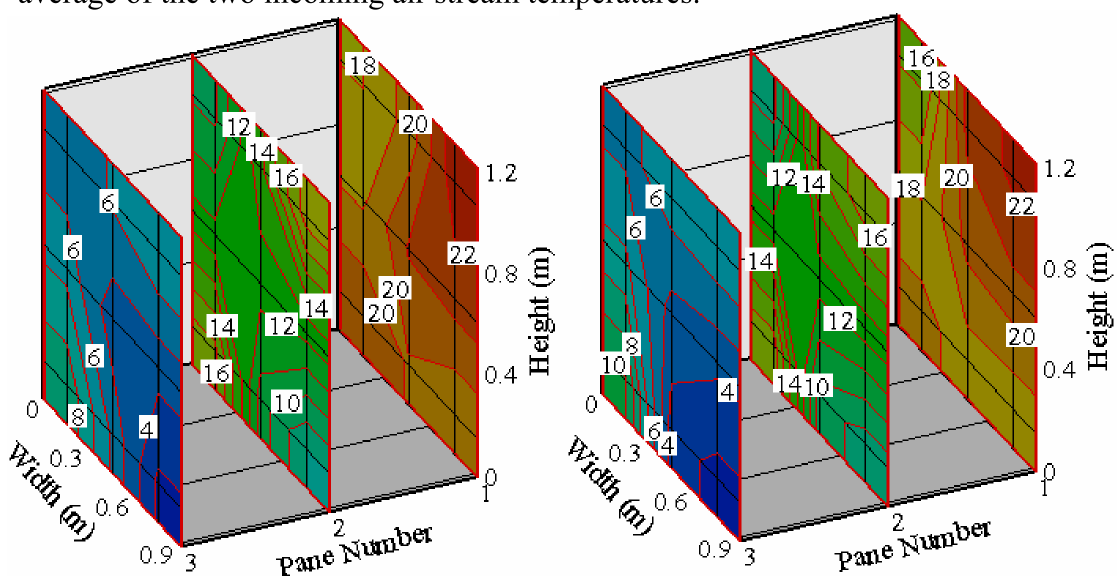
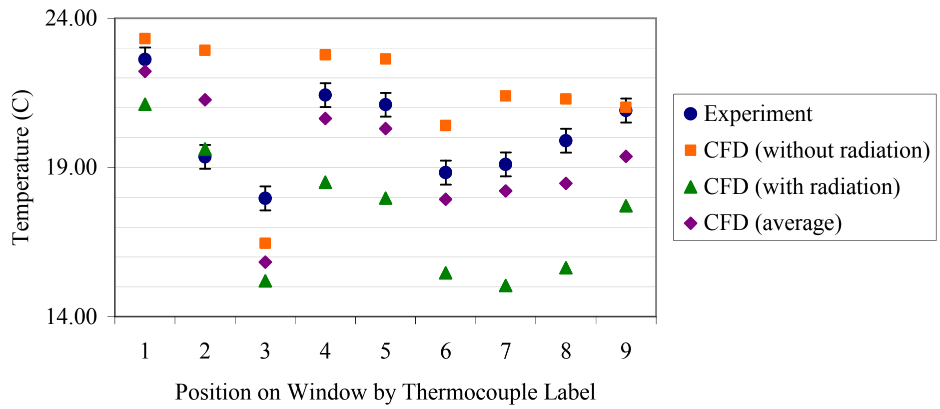
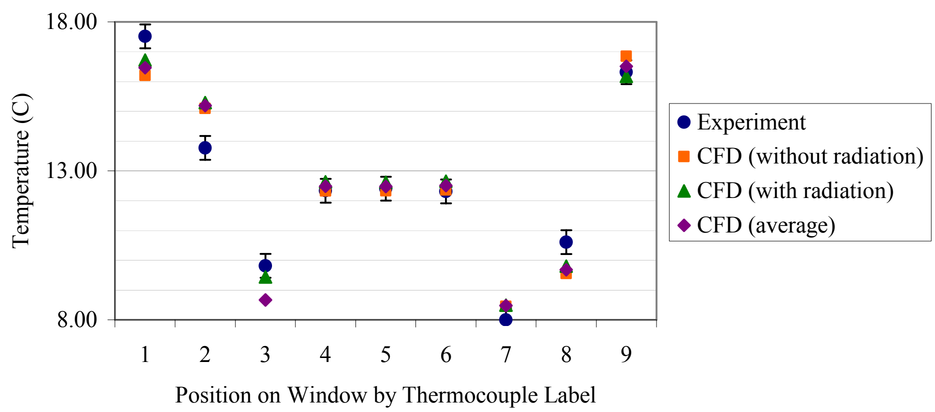


Fig. 6. Experimental (left) and computational (right) glass pane temperatures under the winter conditions with an airflow rate of 15 L/s (Pane 1 is the inner pane).

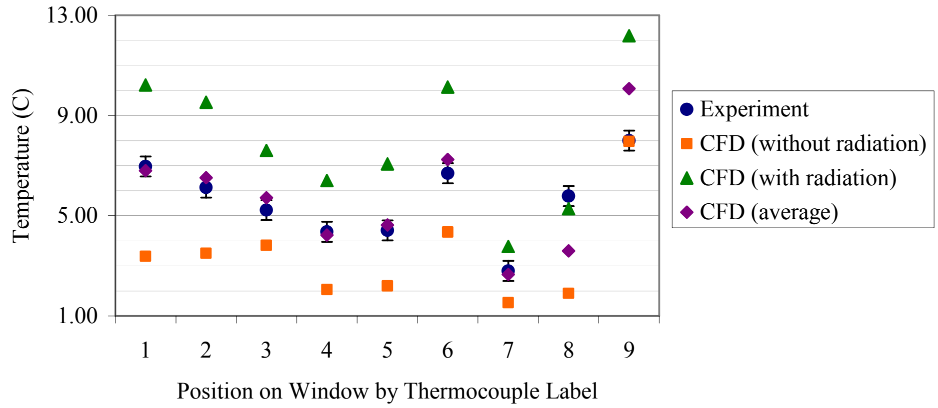
Fig. 7 gives a more detailed look at how the temperatures at each thermocouple location compare to each corresponding simulated temperature. The thermocouples are numbered in Figure 5. Each diagram plots the experimental data and three CFD results for simulations without radiation (Step 1), with radiation (Step 3), and the final averaged value (Step 4). Although the experiment does not include solar radiation, a CFD model without radiation proved to be insufficient for such an experimental case. As discussed in the previous section, Step 1 over-predicted the inner surface temperature and under-predicted the outer surface temperature. Step 3 was the opposite. The surface temperatures obtained at Step 4 show a deviation of no more than about 1 K for most of the places measured. By comparing the computed air temperatures at the exhausts with those measured, the difference again is very small (less than 1 K).



(a) Inner pane



(b) Middle pane



(c) Outer pane

Fig. 7. Comparison of the computed window pane temperatures with the experimental data measured in 9 different places for the winter conditions with an airflow rate of 15 L/s.

Similar results were found for the analysis of the winter conditions with a flow rate of 10 L/s and the summer conditions with a flow rate of 10 and 15 L/s. Fig. 8 shows the comparison for the summer condition with 10 L/s. For the range of temperatures under consideration in this study, an error of less than 1 K is small and tolerable. Thus, the proposed computational method is valid and can be used for energy analysis of a building with the dual-airflow windows.

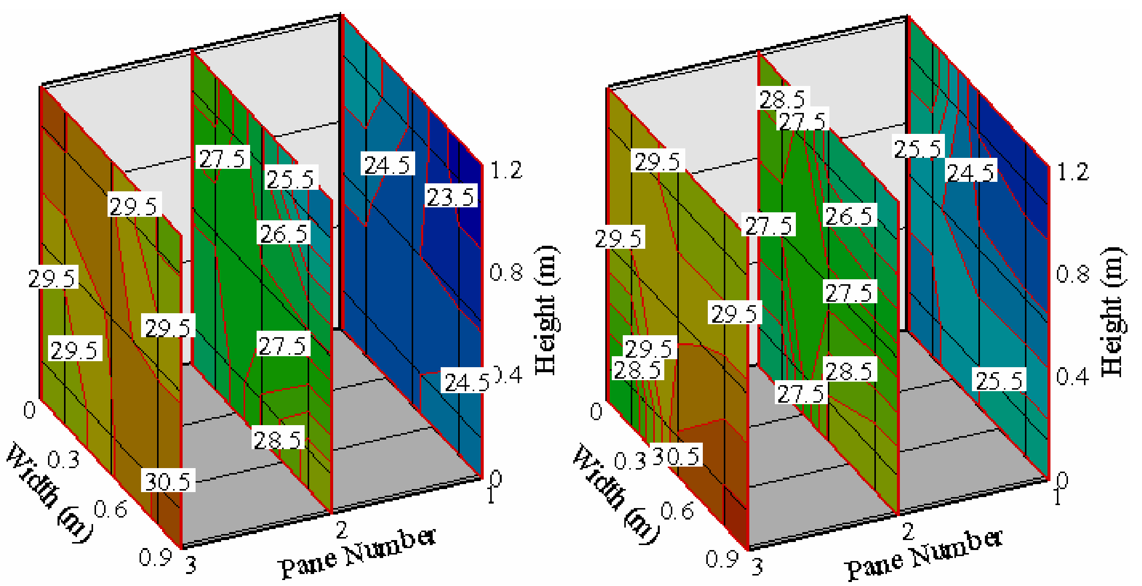


Fig. 8. Experimental (left) and computational (right) glass pane temperatures under the summer conditions with an airflow rate of 10 L/s (Pane 1 is the inner pane).

5. Conclusions

This paper proposes a new computational method that can calculate airflow through the cavities and air and glass pane temperatures of a dual-airflow window. The method first uses Computational Fluid Dynamics (CFD) to calculate flow and temperature without considering radiation. The time consuming discrete ordinates radiation model in CFD is replaced by a separate coded calculation that estimates surface-to-surface radiation and solar radiation. The radiative heat transfer calculated by the code calculation is set as heat sources or sinks in a second CFD simulation. The final results use the averaged CFD results with and without radiative heat transfer.

Due to the complexity and nonlinearity of the radiation exchange, the new computational method has been validated with experimental data from a full-scale, dual-airflow window under winter and summer conditions at different airflow rates. The difference between the computed air and surface temperatures and the measured data is generally less than 1 K. Thus, the new computational method is validated and is recommended for further use in hour-by-hour energy simulations by an energy simulation program.

Acknowledgement

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