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A Simplified Tool for Predicting the Thermal Behavior and the Energy Saving Potential of Ventilated Windows

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Abstract
Currently, the studies of ventilated windows mainly rely on complex fluid and thermal simulation software, which require extensive information, data and are very time consuming. The aim of this paper is to develop a simplified tool to assess the thermal behavior and energy performance of ventilated windows in the early design stage. The simplified tool is developed to treat different ventilation modes: pre-heating, self-cooling and by–pass, and an operational strategy is established to determine the most energy efficient mode in each time step. Cavity air temperature and energy demand are calculated based on hourly weather data. The accuracy of the simplified tool is validated by full-scale experiments and numerical simulation. In addition, a case study on a single family house with ventilated windows in the Danish climate is present. The results indicate that ventilated windows have apparently advantages over conventional windows on the indoor thermal comfort and energy saving.

Keywords - ventilated window, pre-heating, energy saving, thermal comfort

1. Introduction

The need for energy conservation and acceptable indoor environment in buildings leads to an interest toward new building envelope technology. Ventilated window is regarded as one of promising solutions, which can fulfill the needs for energy efficiency, thermal and visual comfort[1][2]. The ventilated window is composed of two parallel panes forming a cavity where airflow is passing through by means of mechanical or natural ventilation. It can achieve different thermal and energy performances depending on the origin and destination of air flow as well as the driving force[3]. In addition, the climatic conditions that the heat transfer and ventilation through window mainly depends on are highly dynamic. Therefore, the assessment of ventilated windows becomes a complicated task.

In the literatures, the studies of ventilated windows mainly relied on complex fluid and thermal simulation software. G. Flamant determined the energy performance of ventilated window by applying several software tools: WIS, CAPSOL, TRNSYS, etc.[4]. H. Manz developed a three level modeling approach by combining a spectral optical model, a CFD model and a building energy simulation model[5]. These simulations involve numerous parameters and extensive interactions between models, which are very time-consuming and require professional knowledge. In some other studies, researchers provide advanced mathematical models to evaluate the performance of ventilated window. K. Ismail investigated ventilated window under forced air flow conditions by a one dimensional unsteady model[6] and analyze a naturally ventilated window by a two-dimensional transient model[7]. J. Carlos created a mathematical model to predict air flow rate and temperature rise for specific operation conditions[8]. However, these models rarely couple with the building energy calculation.

This paper presents a simplified tool for predicting the thermal behavior and energy performance of ventilated windows. This tool is able to treat different ventilation modes and a control strategy is developed. The accuracy of the simplified tool is validated by well-validated software and full scale experiments. In addition, with the help of this tool, two ventilated windows with different glazing configurations are analyzed and compared with a closed cavity window in terms of cavity air temperature and their impact on the energy consumption of a single family house in Danish climate.

2. The background of ventilated window

The main characteristic of ventilated windows is that it is possible to regulate its thermal properties by adjusting ventilation mode, depending on indoor and outdoor conditions. As presented by O. Kalyanova [3], three basic modes are commonly used, named as pre-heating mode, self-cooling mode and by-pass mode.

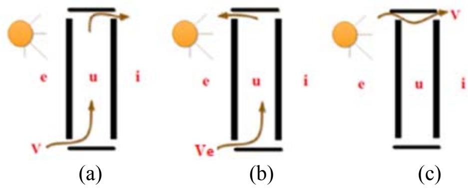

Fig.1 Schematic of ventilation mode of a ventilated window. (a) Pre-heating mode (b) Self-cooling mode (c) By-pass mode

In the pre-heating mode Fig. 1(a), outdoor air enters the cavity through the bottom opening and then is delivered to the indoor via the opening located at the top. This mode warms up outdoor air by the heat reclaimed from indoor and also by solar heat, and it is particularly used in the heating season. The air flow is normally driven by a fan-unit within the window. It is especially suitable for renovated buildings, where a ventilation heat recovery unit is not available.

While, in the self-cooling mode Fig. 1(b), outdoor air enters the cavity through the bottom opening and is expelled to the outdoor from the top. The air flow is driven by buoyancy and/or wind. This mode can remove surplus heat or solar heat gain from the window in cooling season. However, in order to fulfill the ventilation needs, the self-cooling mode needs to cooperate with a by-pass mode, where outdoor air is directly sent into the room through the window opening, Fig. 1(c). The by-pass mode can be driven by a fan-unit.

3. Methodology of the simplified tool

3.1 Definition of ventilated window properties

Different from conventional windows, the U-value of ventilated window is dynamic, which relies on ventilation modes and air flow rate through the cavity. In order to simplify the calculation process, the ventilated window glazing is separated into three individual parts: an external pane, a ventilated cavity and an internal pane. Window frame will be regarded as an individual building element and calculated separately.

The properties of each individual part (external pane, internal pane and frame) are calculated by WIS[10] under the steady state condition in terms of U, g and τ_e values (thermal, total solar and direct solar).

3.2 Estimation of air temperature and flow rate in the cavity

An characteristic of ventilated window is the airflow through the cavity. Distinction is made between different ventilation modes due to the origin and destination of the airflow. Consequently, different calculation approaches are developed for the cavity air temperature.

3.2.1 Pre-heating mode

Pre-heating mode is driven by mechanical ventilation, where a constant airflow is supplied into the room through the cavity to maintain an acceptable indoor air quality. The mean air temperature in the cavity ϑ_u can be calculated based on DIN V 18599 approach[11]. It is determined by the heat gains Φ_u into the cavity due to solar heat or internal heat source as well as the heat transferred from indoor and outdoor environment by ventilation and transmission. It can be estimated by (1):

$$\vartheta_u = \frac{\Phi_u + \vartheta_i (H_{T,iu} + H_{V,iu}) + \vartheta_e (H_{T,ue} + H_{V,ue})}{H_{T,iu} + H_{V,iu} + H_{T,ue} + H_{V,ue}} \qquad (1)$$

For ventilated windows presented in this paper, ventilation heat transfer coefficient between indoor and cavity $H_{V,iu}$ is zero. This means that no heat transfer from indoor to cavity via ventilation is predicted. While the heat transfer coefficient of ventilation between the window cavity and the outdoor, $H_{V,ue}$ is expressed as (2):

$$H_{V,ue} = \rho_a \cdot c_a \cdot V \qquad (2)$$

3.2.1 Self-cooling mode

The self-cooling mode is driven by natural ventilation, therefore, the airflow rate through the cavity is dynamic and depends on the weather conditions. A pressure-balance equation is adopted to evaluate the air velocity inside cavity. The pressure balance equates the buoyancy pressure acting on the cavity air to the pressure losses associated with cavity airflow between the inlet and outlet openings, as presented by Hellström [10].

$$\Delta P_{drive} = \Delta P_{loss} \quad (3)$$

$$\Delta P_{drive} = \frac{|\vartheta_u - \vartheta_e|}{T_e} \rho_a \cdot g \cdot H_{cav} \quad (4)$$

$$\Delta P_{loss} = \frac{1}{2} \cdot \xi_{tot} \cdot \rho_a \cdot v^2 \quad (5)$$

The mean air temperature in cavity ϑ_u can be derived as:

$$\vartheta_u = \vartheta_e + \left(\frac{H_{T,iu} \cdot (\vartheta_i - \vartheta_e) + \Phi_u}{h_v + (H_{T,iu} + H_{T,ue})/dT^{0,5}} \right)^{(2/3)} \quad (6)$$

$$h_v = f \cdot \rho_a \cdot c_a \cdot \Delta\vartheta_{rel} \cdot A_{cav} \cdot \left(\frac{2 \cdot g \cdot H_{cav}}{\vartheta_e \cdot \xi_{tot}} \right)^{0,5} \quad (7)$$

3.3 Coupling with building energy calculation

The main objective of this simplified tool is to estimate the energy saving potential by using ventilated windows. This step aims to link the window energy results to the building energy demand. The calculation method is based on EN/ISO 13790[12], where net heating and cooling demand is described by an energy balance of a building zone, by considering the elements transmission, ventilation losses as well as solar and internal heat gains. The referenced method is based on mean monthly values, which can gives correct results on an annual basis, but the results for individual months close to the beginning and the end of the heating and cooling season have large relative errors. In order to provide a more reliable prediction in the early design phase, it is possible to modify this method and perform the calculations on an hourly basis with application of an operational strategy.

The heat gains or heat losses through the ventilated window include heat flow from room to window by transmission, $Q_{tr,win}$; ventilation loss induced by air entering the room from the cavity, Q_{ve}; and also the solar heat gain transmitted into the room via the window, Q_{sol}.

$$Q_{tr,win} = Q_{tr,g} + Q_{tr,F} = U_{iu} \cdot (\vartheta_i - \vartheta_u) \cdot A_{iu} \cdot t + U_F \cdot (\vartheta_i - \vartheta_e) \cdot A_F \cdot t \quad (8)$$

$$Q_{ve} = \rho_a \cdot c_a \cdot V \cdot (\vartheta_i - \vartheta_{outlet}) \cdot t \quad (9)$$

$$Q_{sol} = F_{F,iu} \cdot A_{iu} \cdot g_{eff,iu} \cdot F_{F,ue} \cdot \tau_{e,ue} \cdot I_s \cdot t \quad (10)$$

Beside the heat gain/loss through the ventilated window, building energy demand is also influenced by heat transmission through other envelops $Q_{tr,other}$, such as wall, floor, roof, etc., and internal heat loads Q_{int}, such as heat release by occupants, equipment, etc. Thus, in each building zone, energy needs for heating and cooling are calculated by the total heat losses and heat gains. The utilization factor η is introduced to account for the interaction between building and systems, which is based on a quasi-steady-state method.

$$Q_{H,nd} = Q_{H,ls} - \eta_{H,gn} \cdot Q_{H,gn} \quad (11)$$

$$Q_{C,nd} = Q_{C,gn} - \eta_{C,ls} \cdot Q_{C,ls} \quad (12)$$

Where:

$$Q_{ls} = Q_{tr,win} + Q_{tr,other} + Q_{ve} \quad (13)$$

$$Q_{gn} = Q_{sol} + Q_{int} \quad (14)$$

3.4 Control strategy

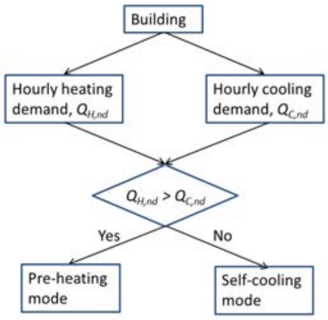

Fig.2 Control strategy of ventilation mode

Once the calculation method for building energy demands is defined, the final step is to determine the most energy efficient ventilation mode in each time step. Instead of defining a seasonal control strategy based on outdoor climate, a control strategy based on hourly energy performance is applied in this tool. This is because seasonal operational strategy normally neglects the impact of the changes on the outdoor temperature and solar radiation during a day and internal heat load variation in the building. Fig. 2 illustrates the control strategy of ventilation mode. The ventilation mode is based on the hourly energy demand in the building. If heating demand is the dominant, preheating mode will be applied. While, if cooling demand is the dominant in this hour, self-cooling combining with by-pass mode will be used.

4. Model validation

4.1 Description of window samples

Two ventilated windows and a closed cavity window are compared in terms of thermal behavior and building energy demand. In order to make different window configurations more comparable, all window samples have the same layers of glazing, coating as well as frame material. As shown in Fig. 3, Sample 1 is a ventilated window with double glazing facing outdoor and single glazing facing indoor, while, Sample 2 has single glazing facing outdoor and double glazing facing indoor. The reference closed cavity window has the same configuration as Sample 1, but the only difference is without ventilated cavity. All window samples have same dimensions of 1.48 m * 1.23 m. Due to the impact of ventilation through the cavity, the U-value and g-value of the ventilated window are dynamic. Therefore, the static U-value and g-value are calculated by dividing the window into an external pane and an internal pane. The properties of glazing are calculated by WIS in CEN mode, as shown in Table 1.

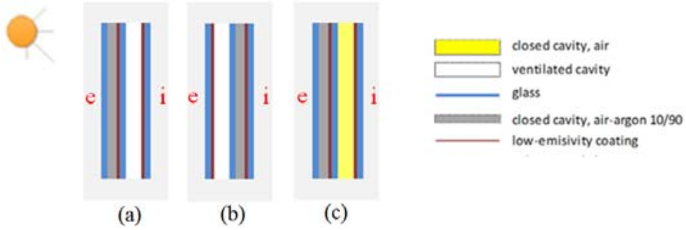

Fig. 3 Schematic of two ventilated windows and a closed cavity window (a) Ventilated window Sample 1; (b) Ventilated window Sample 2; (c) Reference closed cavity window

Table 1: Window properties

Window type	Transparent					Frame	Window (static stage)
	U_{ue}	U_{iu}	$\tau_{e,ue}$	$g_{eff,ue}$	$g_{eff,iu}$	U	U
Sample 1	1.29	5.73	0.526	0.63	0.635	1.01	0.95
Sample 2	3.24	1.29	0.59	0.625	0.63		
Reference	0.73		0.53				

4.2 Experimental study

The pre-heating effect of ventilated window is validated by measured results using Hot-box method. Sample 1 is chosen as a tested example, which is placed between a cold chamber and a hot chamber and exposes to an artificial sun (Fig. 4). The cold chamber simulates the outdoor environment with 0 ^{o}C and the hot chamber simulates the indoor environment with 20 ^{o}C. The air flow through the ventilated window is generated by a fan and keeps at a constant flow rate of 4 l/s. In addition, to avoid uneven temperature distribution of the chambers, recirculating fans are installed to provide fully mixed air distribution.

The artificial sun is built of 56 OSRAM Ultra-Vitalux300 W lamps, to simulate a clear sky condition with the solar radiation of 450 W/m^2. Two pyranometers are used to measure the solar radiation received on the external surface of the window and the solar radiation transmitted into the hot chamber. A aluminum plate painted into black is installed in the hot chamber just behind the window, in order to absorb the solar radiation. In addition, all the internal surfaces of hot chamber are painted into black. On the contrary, all internal surfaces of the cold chamber are covered with silver foil to highly reflect the solar radiation

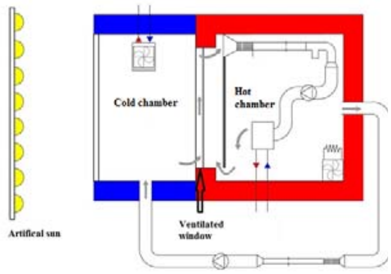

Fig. 4 Scheme of Hot Box set-up with artificial sun

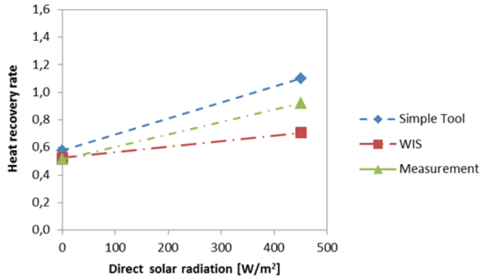

Fig. 5 Comparison of heat recovery rate of Sample 1 by different approaches

Special attention is paid on measuring the thermal performance of the window, including inlet and outlet air temperature of window as well as cavity air temperature. Silver coated thermocouples are placed in the top and bottom opening of window to avoid absorbance of radiation. A thermopile also used to measure the temperature difference of ventilated air. Cavity air temperatures are measured in five vertical levels (0.13 m, 0.43 m, 0.73 m, 1.03 m and 1.33 m).

Fig. 5 compares the heat recovery rates of Sample 1 determined by different approaches. Because the experiments are only conducted under two solar radiation intensities conditions (0 W/m^2 and 450 W/m^2), the comparison is limited to these two cases and may increase the uncertainty. In the condition without solar radiation the deviations between different approaches are less than 10%. However, in the condition with solar radiation, the results don't match well with each other. The simplified tool predicts the highest heat recovery rate of 1.1. While the results by WIS and measurements are 0.7 and 0.9, with deviations of 36% and 16%, respectively. The deviation can attribute to that all solar heat captured by the cavity is considered to preheat the ventilation air in the simplified tool. While in practice, a part of solar heat is used to heat the glazing and frame. Thus, the tool overestimates the effect of solar radiation on raising the air temperature through cavity, which also results in underestimation of draught risk closed to the window.

4.3 Numerical model

As only limited sets of weather conditions are studied by the full-scale experiment, numerical simulations by means of WIS is implemented to verify the accuracy of the tool in terms of cavity air temperature and heat recovery rate. The simulations by WIS are performed by defining the window configurations and the mean hourly environmental conditions. Two typical days in the Danish climate are analyzed, where the climate data are presented in Fig. 6. The reason for choosing these two days is to ensure that the validation cover both the pre-heating mode and the self-cooling mode.

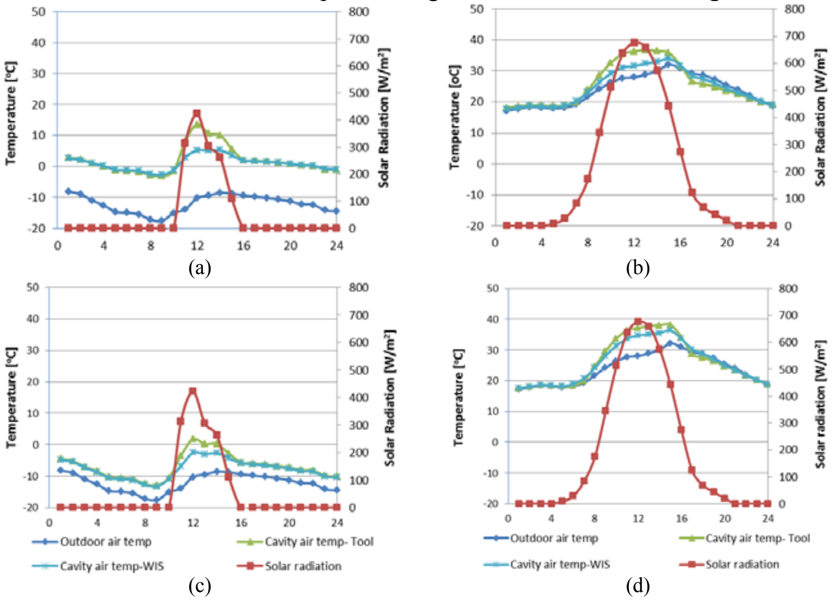

Fig. 6 Comparison of calculated cavity air temperatures by the developed Tool and WIS (a) Sample 1 in sunny winter (b) Sample 1 in sunny summer (c) Sample 2 in sunny winter (d) Sample 2 in sunny summer

Fig.6 represents the mean cavity air temperatures obtained by the simplified tool compared with the results by WIS simulation. It's clear that good agreements have been achieved in the conditions without solar radiation or with low solar radiation (less than 100 W/m^2), where the deviation is less than 1^{o}C for both ventilated window samples. However, when the solar radiation is strong, the simplified tool predicts higher cavity air temperatures than WIS. Furthermore, Fig.7 indicates that Sample 1 has a better performance on pre-heating of the ventilated air than Sample 2. In a sunny winter day, when incident solar radiation is maximum (422 W/m^2), the mean air temperature rise in the cavity is 15.5 ^{o}C for Sample 1, while for Sample 2 it is only 7.7 ^{o}C. During night, the cavity air temperature for Sample 1 is still 7 ^{o}C warmer than that of Sample 2. This indicates that double glazing facing outdoor efficiently prevents heat loss to outdoor during winter and most of the heat reclaimed from indoor use to pre-heat airflow through the cavity. During a sunny summer day, Sample 1 has slightly lower cavity air temperatures than Sample 2 during the day. However, the temperature difference is quite limited. This is because the external pane with higher thermal resistance reduces the transmission gain from the outdoor environment.

5. Case study

A single family house is chosen as a reference building (Fig. 7). The net volume of the heated zone is 375.1 m^3. There are 10 windows in this building, 4 facing south, 1 facing north, 3 facing west and 2 facing east. The airflow rate through each window is 4 l/s based on the minimum ventilation requirement of residential buildings. The overall heat transfer coefficients of the building elements are: external wall 0.28 $W/(m^2.K)$, roof 0.2$W/(m^2.K)$, external walls towards soil or wall towards unheated rooms 0.35 $W/(m^2.K)$ and external door 1.8 $W/(m^2.K)$. The set-point of indoor air temperature is 20 ^oC during the whole year. The other boundary conditions of the reference building are defined based on DIN V 18599[11].

Fig. 7 Picture of the one family house

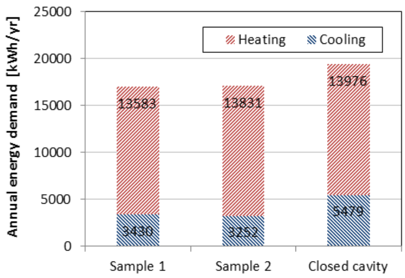

Fig. 8 Annual energy demand of reference building

Fig.8 shows the annual energy demand of the reference building in Danish Climate. It is clear that ventilated window Sample 1 is the most energy efficient solution, which saves 13% energy than closed cavity window. The energy saving potential of the ventilated window, Sample 2, is also significant, and requires 12% less energy than closed cavity window. It can be observed that Sample 1 is superior on reducing heating demand, while Sample 2 is superior on reducing cooling demand. However, the differences between these two ventilated window samples are limited.

6. Conclusions

A simplified tool has been developed to predict thermal behavior and energy performance of ventilated windows. This tool takes into account different ventilation modes, and an operational strategy is included to determine the most energy efficient mode based on an hourly energy demand.

The pre-heating effect of ventilated window is validated by measurement and numerical simulation. The results indicate that ventilated windows perform well on warm up outdoor air, which can significantly reduce draught risk in winter. In the case without solar radiation or with low solar radiation, a good agreement has been reached between the simplified tool and the other approaches. However, the major deviation occurs, when solar radiation is significant. Both WIS simulation results and measurement results indicate that the simplified tool overestimates the effect of solar radiation on increase the cavity air temperature. A loss coefficient taken into account the ratio of solar heat used to preheat the cavity air to the total solar radiation captured in the cavity should be investigated in the further study. Finally, the case study on a single family house indicates that ventilated windows have a remarkable energy saving potential than the closed cavity window.

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