Investigations of Stack Ventilation Operations Using An Energy Modelling And The Bas System

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Abstract

Green buildings have been intensively constructed due to energy crisis and damaged environmental issues. Additionally, a green building focuses on efficient resource utilization and reducing environmental damage. Mechanical designers emphasize solving energy problem issues in large commercial buildings via a stack ventilation application; it can be used to reduce cooling load and mechanical fan power consumptions. However, stack ventilation installation has been problematic due to Thailand climate, because heat is absorbed on the lower floor of a building causing higher temperature than upper floors; this issue obstructs buoyancy force. Without consideration of the concern, mechanical designers may misunderstand stack ventilation operations from its theory. To avoid the issue, this research applies the three software for assuring the performance composing of (1) LoopDA for stack ventilation simulation to acquire different temperatures for buoyancy force; (2) SketchUp for developing a simplified building configuration; and (3) TRNSYS used for full energy modelling with and without stack ventilation. The energy modelling is validated via the existing building automation system (BAS) data in the example building with the accuracy within ±10 %. The verified building model can be further used to test the stack ventilation operations via the potential simulation instead of sensor installations.

Keywords: Energy Modelling; Green Building; LoopDA; Stack Ventilation; TRNSYS

1. Introduction

Due to population growth, the number of buildings has been increasing continuously, causing inefficient energy use and affecting the more severe environment. That said, green building construction is, therefore increasingly expansive in developing countries because this building type is mainly designed to use efficient resources, reducing wastes, pollution and environmental destruction. One of the requirements in green buildings is the application of sustainable energy, which mechanical designers focus on reducing electrical energy consumptions of heating, ventilation and air conditioning (HVAC) systems, approximately 70 percent of the total electrical energy in large Thai buildings [1]. Natural ventilation is widely utilized to reduce the workload of air conditioning systems...
and mechanical fan ventilation called “stack ventilation”; it is an alternative way to reduce inside temperature of the building and to increase the effective electrical energy greatly, which uses the principle airlifting to create natural movement due to temperature differences [2, 3].

Since stack ventilation is a vertical airflow resulting from the differences between outdoor air temperatures and building interior temperatures, this system typically occurs when higher temperature difference causes lower air density; entering the air in the building will lift up and leave at any openings on the top of a building. However, in reality, it is unable to produce theoretical airflow, especially in tropical countries because a basement floor absorbs heat causing the temperature of a lower level to be higher than the top level of the building. Thus, the air cannot be lifted without buoyancy forces. In the design process, if designers neglect to consider this point, it may cause design errors. To reduce errors, energy simulation programs [4] and real-time measurement systems called building automation system (BAS) can be used to track the system performance from the design phase to the construction phase and throughout the building use. One of the programs used is called “LoopDA” that is not complicated and can be used to enhance and recheck typical design processes. This program can calculate pressure variations according to the height of a building as well as calculating the minimum temperature difference between the top and lowest levels of the building.

In order to solve the aforementioned problems, this article investigates the performance and behavior of a stack ventilation system in an example building. The methodology includes the following three steps: (1) simplified pressure and temperate differences are estimated by LoopDA program (NIST) [5]; this step is able to analyze the temperature differences between inside and outside the building. In addition, the optimum airflow rate is computed based on the possible size of the opening at the bottom and the top of the building (2) TRNSYS simulation studio is an energy modeling program used to create a building model including simplified zones, chiller plant system and building chimney. The model can simulate the airflow in the chimney, and (3) BAS of the building is used to obtain the actual zone temperature and humidity to validate the accuracy of the building simulation. The findings can be further used to assure the stack ventilation concept before construction.

2. Background

2.1 Stack Ventilation

The temperature differences between inside and outside of the building cause pressure differences; this causes natural airflow movements into the building called “Stack Effect” as depicted in Figure 1. This airflow can be used to reduce the temperature inside the building and can be used to reduce the electrical energy used in air conditioning systems [6]. The air pressure inside the building depends on a building height corresponding to the correlation as Equation (1):

$$\frac{dp}{dz} = -\rho g$$

Where z is the vertical height, \(\rho\) is the density and g is the gravity acceleration. Due to a relatively small change of density versus the height of the building, the density used in the equation is constant and \(p_0\) is defined as the pressure at the ground level.

$$p = p_0 - \rho g z$$

Figure 1. The airflow in summer and winter

Figure 2. Pressure direction versus height in winter
In the winter, the inside air on the ground floor of the building is typically higher than the outside. Thus, indoor air density is lower than the density at the higher-level resulting indifferent pressure between inside and outside. As a result, the airflow enters at the bottom and then leaves at the top of the building. In the summer, the flow direction is opposite to the winter because the inside air temperature on the ground floor is lower than outside temperatures leading to higher density and pressure than the outside conditions. Therefore, the outside air flows into the top of the building, and then leaves at the bottom of the building as shown in Figure 1.

From Figure 2, the pressure is varied according to the height of a building in which \( h \) is the neutral height, and is equal to half the height of the building; it can find the differential pressure between inside and outside building from Equation (3).

\[
\Delta p_s = p_A - p_z = (\rho_A - \rho_z) g(h - z)
\]  

In this equation, the pressure difference \( \Delta p_s \) of the opening is used to calculate the equilibrium balance pressure, and \( \rho \) is the density of air passing through openings. The pressure difference is caused by external wind when \( z \) is the height varied from the floor. The stack ventilation can be estimated by the following Equation:

\[
\Delta p_s = \rho_A \left( \frac{T_A - T_z}{T_z} \right) g(h - z)
\]  

When \( T_A \) is outside air temperature and \( T_Z \) is indoor air temperature, the computed pressure is used to determine the airflow direction of the building as shown in Figures 1 and 2.

2.2 LoopDa Program

LoopDA is a program used to design natural airflow developed by the National Institute of Standards and Technology (Dols et al. 2012). This program can determine the size of air outlets to achieve the desired airflow rate for stack ventilation. By using the method of creating air flow loops, an opening size depends on the pressure of the wind and the pressure of the stack effect. The steps are as follows:

1. Sketch a simplified building into the program in front or side view of the building.
2. Specify the outside temperature, air velocity and data in each zone including the type of opening in each zone and the details of any openings.
3. Draw airflow lines in each loop and consider the airflow rate in each loop based on the minimum required ventilation flow rate for and heat flow rate.
4. Consider the opening size with the graph obtained from the LoopDa simulation, and then check the flow rate from the simulation; the computed/calculated value must be close to the design value. A minimum desired airflow rate equation is related to the temperature of the air inlet and outlet as follows:

\[
Q_{cool} = \frac{UA_s(T_{ambt} - T_{dez}) + q_{int}A_f + q_{other}}{\rho C_p(T_{dez} - T_{ambt})}
\]

From Equation (5), the heat balance equation is generated between the air temperature of entering opening and exiting opening. The variables are as follows:

\( Q_{cool} \) is the airflow rate \( (m^3/s) \); \( U \) is the heat transfer coefficient for overall heat transfer through the surface; \( A_s \) is an envelope surface area \( (m^2) \); \( A_f \) is the outside surface area; \( T_{ambt} \) is the ambient
temperature of a building, $T_{des}$ is an opening design temperature (K); $\dot{q}_{int}$ is the internal heat gain per area (W/m²), and $\dot{q}_{other}$ is another internal heat.

In addition, the equation of the opening airflow rate ($Q_d$) can be computed by Equation (6) with differential pressure ($\Delta P_{wind}$) caused by the outside wind which can be determined by Equation (7).

$$Q_d = C_d A \sqrt{2 \Delta P / \rho} \quad (6)$$

$$\Delta P_{wind} = \frac{1}{2} \rho C_p u^2 \quad (7)$$

where $C_p$ is the pressure coefficient of the outside air passing through an opening, and $u$ is the wind velocity.

Based on the aforementioned equations, all variables of stack ventilation can be related in terms of the energy balance equation at steady state condition shown in Equation (8).

$$\sum_{\text{inlets}} m_j C_p T_j - \sum_{\text{outlets}} \dot{m}_i C_p T_i + U A_s (T_{ambt} - T_i) + \sum_{\text{heat sources}} \dot{q}_i = 0 \quad (8)$$

However, in real cases of the design process, one of the significant equations that designers practically forget to re-check is the equilibrium equation of the pressure balance, the total pressure in the zone which must be equal to the total released pressure:

$$\sum_{\text{unsized}} \Delta P_i = \Delta P_{stack} + \Delta P_{wind} - \sum_{\text{sized}} \Delta P_j \quad (9)$$

From Equation (6) to (10), $C_d$ is the discharge coefficient (m/s); $m$ is the mass flow rate through openings; $\Delta P_i$ is the unsized opening pressure (Pa); $\Delta P_j$ is differential pressure of specified openings (Pa); $\Delta P_{stack}$ is the pressure difference from the stack effect, and $\Delta P_{wind}$ is the pressure difference from the wind.

3. Methodology

3.1 LoopDA building model

The building example in Figure 3a) can be simplified into four zones (Figure 3b) including low-level office; high-level office; basement and the building chimney. This building can be created as a simple model on the SketchUp program as shown in Figure 3b) so as to study stack ventilation and wind through the chimney for reducing activity area load without using the air-conditioning system.
3.2 SketchUp building model
To simulate zone conditions of the example building, SketchUp model is required for assigning the connecting zones in TRNSYS program. The simple model with the dimensions consists of the two office zones, basement floor and the chimney as shown in Figure 3 b.

3.3 TRNSYS simulation model
The actual air-conditioning system components of the example building are simulated with TRNSYS program using the measured weather data from BAS ranged from 24°C to 35°C for the outdoor air temperature and the humidity range between 50 and 75% relative humidity as shown in Figure 4. This simulation model consists of (1) a cooling tower, three water-cool and normal water flow chiller units (2) two simplified cooling coils and constant air volume fans for the two office zones (3) three constant condensers and primary pumps (4) SketchUp model embedded into TRNSYS program, and (5) The measured weather data from the BAS of the building.

![Figure 4. TRNSYS model for the water-cool chiller system of the example building](image)

3.4 Validation of the example building model
The building simulation model using TRNSYS is validated via the data obtained the BAS of the building before installing the stack ventilation system. The test is scheduled Monday through to Friday, using the operation period and the actual opening and closing building information. Then, the validation of the model is conducted via the comparisons between the zone temperature and relative humidity of the BAS data and TRNSYS simulation.

3.5 Stack effect investigations
From the verified model, it can be used to further simulate airflow inside the chimney by using air flow data from LoopDA to investigate the stack effect instead of physical sensor installations due to cost-prohibitive and installation difficulty issues.
4. Results

4.1. LoopDa Program

Air-flow through the chimney is simulated with the wind speed at 3 m/s according to the design condition. Also, internal heat gain is 6000 W added (recommended value from a designer) to the top of the chimney in order to create sufficient stack pressure. By inserting the internal heat into each floor equally, heat flow at 2000W can create a layer of temperature in the chimney as shown in Figure 5.

4.2. BAS data

The measurement data of the example building can be downloaded from the BAS (Figure 6) using the web browser control. Indoor relative humidity and temperature of the tow zone offices including outdoor air data are from 121/0 2018/to 121/62018/.

4.3. TRNSYS model validation

In Figure 7, the temperature of the simulated model is compared to the actual BAS data; the maximum temperature difference is around 3.6°C and the minimum temperature difference is -1.8°C for the whole periods. However, if the work periods are considered only, the temperature differences are within ±5% errors, while relative humidity differences are within ±10%, which is accurate enough within ±15% according to ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) Guideline 14 [7] for measurement of energy saving applications.
4.4. Stack ventilation effect
The data of LoopData are used as the inputs of stack ventilation simulation in the building’s chimney. When comparing the zone temperature next to the chimney with wind velocity 3 m/s, there is the air flowing through the chimney causing the average office temperature to decrease by 0.2% from the original temperature (red-line in Figure 8). In terms of energy based on the equations in Ref [8], the enthalpy is 6900W, which is close to the energy obtained from the loopDA model on 6000W. The findings are the heat sources from 5500 to 6900 W required to incur natural stack ventilation in the chimney of the building.

5. Conclusion
The temperature layer in the chimney causes sufficient stack pressure to increase airflow according to the stack ventilation theory. The system development process in this research can be used to test the design of a stack ventilation system efficiently before the actual construction begins. However, real air-flow stack ventilation should be measured by physical sensors for leveraging building simulation platform for larger building systems.
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