SIMULATION OF THERMAL PERFORMANCE OF BUILDINGS INCORPORATING BREATHING WALL ELEMENTS

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ABSTRACT

The breathing wall combines the air transferring through porous media and heat exchange, and also acts as an air filter. Therefore it has the advantage of supplying ventilation air to the building with less energy consumption. This paper presents an investigation into the thermal performance of buildings incorporating breathing wall elements, using the commercial software package TRNSYS. Annual energy consumption of the building, under an hourly changed environment temperature condition, is obtained. For the purpose of supplying guidelines for the implementation of breathing walls, simulations are performed under a range of air flow rates, with the variation of insulation thickness, as well as the ratio of breathing wall to normal wall. The simulation results show that energy consumption of building incorporated with breathing wall element is reduced due to the fact that the wall has been transformed into an air supplying ventilator and heat recovery device. The study also illustrates that the thermal performance of the breathing wall is directly influenced by air flow rate. For the whole range of air velocities in the simulation, which are 0.0002m/s to 0.00125m/s, the difference of energy saving extent is 6%~12%. The energy saving will be even smaller when considering the possible increase of fan power, because the pressure gradient is higher in the building with breathing wall. Therefore, to make the technique of breathing wall more applicable, further study is needed to combine this technique with natural ventilation.

INTRODUCTION

A breathing wall is a porous wall that acts as a heat exchanger. When air transfers through the dynamic insulated wall, it exchanges heat with solid matrix of the wall. So in winter, the air passing through the wall is warmed before entering the indoor space (and it is cooled in summer), and the amount of warming or cooling depends on such factors as the air velocity, the configuration of the wall, and the path the air takes through the wall.

This treatment of exterior walls as heat exchangers has the potential to increase or maintain the air change rate in the space, while decreasing the building's energy consumption. Of course, it is not a free lunch, since the act of heating the air as it passes through the wall also works to cool the wall, and affects its performance. To analyse the performance of a dynamic insulated wall requires that one use an approach that is different than the conventional approach to analysing wall performance.

By the 'conventional approach', we mean the manner of analysis which separates the heat loss through the envelope into 'infiltration heat loss' and 'conduction heat loss'. The 'infiltration heat loss' considers the infiltration or exfiltration of air through cracks or gaps in the envelope, and assumes that no heat transfer occurs between the air passing through the crack and the solid of the envelope surrounding that crack. This assumption is usually justified if the path through the envelope is fairly direct and the air velocity is sufficiently high. However, a dynamic insulated wall is designed to ensure a longer, more diffuse, air path through the wall, and a slow air velocity, so this assumption cannot be used. The 'conduction heat loss' in the conventional case also does not consider the effect of heat transfer with air passing through it, which again cannot be used in the analysis of a dynamic insulated wall.

As discussed in the next section, analytical techniques have been developed for breathing walls. This paper discusses the basic principles and governing equations, and works toward ways of implementing these principles and equations into TRNSYS building simulation program. A simple approach is presented here (applicable only for fan-powered air flow through the wall), along with simulation results, and a more detailed approach is discussed (which could also consider such possibilities as using natural ventilation principles to power the air flow through the wall).

There is currently a strong need for the integration of this analysis of dynamic insulated walls into building simulation programs, so that building designers can more easily consider this technology, which is just now beginning to enter the marketplace (for example, the dynamic insulation product Energy*flo*™ cell has been developed by The Environmental Building Partnership Limited, United Kingdom). This is a technology with promise in terms of energy savings (experimental results of 7-14% energy savings were reported by Baily (1987), and simulation results by Krarti (1994) suggest savings of up to 20%). And depending on the wall configuration and use, it may also be of benefit to the indoor air quality – it may allow for higher air change rates, and the wall itself can act as an air filter (Taylor et al., 1999).

In dynamic insulation, air can also be directed through the wall through a combination of air cavities, such as in the structure presented by Chebil et al (2003). Comparatively, the breathing wall is easier to implement. From the point of view of theoretical analysis, the air cavity combination structure needs a two or three dimensional simulation, while the in breathing wall structure the air flow is mainly one dimensional. In this paper, the simulation and analysis is carried out only for the breathing wall structure.

THEORETICAL ANALYSIS OF DYNAMIC INSULATED WALLS

Heat transfer in the breathing wall

In the conventional approach of estimating heat loss through the wall, the process of conduction and infiltration are separated. However, when air flows through the wall, the temperature profile changes because of the heat exchange between the air and the solid matrix of the wall, which means the conduction and infiltration are coupled in the actual situation. Thus, it is pointed out in the literature that the conventional method actually overestimates the real heat loss (Bhattacharyya and Claridge, 1995). This is called 'infiltration heat recovery'. Generally, at normal infiltration rates, the infiltration heat recovery efficiency is about 5-20%, according to the numerical simulation results (Qiu and Haghighat, 2005).

The model of heat transfer in porous materials is generally based on a two media treatment, in which considers the heat transfer in each phase and the interaction between them. However, if the air flow rate is very low, then a one-medium treatment can be used. This treatment assumes that within the wall, the air phase and the solid matrix are under the same temperature. In the breathing wall, the air velocity range is usually from 0.0005m/s to 0.005m/s. Even considering a higher air flow velocity in the study of infiltration heat recovery in the normal wall, a CFD simulation of the heat exchange between air and solid matrix demonstrated that as the airflow deepen into the insulation, its temperature increases rapidly and eventually becomes very close to the solid matrix temperature at a very short distance (about 5×10^{-5}m) (Buchanan and Sherman, 2000). Therefore, the one-phase assumption can be used with only a small error.

One of the basic considerations in the current design of a breathing wall is to ensure that air uniformly transfers through the wall (Dimoudi, et al, 2004). Therefore heat transfer process in the breathing wall can be described using the one dimensional model as follows (Kaviany, 1995):

$$(\varepsilon\rho_a C_{pa} + (1-\varepsilon)\rho_s C_{ps})\frac{dT}{dt} + u\rho_a C_{pa}\frac{dT}{dx} = k_{eff}\frac{d^2T}{dx^2} \quad (1)$$

Where T is temperature, ε is the porosity of the porous material, ρ_a and C_{pa} are the density and specific heat of the air, ρ_s and C_{ps} are the density and specific heat of the solid matrix, and u is the velocity of the air flow. The effective thermal conductivity of the porous media k_{eff} , which changes with the porosity value, is calculated as:

$$k_{eff} = \varepsilon k_a + (1-\varepsilon)k_s \quad (2)$$

Where k_a is the thermal conductivity of air, k_s is the thermal conductivity of the solid matrix.

By performing a numerical solution for equation (1), it is found that the temperature profile in the wall will reach steady state within 1 hour, if ε is greater than 0.9. Therefore in the case of high porosity, the influence of the unsteady term in equation (1) is limited and can be neglected. This means that the hourly changed environment temperature, which is generally considered in the building simulation, has little influence to the result in this study.

Under the steady state condition, by setting the exterior and interior surface temperature equal to the outdoor and indoor temperature, an analytical solution can be obtained for equation (1). Based on it, the dynamic U-value is derived as follows to represent the conductive heat transfer in the breathing wall:

$$U_{dyn} = \frac{Pe}{R(e^{Pe}-1)} \quad (3)$$

Where R is the effective thermal resistance of insulation material in the static condition, and the

Peclet number Pe is defined as follows:

$$Pe = \frac{u\rho_a C_{pa} L}{k_{eff}} \qquad (4)$$

Where L is the thickness of the breathing wall.

The dynamic U-value will be used in the simulation of thermal performance of breathing wall.

Heat balance approach for the overall thermal performance of the breathing wall

As would be expected, the U_{dyn} value approaches to the static U-value of the wall as the air velocity through the wall approaches zero. Its value decreases with the air velocity. However, this does not mean that with the increase of air velocity, the heat loss through the wall will reduce. As a matter of fact, U_{dyn} only expresses only a smaller part of the heat loss in most of the velocity conditions.

Therefore a model is presented considering the combined heat loss of conduction and ventilation in the breathing wall. As there is no heat source in the wall, the total heat flux at any surface across the wall will not change. Corresponding with the derivation of U_{dyn}, the condition at exterior surface is studied. At this surface, the overall heat transfer rate is:

$$\begin{aligned} Q_T &= Q_{cond} + Q_{vent} \\ &= U_{dyn} A\Delta T + \dot{m} C_p \Delta T \qquad (5) \\ &= U_{dyn} A\Delta T + u\rho_a C_{pa} A\Delta T \end{aligned}$$

Where $\dot{m}$ is the mass flow rate through the breathing wall, and A is the area of the wall. From equation (5), an overall heat transfer coeffecient can be deived as

$$\begin{aligned} U_T &= Q_T /(A\Delta T) \\ &= \frac{Pe}{R(e^{Pe} - 1)} + \rho_a u C_{pa} \qquad (6) \\ &= \frac{Pe}{R(e^{pe} - 1)} + \frac{Pe}{R} \end{aligned}$$

The overall heat loss coefficient is related to the static thermal resistance of the wall, as well as the *Pe* number. It is convenient to use this coefficient to analyze the thermal performance of the breathing wall, and the performance of the building incorporated with breathing wall elements.

Figure 1 is the variation of overall heat loss coefficient with the velocity, considering the thickness of the breathing wall as 0.1m or 0.2m, respectively. It can be seen that the overall heat transfer is determined by the air flow rate. When air velocity is zero, the overall heat transfer coefficient is equal to the static U-value of the wall. With the increase of air velocity, the total heat loss through the wall increases. The figure also shows that the results on the condition of wall thickness being 0.1m or 0.2m almost overlap. Thus the influence of thickness to the overall thermal performance of the breathing wall can be ignored. This implies that one advantage of a breathing wall is that it is possible to reduce the energy consumption with less building material.

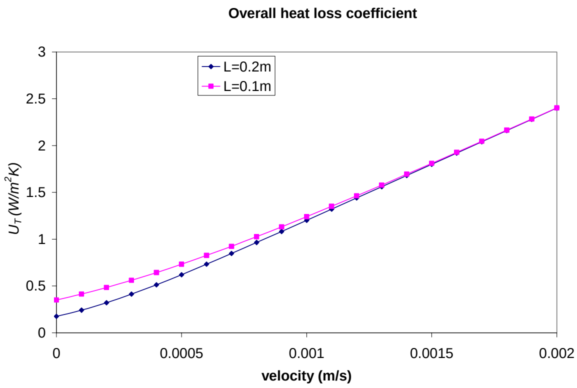


Figure 1. Overall heat loss coefficient of breathing wall

The results of overall heat transfer coefficient obtained by equation (6) are compared with the experimental data from Baker (2003). In his measurement, a 0.17m cellulose fibre insulation breathing wall construction is adopted. To correspond with the analytical model, the overall heat transfer coefficients from the experiment, including both conduction and ventilation heat loss, are used. The results from the analytical model and experiment are illustrated in Fig 2. We can see that these results agree very well. Thus the analytical model can predict the energy consumption of the breathing wall with a good precision.

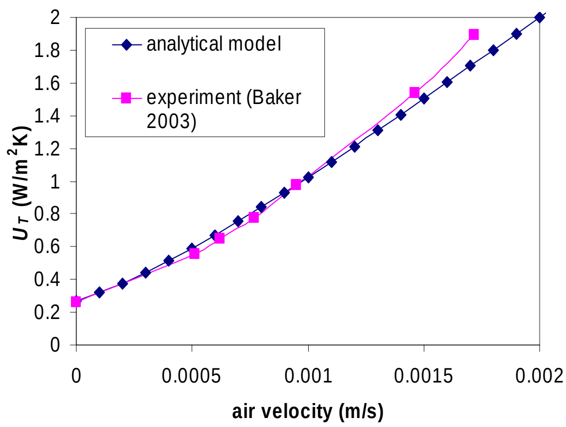


Figure 2. Comparison of results of analytical model and experimental data

TRNSYS SIMULATIONS INCLUDING A BREATHING WALL WITH CONSTANT FLOW RATE

A simple building model was constructed for demonstration using the Type 56 (Detailed Multi-Zone Building) module in TRNSYS. It represents a single-room building, $4.5m^2$ by 2.5 m high. A $0.6m^2$ single glass window is inserted in the south wall. It is also assumed there is one person in the room. Two variations of this model were used – one composed entirely of standard wall constructions, and the other with a breathing wall on the west façade.

It was assumed that both buildings were built with tight construction, so only a small amount of air could infiltrate or exfiltrate through cracks (the infiltration rate in the Type 56 model was set to 0.1 ACH in both models). In the model without a breathing wall, ventilation air is brought in through a duct and heated or cooled within the space (the ventilation rate in the Type 56 model was set according to the desired air-change rate being tested for, and the ventilation temperature was set to the outdoor air temperature). The conductive heat transfer for each wall was determined by using a standard wall type, including 0.2m brick, 0.1m or 0.2m insulation layer, and 0.01m plasterboard as interior surface.

In the model with a breathing wall, it was assumed that there would still be some air flow through direct cracks at the wall joints, so the infiltration rate (which assumes no heat transfer between the wall and the air passing through it) was kept the same as in the other model. However, in considering the slower air passage through the porous matrix of the breathing wall, the model uses the 'dynamic *U*-value' discussed above to account for the conductive heat losses through the breathing wall. The ventilation air temperature in the Type 56 model was also set to the outdoor air temperature, thus the ventilation heat loss is the same as the other model. The wall type for the west façade was changed to a wall whose dynamic *U*-value is determined by the equation (3). This was achieved by defining a new mass-less wall element in the TRNSYS library.

The simulations were carried out for different air change rates for the building. Modifying the air change rate in the normal-wall building model was simply done by changing the ventilation rate. For the breathing wall building model, an increase in the air change rate requires an increase in the air velocity through the wall, which alters the 'dynamic *U*-value'.

The requirement of ventilation for this simple building is considered to be in the range of 0.2 ACH to 1.0 ACH. According the volume of the room, the air velocity through the wall is from 0.00025m/s to 0.00125m/s. A series of velocities in this range is input to equation (3) to calculate the corresponding dynamic *U*-values used in the simulation. These air velocities with their associated ventilation rates, and U_{dyn} values are illustrated in Table 1.

Table 1
Heat transfer coefficients for the breathing wall

AIR VELOCITY (m/s)	**ACH** (1/h)	**0.2m INSULATION** U_{dyn} (W/m^2)	**0.1m INSULATION** U_{dyn} (W/m^2)
0.00025	0.2	0.20	0.056
0.0005	0.4	0.112	0.015
0.00075	0.6	0.060	0.0035
0.0001	0.8	0.031	7.4E-4
0.00125	1.0	0.015	1.5e-4

The simulation is carried for the whole year period. The indoor temperature is set up as constant and is 22ºC, while the outdoor temperature is determined by the weather data of Madison, WI, the United States.

In the simulation, it is assumed that the exterior surface temperature of the breathing wall equals to the outdoor temperature, as air is constantly transferring through it. There might be a small error of this treatment if long wave radiation is considered. However, it is assumed that this change is small enough that it can be safely ignored in our first-pass model.

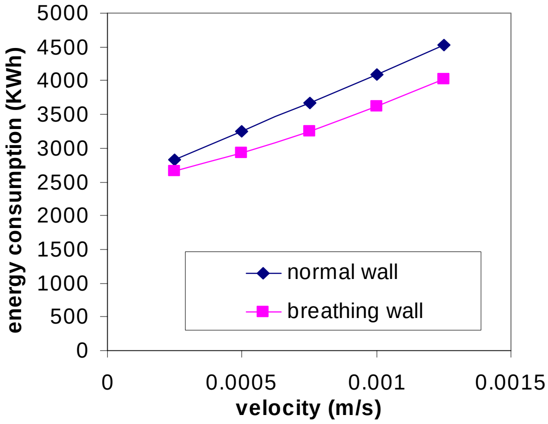
In the current simulation, the energy consumption of fan is not included. However, as pressure gradient increases in the buildings which install breathing wall elements, the fan power used for will also increases. Further study will be conducted considering this.

RESULTS AND DISCUSSION

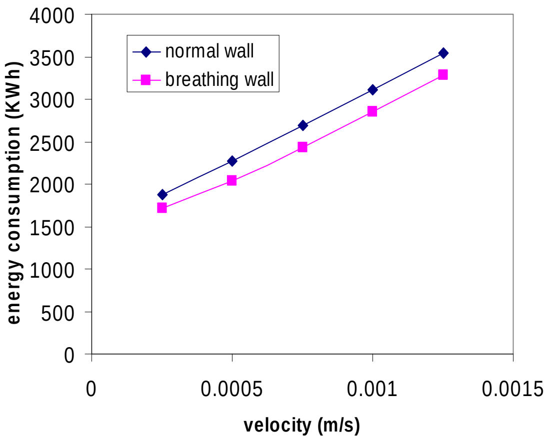
Energy saving of breathing walls

By performing the simulation using TRNSYS, the energy consumption of the building under each condition can be obtained. Results are analyzed concerning the following aspects:

- Total energy consumption of the building with or without breathing wall
- Percentage of energy savings by using breathing wall element
- Advantages of the implementation of breathing wall



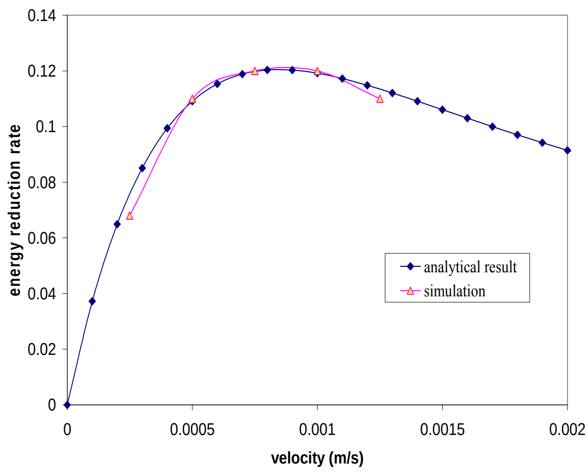
(a) Walls with 0.1m insulation



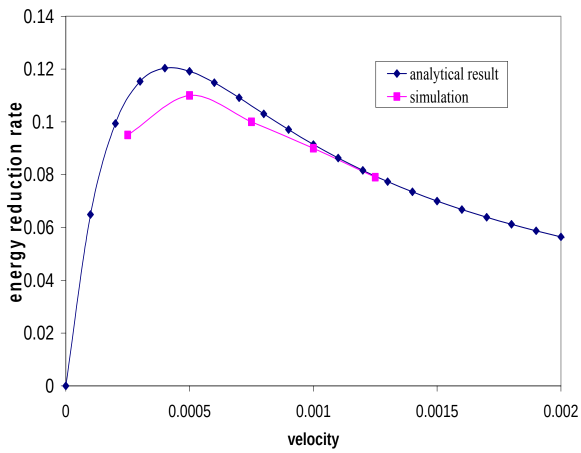
(b) Walls with 0.2m insulation

Figure 3 Energy consumption

Figure 3 illustrates the annual energy consumption of the building with normal walls only, and that of building whose west wall is breathing wall, with the insulation being 0.1m or 0.2m thick, separately. Results in these two figures show that similar with the result of the building with normal walls only, the energy consumption of the building incorporating breathing wall elements increases almost linearly with the air flow rate. It can also be noticed that under each air flow rate, energy can be saved by using breathing wall in the buildings. With the increase of air flow rate, the difference of energy consumption for the building with normal walls only and that incorporating breathing wall increases, especially for the condition that the insulation is 0.1m.



(a) Walls with 0.1m insulation



(b) Walls with 0.2m insulation

Figure4 Energy reduction rate

Figure 4 illustrates the energy reduction rate of breathing wall with an insulation thickness of 0.1m or 0.2m, obtained by TRNSYS simulation. The results show that the energy reduction rate is higher if 0.1m insulation is adopted in the normal wall and in the breathing wall. The energy saving extent under this condition is about 10% -12% at most of the air flow rates. Comparatively, if the 0.2m insulation is used in the normal wall and in the breathing wall, then the energy reduction extent is lower, being 8%-11% for the velocities higher than 0.00025m/s. Meanwhile, under each insulation thickness, there is a range of the velocities that has the highest energy reduction rate. For example, for the 0.1m insulation condition, the optimum velocity for energy saving is about 0.001m/s, while for the 0.2m insulation condition this velocity value is about 0.0005m/s. However, besides the results of very low velocities, the difference of energy reducing extent is within 5% over a wide range of velocities.

To verify the idea of using TRNSYS to simulate the thermal performance of the breathing wall, the energy saving capability, obtained by comparing the overall the heat transfer coefficient of the breathing wall and the *U*-value of the normal wall, is also shown in the figure. It can be seen from the figure that the simulation results agree well with the above analytical results.

When it comes to the application of breathing wall elements, there might be problems to have the wall completely use breathing wall elements, due to other restrictions, such as the structure requirement. Parts of the wall may still be the normal wall. This will affect the efficiency of the breathing wall. Figure 5 shows the energy reduction rate of building under the following two conditions: (1) the west wall completely uses breathing wall elements, (2) 50% area of the west wall is breathing wall elements. It can be seen that if the breathing wall only accounts for 50% of the west wall, then the energy saving capability reduces to only one half of it is under the condition that the west wall completely incorporating the breathing wall elements.

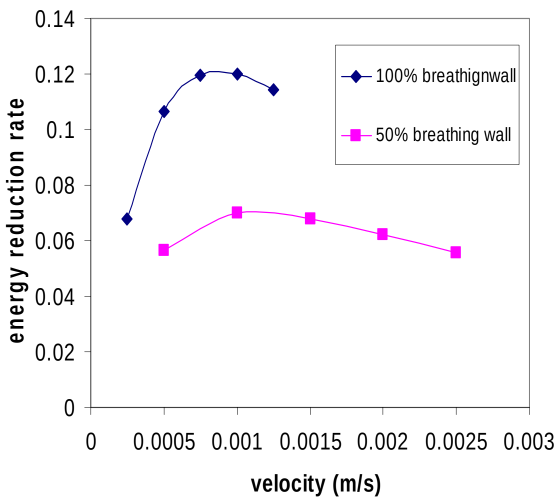


Figure 5 Influence of ratio of breathing wall to normal wall

Figure 6 shows the ability of energy reduction compared with building only having 0.1m insulation normal walls, by increasing the insulation thickness to 0.2m, or using 0.1m breathing wall element, respectively. It can be seen that at a higher velocity range, for example over 0.001m/s in this study, energy saving by using thinner breathing wall elements can reach almost half of that obtained by increasing the wall insulation to 0.2m. This means that concerning the energy consumption and reducing construction cost at the same time, one advantage of the application of breathing wall is that it is possible to achieve energy saving by using less building material.

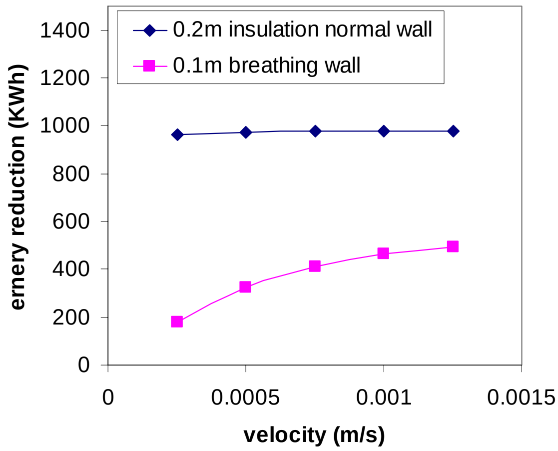


Figure 6 Energy reduction by increasing wall thickness and using dynamic insulation

Combining the dynamic insulation with natural ventilation

The simulation above shows that the overall energy saving by applying breathing wall is about 6-12%, in most of the air flow conditions. This is less attractive for the implementation if a fan is operating all the time, as the fan power might increase as discussed previously. One possible option is to combine this technique with natural ventilation, or hybrid ventilation, taking the advantage of pressure gradient by wind and stack effect (Etheridge and Zhang, 1998).

Therefore, it is necessary to investigate if it is possible to combine the technique of breathing wall with natural ventilation. As the air flow velocity in the building wall is very slow, it is in the Darcy's regime. The air velocity is related to the pressure gradient according to Darcy's law. It is easy to find that the required pressure gradient for breathing wall can be provided by natural factors, if it is applied to a small residential building and the material of the insulation is properly selected, i.e., under the condition that the air permeability of the material be greater than the magnitude of $10^{-9}m^2$.

However, the simulation results in this study demonstrate that the energy consumption of building incorporating breathing wall elements is directly connected with the ventilation rate, thus the heat loss might increase dramatically under the condition of strong wind, if the natural ventilation is adopted. Therefore, the system needs to be carefully designed to control the heat loss. This needs to be further studied in the future.

CONCLUSION

This paper presents an investigation of thermal performance of buildings incorporating breathing wall elements. The results and analysis achieve the following conclusions:

1. The heat loss coefficients obtained by the one dimensional analytical model can be applied in the engineering implementation;
2. Building simulation tools, such as TRNSYS, can be used to study the thermal performance of buildings incorporating breathing wall elements;
3. Generally, the energy saving by using breathing wall elements is less than 15%. The energy saving extent could be even smaller because of the possible fan power increase;
4. Combining the breathing wall with natural ventilation is the possible option to overcome the problem of the fan power increase. However, it also meets with the problem of the dramatic increase of heat loss under the strong wind condition.

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