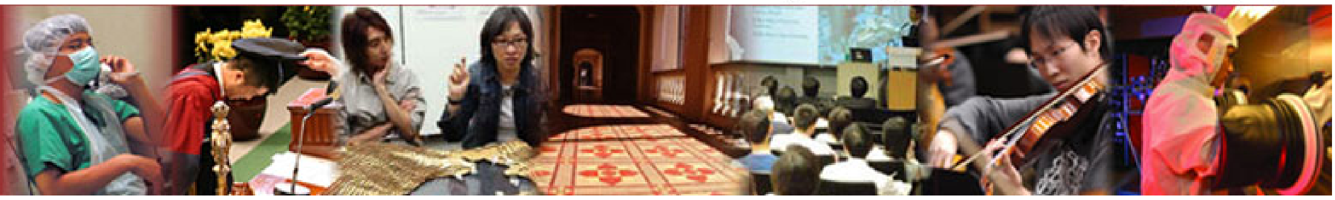

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A MATHEMATICAL MODEL FOR A HOUSE INTEGRATED WITH AN ELEVATED CHINESE KANG HEATING SYSTEM

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ABSTRACT

Chinese kang, a potentially energy-efficient domestic heating system in China, uses high thermal mass to store surplus heat from the stove during cooking and releases it later for space heating. In this paper a preliminary mathematical model is developed for a House Integrated with an Elevated Kang system (HIEK). This model considers the transient thermal behaviors of building envelope, kang system and indoor air. The macroscopic approach is used to model the thermal and airflow process for the elevated kang system. The numerical method for solving the resultant non-linear equations of HIEK is proposed and implemented. The HIEK model is preliminarily evaluated using the measured data from a field survey, and agreement is reasonably good. This model can be used to predict the indoor air temperature for multi-zone HIEK by inputting the basic parameters like geometry, physical properties of building and kang. The model can be easily extended for investigating the thermal performance of a kang system and its influence on indoor thermal environment and building energy consumption. Finally, suggestions for incorporating the kang model into existing building simulation tools are also described.

KEYWORDS

Chinese elevated kang, Building energy simulation, Natural ventilation, Thermal mass storage.

INTRODUCTION

With the rapid economical development and urbanization in China, the living environment of people in rural areas has received increasing attention. In Northern China, Chinese kangs have been used for home heating for more than 2,500 years (Men 2004). Chinese kang, a potentially energy-efficient domestic heating system, uses high thermal mass to store surplus heat from the stove during cooking and release it later for space heating. It's an integrated system also for sleeping and ventilation, and has been widely used by rural families in Northern China. It was estimated that there were 66.85 million Chinese kangs used by 43.64 million rural families in 2004.

Meanwhile, home heating consumes the majority of the energy used in rural areas in Northern China. It is expected that the energy consumption for home heating in rural areas will continue to rise due to the rising living standard. There is also a trend for some farmers to replace the traditional kangs with modern beds combined with other heating systems, such as a radiator system using a small furnace and coal. If all the families followed this way, it may become very difficult to afford such large energy demand in China in the near future. One of the alternatives is to improve and even renovate the existing available heating techniques, and the kang is just one of them. Investigations have shown the strong potential of energy-saving while providing a comfortable indoor thermal environment by the elevated kang, the latest design of kang (Chen et al. 2007).

However, Chinese kangs have slowly evolved largely by accumulation of experience, and there are few theories or any scientific basis on which a kang heating system can be suitably designed. In order to establish a principle-based design approach, we analyzed the airflow and thermal storage characteristics of kang. But questions like how the elevated kang influences indoor environment and/or building energy consumption are unknown and have not been scientifically studied. Therefore, transient approaches appear essential to evaluate the thermal performance of such a building. The main task of the thermal process simulation of HIEK is to set up a suitable mathematical model that can predict the thermal environment (mainly indoor air temperature). By this model, scientific analysis of each building unit's effect on indoor air can be obtained, the heat input and operation pattern of the elevated kang in terms of comfortable indoor air temperature can be quantified, and this model can also serve as a design tool. Therefore, the objectives of this research are a) to develop the mathematical model for HIEK, including a macroscopic thermal and airflow model of elevated kang and combining it into a detailed multi-zone building energy simulation program; b) to validate the simulation results with preliminary field data, and c) to evaluate the indoor thermal environment with this model.

THE MATHEMATICAL MODEL

With the help of *Building Energy Simulation* (short for 'BES') method, the transient building load can be obtained, and then the heating system performance can be evaluated and improved accordingly. There are mainly two methods for BES, one is the *heat balance method* (Pedersen et al. 1997, McClellan and Pedersen 1997, Liesen and Pedersen 1997), and the other is the *weighting factor method* (Ayres and Stamper 1995). Heat balance method allowed some significant assumptions of linearity in the *weighting factor method* to be dropped, and it solves heat balances for the room air and at any surface of fabric components.

In this paper, heat balance method is utilized to simulate the thermal process of HIEK. The building thermal process mainly depends on the heat loss/gain of each unit in building. This results from transmission and ventilation heat losses as well as the internal and outside heat gain, such as kang and solar radiation. Heat balances consider all important energy flow paths, see Fig.1: transmission through the envelope and kang plates, radiation exchange between internal surfaces, solar radiation, convection from indoor air to wall and window surfaces, etc. These heat balances are established and solved at each time step to estimate surface and room-air temperature, and heat fluxes. Our mathematical model includes the following elements.

Elevated kang model

- Basic principle and modeling method

An elevated kang serving as the main heating equipment in rural families utilizes the surplus heat of hot smoke from a stove. With cooking, the air in the kitchen is driven into the stove by the buoyancy force caused by a temperature difference between outdoor air and the hot air/smoke in the kang and chimney, and the indoor air pollutants or leakage smoke can be exhausted along with this flow. The hot air in the stove heats up the kang body as it moves, before entering the chimney. During the non-cooking period, the heat stored in the kang body is released into the bedroom by both heat convection and radiation, and keeps the room warm. This airflow process of elevated kang is similar to buoyancy-driven ventilation (Li and Delsante 2001). Thus, the existing approaches developed for building natural ventilation can be adopted for the airflow analysis in a kang.

For natural ventilation, there are mainly two types of analysis method. The first is a macroscopic approach. This includes the so-called simple analytical methods and multi-zone methods. The main interests are the flow rates through the ventilation openings and/or the average air temperatures in the building or zones if needed. The simple analytical methods are generally applied to simple geometry buildings, e.g. natural ventilation flow rates and air temperatures in a single-zone building with two openings without thermal mass (Andersen 2003) and, under certain conditions, multiple solutions for the flow exist (Li et al. 2001). The multi-zone methods are used for more complex buildings with a number of zones. A numerical method is usually needed to solve the system of non-linear equations, which is obtained by considering the mass balance and energy balance in each zone (Li 2002). The second type of analysis method is the microscopic approach, i.e. computational fluid dynamics (CFD). Considering the relatively small sizes of space in kang heating system, the uniform air temperature in each zone is assumed, which is often applied in building thermal analysis. Besides, there are coupling heat transfers between smoke flow and inside surfaces of kang plates, and the elevated kang and indoor air. Therefore, it's more adaptive to analyze the thermal and airflow of the elevated kang with the macroscopic method, and that will help to easily incorporate it into the whole building thermal simulation program.

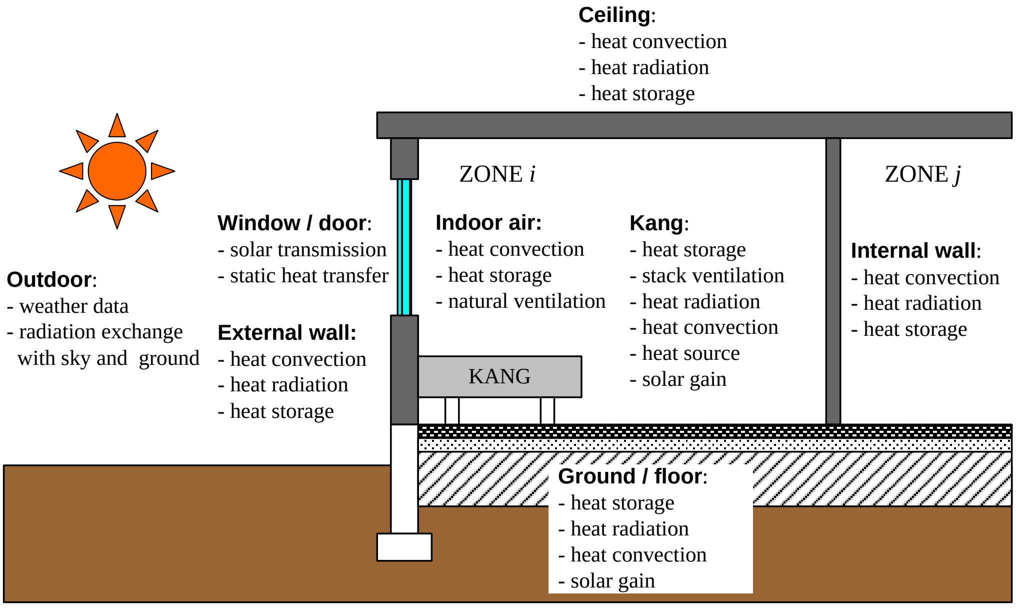

Figure 1 Elements considered in the HIEK model

The entire elevated kang heating system is divided into three zones, Zone 1 (stove), Zone 2 (kang main body) and Zone 3 (chimney), as shown in Fig.2. In our analysis, we assume that the air always flows upward from the stove to the chimney. For the sake of simplicity, the air in all zones will be assumed to be fully mixed, i.e. the air temperature distribution is uniform.

- Heat balance equations

In Zone 1, the fuel burns during cooking and releases heat; part of which is used for cooking, and part of which is lost through the stove walls, and the remaining is transported into the kang for heating. It is known that the combustion process is very complex, so we treat the smoke as ideal air, neglecting the effect of smoke compositions on its physical properties such as density. A heat source *E* is also assumed to be in the stove for heating up the cold outdoor air that enters the stove, which then becomes hot air that travels into the kang. Thus, the heat balance equation in this zone is,

$$E + mc_p\left(T_o - T_1\right) = 0 \qquad (1)$$

In Zone 2, hot air flows through the flue inside the kang and heats up the kang plates with the temperature decreasing along the flow direction. The kang main body absorbs heat from the hot air in the flue via convective heat transfer. However, during non-cooking periods, if the stove gate is not closed, the residual heat in the kang body will maintain a continuous air flow through the chimney, and such airflow cools down the kang body. In practice the stove gate ought to be closed during non-cooking periods to minimize heat loss, and a simple on/off flow rate control is used in modeling. Thus, the thermal storage characteristic of kang plates should be considered, and heat transfer through the kang plates is simplified into one-dimensional transient process for the sake of thin kang plate. The temperature for a control volume within the plate is governed by:

$$\rho_k c_k \frac{\partial T_k}{\partial t} = \lambda_k \frac{\partial^2 T_k}{\partial z^2} \qquad \text{(2-a)}$$

As for the inside of plates, they absorb the heat from the hot air from Zone 1 by convection, and we have,

$$-\lambda_k \left.\frac{\partial T_k}{\partial z}\right|_{z=0} = h_{ki}\left(T_2 - T_{k,z=0}\right) \qquad \text{(2-b)}$$

As for the outside of plates, they release the stored heat to indoor air with the form of both convection and radiation,

$$\lambda_k \left.\frac{\partial T_k}{\partial z}\right|_{z=\delta} = h_{ko}\left(T_{ai} - T_{k,z=\delta}\right) + \sigma F_{MRT_k}\left(T_{MRT_k}^4 - T_{k,z=\delta}^4\right) \qquad \text{(2-c)}$$

Here, the heat transfer coefficient between hot smoke and inside surfaces of kang plate can be deprived from equation in (Holman et al, 1997) for Re value within 40~4000. For outside surface of kang plates, the heat transfer coefficient of radiant floor heating is taken for reference, and the value is 7.5 W/m^{2}K as the surface temperature is 30 ^{o}C (Hisashi et al, 2004).

In Zone 3, the air from Zone 2 is exhausted though the vertical chimney. It is also assumed that the chimney wall is adiabatic, e.g.

$$mc_p\left(T_2 - T_3\right) = 0 \qquad (3)$$

- Flow rate equation

The stack pressure depends on air density differences and height of the opening above or below the neutral level. Assuming that the air has the same composition inside and outside the kang, the density depends on air temperature only. By also considering the wind pressure difference between the two openings, the total pressure difference resulting from stack effect and wind is then given by:

$$\Delta P = \left(\rho_o - \rho_1\right) g h_1 + \left(\rho_0 - \rho_2\right) g h_2 + \left(\rho_0 - \rho_3\right) g h_3 \qquad (4)$$

Meanwhile, we know that the total pressure difference as the heating system reaches a steady state should equal the total flow resistance. The total flow resistance includes all frictional resistances and local resistances caused by changes of the airflow direction or section areas in every zone, e.g. the flow resistance due to the smoke stopper and pillars inside the kang, i.e.

$$\Delta P = \Delta P_s + \Delta P_k + \Delta P_c \qquad (5)$$

Building thermal model

- The envelope model

The envelope model is based on the heat balance equation for each element of the envelope. The heat transfer through the high thermal inertia elements such as walls and roof is analyzed by using one dimensional time-dependent heat conduction equations. The governing equation in the building

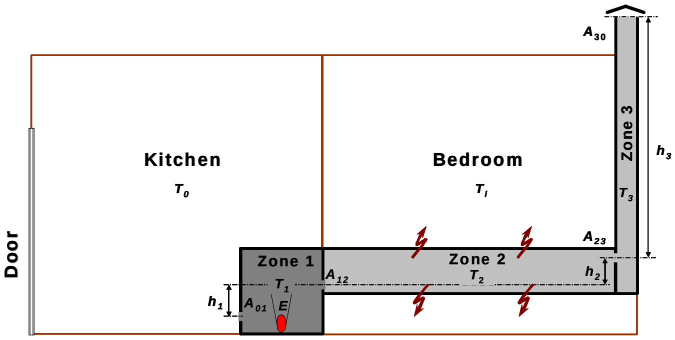

Figure 2 The general notation for the macroscopic model of elevated kang heating system

envelop is the same as Eq(2-a).

As for external walls or roof, on the outside of the room, the walls and roof are exposed to global solar radiation (in daytime) and sky radiation (in nighttime), and have heat convection with outside air. Thus, the external boundary condition is as follow:

$$-\lambda_w \left.\frac{\partial T_w}{\partial x}\right|_{x=0} = h_{co}\left(T_e - T_{w,x=0}\right) + q_{LWR} + q_S + q_R \qquad \text{(6-a)}$$

On the inside, the long-wave radiations between inner surfaces are included, and then,

$$\lambda_w \left.\frac{\partial T_w}{\partial x}\right|_{x=L} = h_{ci}\left(T_{ai} - T_{w,x=L}\right) + \sigma F_{MRT_i}\left(T_{MRT_i}^4 - T_{w,x=L}^4\right) \qquad \text{(6-b)}$$

As for the internal wall, an analogous model as above can be used except that the solar radiation part in the outside boundary condition is omitted and the outside temperature and heat convective coefficient can be replaced with those of the neighboring zone. The surface convective heat transfer coefficients for the wall, floor and ceiling used in the simulation were adopted from (Arvind K 2001).

Rural residences in China are often single-layer buildings, whose grounds are directly contacted with the soil. Much heat may be lost through the ground part, and the thermal behavior of the ground in rural house with kang heating has never been investigated. There have been some excellent efforts in analyzing the floor construction and foundation, including boundary conditions, multidimensional analysis (Adjali et al. 2000) and soil properties such as material and water content (Jassen et al. 2002). In fact, it's more accurate to use a multi-dimensional consideration of the influence from the foundation and ground volume. However, the solution generally requires much more computer resources. Adjali et al. (2000) performed numerical simulations for a ground-coupled floor slab and compared the results with measurements. It was found that the purely conductive earth-contact model can accurately predict the thermal behavior of ground part and a two-dimensional analysis was found to be adequate. Anderson (1991) introduces a characteristic dimension of the floor to simplify the three-dimensional problem to a two-dimensional one with some accuracy demand. The characteristic dimension is defined as follows,

$$B' = A/\tfrac{1}{2}P \qquad \text{(7)}$$

Even with simplifications, while in the multi-zone building thermal simulation, there is still significant effort needed to apply the two-dimensional methods. And in some available simulation tools such as SUNREL (Anon.), a one-dimensional transient heat conduction equation with constant properties, is used to solve the ground-coupled heat transfer phenomena. For slab-on-grade floors, two paths for heat transfer are considered: a) a wide strip around the perimeter of floor loses most of its heat to the ambient; b) the remaining central section of the floor exchanges heat with the deep ground. In this paper above two models are utilized respectively for single-zone and multi-zone cases.

Due to the low thermal inertia of doors and windows, the heat transfers through them are dealt with the simple energy balance equation with the form of,

$$Q_i = U_i A_i \left(T_{ai,1} - T_{ai,2}\right) \qquad \text{(8)}$$

- **Radiant heat transfer model**

The radiant heat transfer between surfaces is dependent on the temperatures, spatial relationships between surface and surroundings, and the material properties of the surfaces. The assumption that is used quite often for BES is to split the radiation into two parts, e.g. shortwave radiation including sunlight and lights and longwave radiation such as radiation from walls, people, and equipments. In this paper, both heat gain through windows in shortwave form and longwave radiation between surfaces of building indoor space are under consideration.

- Shortwave radiation calculation

For the input of solar radiation intensity, a typical ASHRAE dynamic solar model is utilized to simulate the transient solar intensity, which is based on the method presented in (ASHRAE 2005). The interaction of directions of solar beam and different enclosures, and both direct and diffuse radiations incident on the outside surfaces are considered.

The transmission solar radiation through windows is absorbed by inner surfaces and furnishings (only kang plate surfaces considered), and then either re-radiated as thermal radiation or released to the indoor air by convection. Solar gains are commonly assumed to be distributed over the surfaces of enclosure in three manners: a) the solar beam radiation from fenestration is totally projected onto the floor surface, this is realistic for most cases; b) all of the solar inclination projected on one of the walls or c) evenly distribute among the walls and floor except ceiling. The above three internal distributions of the solar radiation on cooling load were compared and discussed in (Liesen and Pedersen 1997), and it's shown that projecting all the solar on the floor matches actual behaviors in many cases. Therefore, with this distribution, the total shortwave radiant flux by solar radiation can be:

$$HG = \alpha_s \left(I_{Di}\tau_{Di} + I_{di}\tau_{di}\right) A_g / A_f \qquad \text{(9)}$$

- Longwave radiation calculation

The Mean Radiant Temperature (MRT) method is used to compute the net longwave radiant fluxes absorbed by the interior faces (Liesen and Pedersen 1997). It has the advantages of modeling the important features of the building including the radiant exchange of inner surfaces and furnishings without exactly calculating view factors. Meanwhile, it should be noticed that the inaccurate view factors and mean radiant temperatures will result in some net imbalance, which can be handled by calculating the total net imbalance and then distributing it equally on all surfaces to preserve conservation of energy. The net radiant flux is calculated for each surface by:

$$q''_{MRT_i} = \sigma F_{MRT_i}\left(T^4_{MRT_i} - T_i^4\right) - R_{Bal} \tag{10}$$

In process, longwave radiant fluxes are given in a scalar form using the surface temperature values computed at the previous iteration.

Multi-zone airflow model

Heat exchange by natural ventilation or infiltration between indoor and outdoor air or air from different adjacent zones is very important to energy balance in BES, especially in rural house with poor air tightness and large openings. The natural ventilation rates depend on many factors, such as temperature difference between indoor and outdoor air, wind speed and crack or gap size etc. As for ventilation of large openings, the patterns of airflow are various and often bidirectional, differing at the upper and lower parts. There have been many excellent models and even software programs, such as MIX (Li et al. 2000), COMIS, and CONTAM, for natural ventilation analysis. In this paper, we implement the MIX code, a Multi-zone Infiltration and eXfiltration program, to analyze the ventilation for multi-zone building. Before calculating the ventilation rates through each opening, the air temperature profiles of each zone need to be known, which can be obtained from the thermal model. In real process, the thermal model will again input the calculated ventilation rates between zones, and then updates the indoor air temperatures in each zone until the precision demand is met. So this airflow model has the potential to be integrated into the thermal model in favor of achieving the accurate thermal process.

Heat balance of indoor air

In each zone, the temperature of indoor air can be determined by heat balance equation, which takes the following items into account: a) the heat fluxes through fabrics with high thermal inertia, such as walls, roof and floor; b) the heat transfer through low thermal inertia windows and doors; c) the heat flux associated with the elevated kang (if have) and d) the heat change caused by ventilation with air exchange between zones or/and outside. All items include the longwave radiant heat transfer between inner faces, and the solar radiant heat transfer is considered in floor part. Then, for zone *i* we have,

$$\rho_i V_i c_{p,i}\frac{dT_i}{dt} = q_{i,w} + q_{i,r} + q_{i,f} + q_{i,k} + q_{i,wd} + q_{i,d} + q^{vent}_{i,in} - q^{vent}_{i,out} \tag{11}$$

SOLUTION STRATEGIES

All of the non-linear equations stated above consist of the whole mathematical model of HIEK, and can be solved by a numerical method. The explicit finite volume method is utilized to solve the nonlinear equations of HIEK for its flexibilities, for example, the convective heat exchange with indoor air, the radiant heat exchange among surfaces, and the heat generated by the kang heating plates can be easily associated with corresponding nodes. Besides, it's relatively easy to formulate and has been widely used in BES. As the number of control volumes is large, less computer memory and running time are required comparing with the implicit method, but the time step should be carefully selected for numerical stability. Also, two issues involving the resolution of this model are critical in procedure. One is about dealing with the coupling between heat and air flow in both kang and BES models; the other is about solving the airflow-thermal problems for multi-zone buildings.

Two main categories of approaches for coupling a thermal model with a flow model are in wide use: a) a de-coupled approach, such as 'ping-pong' coupling, in which the thermal and flow model run in sequence, and b) a coupled approach, with both the thermal and flow model iterating within one time step until achieving convergence conditions. It's known that the coupled approach is capable of generating more accurate results and with more computer resources than the de-coupled one (Hensen 1995). Therefore, the coupled approach is applied to handle the coupling models, and the schematic of the program flow in kang model is shown in Fig.3.

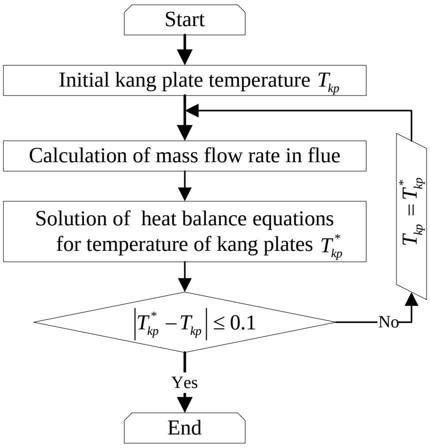

Figure 3 Flow chart of heat and airflow coupling for the elevated kang model at each time step

As for a multi-zone building, the variables, especially indoor air temperature, in difference zones are linked together through heat transfer and air flow. Taking Eq.(11) for example, it is clearly shown that the air temperature of zone *i* is affected by the neighboring zones. By discretization, indoor air temperature at new time step can be written under the form,

$$A_i T_i^* = \sum_{neib} V_j T_j^* + \sum_{env} E_i T_{e,i} + K_i T_{k,i} + F_i T_o + B_i T_i \tag{12-a}$$

Then the set of indoor air heat balances given by Eq.(11), written for all zones, results in a linear set of equations in matrix form,

$$\mathbf{XT^*} = \mathbf{Z} \tag{12-b}$$

For this, the vector of zonal temperature $\mathbf{T}^*$ can be directly solved based on Gaussian elimination.

VALIDATION AND ANALYSIS

Validation

For validation, the results of the simulation model are compared to those of a test room to determine. Two field surveys had been conducted in three rural residences in Dalian of Northeast China to investigate the indoor thermal environments in 2004 (Chen et al. 2007). The field measured data of one room is used for validation, including indoor and outdoor air temperatures, surface temperatures of the kang plates and solar radiance etc. It should be noted that the stove net heat source strength *E* was difficult to obtain, and it's found by trial and error and comparing the calculated surface temperatures of kang plates to the tested ones, and then adjusting the assumed values until the difference are within the range of accuracy, as illustrated in Fig.4, and Fig.5 shows the final-determined heat power.

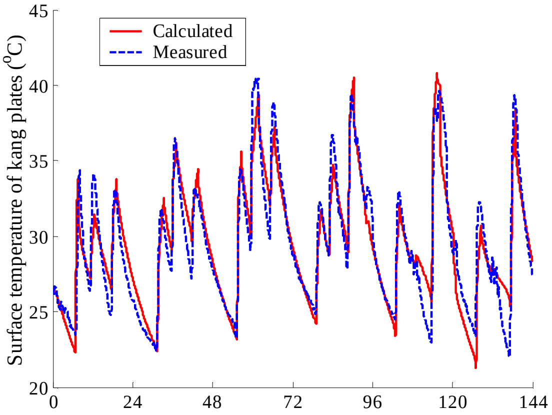

Figure 4 Comparison between calculated and measured surface temperatures of kang plates

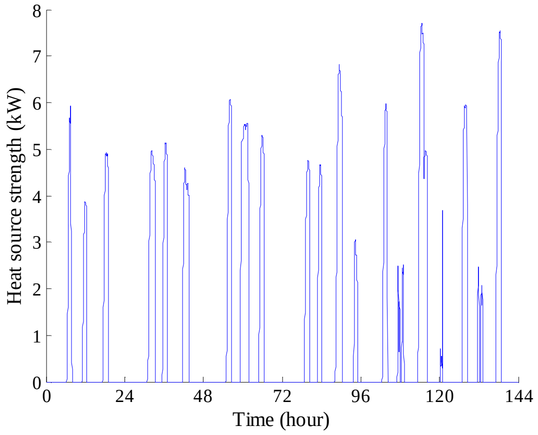

Figure 5 The final fine-tuned heat source strength

Fig.6 compares the time variations of the measured indoor air temperature with the calculated for different percents of free opening (including door and window) size, e.g. Pert=1.25%, 2.50%, 5.00% . The trend of indoor air temperature as Pert=2.50% is well reproduced by the HIEK model analysis. The average difference between the measured and calculated values of indoor air temperature is about 0.1°C during the measured period. Also, some greater differences (<2.5 °C) exist due to the simplicities and nodal nature of the model, neglecting the effect of human's activities and the fact that indoor air is not well mixed, etc.

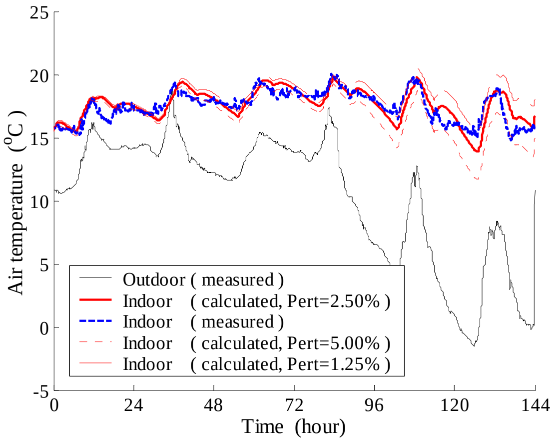

Figure 6 Comparison between calculated and measured indoor air temperatures

Analysis

Fig.7 illustrates air change rates under different opening sizes, and from above stated we know that the variations of air change rate as Pert=2.50% is the actual ones. The values of air change rate increases with the increasing percent of opening size, and that will lead to more heat loss from room, and the indoor air temperature will be lower, especially with higher difference between indoor and outdoor air temperatures shown in Fig.6. Therefore, improving the air tightness of rural residences is one of the efficient ways of maintaining indoor thermal environment in northern cold and severe cold areas.

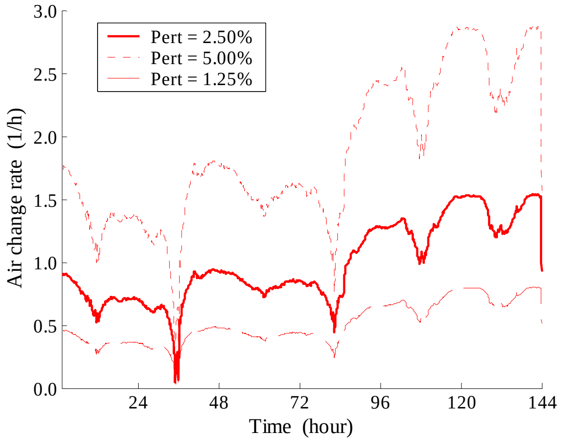

Figure 7 Indoor air change rates under different opening sizes

By simulation, the temporal variations of heat release from kang can be calculated and shown in Fig.8. The heat release rates during the most time are within the range of 300W~700W for a typical elevated kang under the heat resource strength shown in Fig.5. It's can be found that the peak and amplitude of heat power output of the stove are decreased with the kang plates, and so that moderate surface temperature of kang plate can be obtained; Beside, the total heat efficiency of this elevated kang is over 52%, and the elevated kang is indeed a kind of economical heating technique.

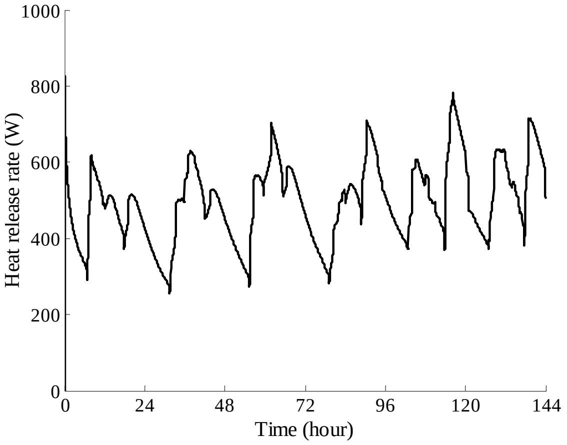

Figure 8 Heat release from kang plates to indoor air

SUGGESTIONS

The HIEK model has been implemented using the computer code of matlab language except the MIX code originally using the FORTRAN language. The frame of program is based on modular structure with one main routine and several subroutines, e.g. the components, such as wall, kang and solar models, are handled within responding subroutines respectively. The components are configured and assembled in the main routine, and also MIX is interfaced to it. For the whole HIEK model, it's implemented with the procedure presented in Fig.9.

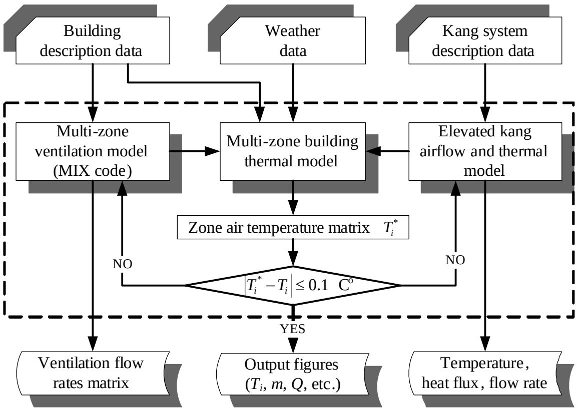

Figure 9 The implementation procedure of the HIEK model

This program can be used to predict the indoor air temperature for multi-zone HIEK by inputting the basic parameters like geometry, physical properties of building and the elevated kang. The input data can be entered through a text file with a fixed format. The functions of model can be easily extended for investigating the thermal performance of kang system and its influence on indoor thermal environment and building energy consumption. Now this program is just under development, and more efforts are needed.

Besides, there have been hundreds of BES programs developed over the past decades, and several of them are widely in use, such as Esp-r, EnergyPlus and DeST, with mature techniques and friendly visual interface. Therefore, it will be more meaningful to incorporate the elevated kang model into an existing software tool for HIEK design, and the core issues are the linkage between kang model and the existing software. As shown in Fig.9 the building thermal and ventilation model can be replaced with the software.

CONCLUSIONS

A detailed modeling work in simulating thermal behaviors of a House Integrated with an Elevated Kang (HIEK) is presented. An macroscopic method is used to analyze the thermal and airflow process of the elevated kang, which is incorporated into a general building simulation procedure. A solution method for the coupled non-linear system of energy balance and flow equations of HIEK is proposed and implemented. This model has been preliminarily validated by some test data, available up to date.

Our simulation results show that a) the air change rate significantly decreases the indoor air temperature with the increasing percent of opening size and higher difference between indoor and outdoor air temperatures; b) the elevated kang is energy-saving by utilizing over 50% of surplus heat of stove smoke, and with moderate surface temperature for sleeping.

Our developed program can be used to elevate the thermal performance for multi-zone HIEK by inputting the basic parameters, and also need improvement. We intend to complete further work to apply our kang model to existing BES tools for design.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	area, m^2
c_p	specific heat capacity of air, J/kg·K
c_k	specific heat capacity of kang plate, J/kg·K
E	heat gain or heat source strength of stove, W
g	acceleration of gravity, m/s^2

h_{ko}	outside convective coefficient of kang, W/m^2
h_i	relative height between openings, m
HG	solar heat gain, W/m^2
I_D	direct solar radiation flux, W/m^2
I_d	diffuse solar radiation flux, W/m^2
m	ventilation mass flow rate of kang, kg/s
P	perimeter of the floor, m
q_i	heat flux in zone *i*, W
q_R	absorbed diffuse radiation from ground, W
q_S	absorbed solar radiation flux, W
q_{LWR}	longwave radiation exchange with the environment, W
$q_{i,out}^{vent}$	heat flux from zone *i* by ventilation, W
$q_{i,in}^{vent}$	heat flux to zone *i* by ventilation, W
q''_{MRT_i}	net radiant flux, W
R_{Bal}	radiation imbalance flux, W
t	time, s
T_o	outside temperature, K
T_i	air temperature in Zone *i* , K
T_{ai}	indoor ari temperature, K
T_k	tempearture of kang plate, K
T_w	tempearture of wall, K
T_e	sol-air temperature, K
T_{MRT}	meat radiant temperature, K
U_i	overall heat transfer coefficient, W/m^2
x	thickness of wall, m
z	thickness of kang plate, m
$\mathbf{X}$	coefficient matrix of zonal temperature
$\mathbf{T}^*$	vector of zonal temperature at next time step
$\mathbf{Z}$	coefficient vector

Greek symbols

α_s	absorptivity of surface
λ	heat conductivity, W/mk
ρ_i	air density in Zone *i* , kg/m^3
ρ_o	ambient air density, kg/m^3
ρ_k	kang plate density, kg/m^3
τ	transmission rate of glass
δ	thickness of kang plate, m
σ	Boltzmann's constant
ΔP	pressure loss, Pa

Subscripts

c	chimney
d	door
f	floor
i	zone number
k	kang
r	roof
s	stove
w	wall
wd	window

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