A user-friendly building energy consumption program

Yilong Jia, Jianxiang Jin
State Key Laboratory of Industrial Control Technology
Institue of Cyber-Systems and Control
Zhejiang University
Hangzhou, P.R. China
jiayilong1989@hotmail.com

Xuanhao Zhou
Research Company
SUPCON Group
Hangzhou, P.R. China
xhzhou@iipc.zju.edu.cn

***Abstract*—Building energy simulation program plays an important role in reducing energy consumption for heating in North China. For the past 60 years, a wide range of building energy simulation programs have been developed. However, in China, building energy simulation programs are not popularized smoothly because of the problems such as unfriendly interface, complex usage and excessively specialized. This paper presents a new building energy simulation program with B/S structure. As a collection of building energy simulation and economic analysis, this program can be accepted by the professionals and non-professionals due to its accuracy and easy operation.**

Keywords-building energy efficiency; simulation program; state-space method

I. INTRODUCTION

Building energy consumption, industrial energy consumption and transportation energy consumption are listed as three main areas of energy consumption and the source of greenhouse gas emissions. The next several years will be critical years for reducing greenhouse gas emissions to achieve the goal of IPCC AR4. It also will be critical for further reduction amounting to less than 50% of today's level by 2050, in order to avoid catastrophic climate change.

Building energy consumption possesses the characteristics of high energy consumption, obvious long-term growth rate along with a large energy saving potential and a relatively low energy-saving cost, therefore, building energy efficiency is regarded as the key link in the goal of IPCC AR4. However, the situation of building energy consumption in China is not optimistic. According to the statistics data, the total area of China residential buildings is about 43 billion m^2. The total national building energy consumption is about 17 billion tons standard coal which accounts for 30% of the total energy consumption in the year 2010. In accordance with the classified usage of building energy consumption, building energy consumption can be grouped into 5 categories: Building energy consumption of rural areas; Building energy consumption of heating zones in North China where heating system is needed; Energy consumption of urban residential building excluding heating ; Energy consumption of common public buildings without heating and electricity consumption of large scale public buildings. Energy consumption of each category is shown in Table 1 [1].

It can be easily deduced from Table 1 that there exists an obvious problem in China: High energy consumption for heating in North China. Actually, in China, energy consumption for heating can reach 20 Kg/m^2 or more if converted to standard coal which exceeds almost 2 times compared to that of Northern Europe with same longitude. China has huge energy efficiency potential in this field. Facing the problem of economic externalities, building energy efficiency for heating in North China encounters many difficulties. This paper introduces a program, the program applies specifically to many aspects of building energy efficiency for heating in North China. It is a collection of building energy simulation function and economic analysis function. It can be widely used by providers of building energy efficiency products, households and relevant government departments.

TABLE Ⅰ. Building energy consumption in China

Items	building area(billion m^2)	total consumption (kWh)	average consumption (kWh/ m^2)
Rural areas(exclusive of non-product energy consumption)	24	90	7.5
Northern cities for heating	6.5	370	57
Cities excluded heating Residential	10	200	13-30
public buildings	5.5	160	20-60
Large-scale public buil-dings	0.5	100	70-300
Subtotal	16	460	29

II. DEVELOPMENT OF BUILDING ENERGY EFFICIENCY PROGRAM

Calculation of building energy consumption is the foundation of building energy simulation and economic analysis, therefore, the basic methods to analyze building energy consumption will be presented first.

A. Introduction to building energy analysis

There are two categories of building energy analysis methods: steady-state calculation methods and unsteady-state calculation methods. The following is an overview of some common methods.

1）Steady-state calculation method of building energy consumption

The steady-state calculation method of building energy consumption simplifies the complex theoretic situation. It is mainly used to study the trend of building energy consumption as well as to make a systematic comparison. On one hand, calculation results will be relatively rough; On the other hand, it has the advantage of high speed and easy to calculate. Common steady-state methods mainly include Degree-Day method and bin method.

The Degree-Day method is a single-measure steady-state method mainly used to estimate the heating energy consumption of small buildings. Although only approximate calculation result can be derived through this method, it can show the trend of building energy consumption.

The assumption that, over a long period, solar and internal gains will offset heat losses when the mean daily outdoor temperature is a set temperature, and that energy consumption will be proportional to the difference between the mean daily temperature and the set temperature, is the foundation of Degree-Day method [2]. Degree-Day method is generally used for an all year round heating or cooling system with a constant indoor temperature setting.

The Bin method, also known as the temperature frequency method, is based on the assumption that there exists linear relationship between heating load and temperature difference between indoor and outdoor. The bin methods consists of performing instantaneous heating and cooling energy calculations at many different outdoor dry bulb temperature conditions, and multiplying the results by the number of hours of occurrence of each condition. This method is more accurate than Degree-Day method.

2) Unsteady-state calculation method of building energy consumption

The unsteady-state methods describe the dynamic change of heating load in a changing environment, commonly including harmonic analysis method, response factor method, finite difference method and state-space method.

Harmonic analysis method regards outdoor temperature as irregular periodic function whose cycle is 24 hours and transfers periodic disturbance into sine or cosine Fourier series, then incorporate the concepts of delay and decay to calculate heating load; Regarding the wall and the room as a linear thermal system, response factor method gets all response factors by system transfer function and then calculate the heating load with the response factors. This method does not require periodic disturbance; Finite difference method takes the building into many discrete nodes and then lists each node's heat-balance equation. It can calculate the heating load after solving these simultaneous node equations; State-space method firstly takes the building into many discrete nodes and lists each node's heat-balance equation like finite difference method. Then, the method needs to get thermal characteristic factors by solving these simultaneous equations. In the end, it can calculate the result with these thermal characteristic factors and time-varying disturbance. our program employs the state-space method.

B. Overview of existing similar programs

In the past 60 years, a lot of building energy simulation programs have been distributed which greatly promote the development of building energy efficiency. Among these programs, there are several representatives: DOE-2 is jointly developed by United States Department of Energy and LBNL; Energy-10 is mainly developed by Sustainable Buildings industrial Council; Dest is developed by Tsinghua university. Drury B.Crawley did a lot work to contrasting the capabilities of building energy simulation programs [3]. Detailed information can be found in his paper .

However, in China, building energy simulation programs are not popularized smoothly. According to the result of questionnaire investigation and constructional interview, popularizing building energy simulation programs encounter such problems as unfriendly interface, complex usage and excessively specialized. Besides these, building energy simulation programs are too far away for households. Actually, households are the key part of building energy efficiency. The programs introduced in next part can solve these problems to a certain extent.

III. SYSTEM DESIGN

A. Structure of the building energy simulation program

Previous building energy simulation programs are hard to use which hinders they promoting smoothly. The building energy simulation program presented here learns from these experiences sufficiently. The core simulation module is designed to be separated from general users and encapsulated in system kernel. General users can get all information they care just by submitting some basic data. Basic framework of this program is shown in Fig. 1.

The program adopts B/S architecture due to the maturity of web development technology. Thus, any household or civil servant can use this program at home, in office or any other place where Internet exists.

Core simulation module is the most important part of the program. The core algorithm adopted by this module is state-space method which is based on building thermal equilibrium. Following section will introduce how to simulate and analyze the building heating energy with space-state method.

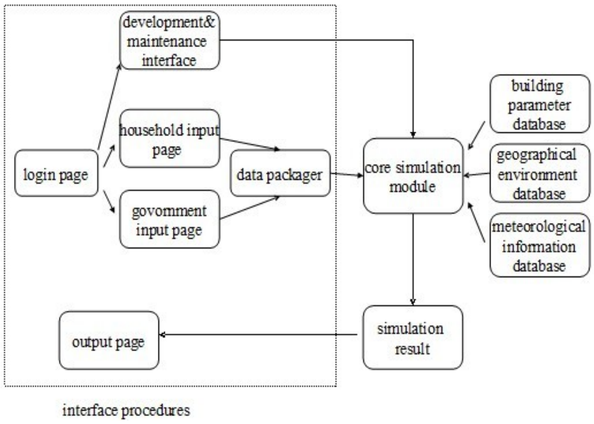

Figure 1. Basic Framework

B. Mathematical model of this building thermal energy simulation program

The unsteady-state temperature field of the building is a time-varying heat conduction equation. In the practical applications, considering the thickness of the wall is far less than the length and width of the wall and the structure of the wall is uniform, the heat conduction equation can be simplified into one-dimension equation as follows.

$$\frac{\partial}{\partial x}(k\frac{\partial T(r,t)}{\partial x}) == \rho c_p \frac{\partial T(r,t)}{\partial t} \quad (1)$$

Three boundary conditions including interior and exterior building surfaces, ground surfaces and deep ground surfaces [4] are added to the equation to analyze heat transfer of building envelope. Specially, as ground surfaces and deep ground surfaces can not be simplified into one-dimension equation, this paper does not introduce them.

The boundary condition of interior surfaces is:

$$-k\frac{\partial T}{\partial x}\Big|_{x=l} = h_{in}(T_{in}-T)+q_l+\sum_j hr_j(T_j-T)+q_{r,in} \quad (2)$$

The boundary condition of exterior surfaces is:

$$k\frac{\partial T}{\partial x}\Big|_{x=0} = h_{out}(T_{0ut}-T)+q_{r,o}+hr_{out}(T_s-T) \quad (3)$$

In above two equations, h_{in} represents convection heat transfer coefficient of interior wall; T_{in} represents indoor temperature; q_l represents solar radiation through the window; hr_j represents long-wave radiation heat transfer coefficient of interior wall; $q_{r,in}$ represents the effect of other indoor heat source; h_{out} represents convection heat transfer coefficient of external wall; T_{out} represents outdoor temperature; $q_{r,o}$ represents long-wave radiation heat transfer coefficient of interior wall; T_s represents synthetic temperature.

For every building envelop similar as the wall, equation (1) (2) (3) can be established. Following equation can describe air temperature field of each room:

$$C_{pa}\rho_a V_a \frac{dT_a}{d\tau} = \sum_{j=1}^{n} F_j h_{in}(T_j(\tau)-T_a(\tau))+q_{\mathrm{cov}}+q_{vent} \quad (4)$$

In the equation, F_j represents the surface area of surface *j*; q_{cov} represents heat source's effect on indoor air including the effect of central heating system; q_{vent} represents heat gain from air exchange.

It is necessary to simulate the entire building as a whole because these equations are coupled.

Using state-space method [5], the building thermal processes can be described by:

$$C\dot{T} = AT + BU \quad (5)$$

Where *T* is an N-dimensional column vector describing the temperature of all nodes in the state space. The dot over *T* represents the derivative of *T* with respect to time. *C* is a diagonal matrix describing the thermal capacity of all nodes, *A* is an *N***N* symmetric matrix describing heat conduction, heat convection and long wave heat radiation among all nodes. *B* is an *N***M* matrix describing the impact of the *M* heat disturbances on the nodes temperatures. And *Q* is an *M*-dimensional column vector standing for the *M* heat disturbances, including outdoor temperature, solar radiation through and absorbed by windows, indoor casual gains and space heating. Thus, *C* and *A* depend on the building structures and *B* depends on the thermal boundary conditions.

Finally, the natural temperature of room *k* can be expressed as:

$$T_k(\tau) = W(\tau-\Delta\tau)+\sum_{j=1}^{M}\psi_{0j}\cdot q_j(\tau) \quad (6)$$

In this expression, the first monomial means the historical effect of heat gain on the room air temperature.

IV. AN APPLICATION EXAMPLE

This test-bed simulates a set of housing which locates in Changping District, Beijing with a building energy efficiency scheme of SUPCON. The intelligent temperature control valve designed by SUPCON is the core product of the scheme. These valves can control the temperature automatically according to users' settings. Specific submission page is shown in Fig. 2 .

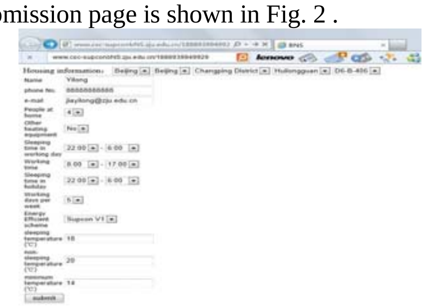

Figure 2. Submission page

In this example, specific settings are shown below: Expected sleeping temperature is set to 18°C; Expected temperature when Nobody at home is set to 18°C; Expected temperature when family are awake is set to 18°C; households work 5 days per week; households go to bed at 22:00 and get up at 6:00; households go out at 8:00 and go back at 17:00. After click the submit button, output page is shown in Fig. 3.

Through the figures, users can clearly understand how much they will save and how comfortable they will feel by finishing those steps as above.

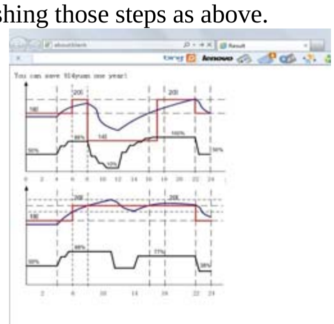

Figure 3. Output page

Notes:Orange represents setting temperature, blue represents indoor temperature, black represents control strategy(valve opening)

V. CONCLUSION

This paper mainly introduces a new building energy simulation program with B/S structure. It is a collection of building energy simulation and economic analysis. The core theoretical foundation of this program is based on state-space method. Approximation analysis of some physical models is utilized to guarantee real-time and feasibility. The advanced architecture and much tested simulation method adopted makes the program can be accepted by the professionals. Another innovation is to provide a simple operation method and economic method which makes the program more friendly to non-professional users. It can reduce the resistance of popularization of building energy efficiency project.

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