SIMULATION ON HYDRAULIC HEATING SYSTEM OF BUILDING UNDER THE CONTROL OF THERMOSTAT RADIATOR VALVES

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ABSTRACT

Considering the dynamic control process of thermostatic radiator valves (TRVs) and adjustement behavior of consumers, as well as heat transfer through neighborhood, the main purpose of this paper is to derive a total model for simulating and analyzing the dynamic behavior of hydraulic heating system with the control of TRVs in multi-family building, based on state space model of room dynamic performance. This is done by treating building and the heating system as complete entities. First of all the dynamic models for rooms, radiators and TRVs are derived. Then the suggested models are formulated as a whole system. Multizone model for the simulation of building thermal performance is complicated and will be more difficult when considering dynamic process of radiators and TRVs, Thus the heat transfer between neighboring rooms is simplified by using explicit difference approximately. Finally, Detailed simulation of an actual building is given to verify the component models and their interactions. The experimental measured neighbor rooms temperature, outdoor temperature and supply temperature are used as input to the model, and the calculated results are compared with the measured air temperature and return water temperature. The agreement between simulant and measured data is quite good.

KEYWORDS

multi-family building simulation, hydraulic heating system, thermostat radiator control valves, variable flow-rate

INTRODUCTION

Like many European countries, China realizes that heat metering and consumption-based billing are critical to encourage space-heating energy conservation by giving individual households the opportunity to regulate their heat energy consumption. Starting in the mid 1990s, the national and local governments of China have supported a range of demonstration projects to study heat metering technologies (JP Building Engineers 2002). The monitoring data obtained from the demonstration projects indicated that thermostatic radiator control valves (TRVs) contributed significantly to reduce heat consumption, and the average reduction was about 10% (Wang Z C 2002). Meanwhile, It brings new problems. TRVs self-adjusting and consumer's regulation behavior make the flow-rate variable in the new systems other than constant in the traditional ones, which requires corresponding changes in design and control strategies of the system (Di H F 2000). Thus a proper simulation model is needed to serve as a useful tool in analyzing such problems.

In order to derive a model for the heat dynamics of a building, two different approaches may be used. The traditional approach is simply to use the knowledge of physical characteristic and well-established models of sub-processes. Most simulation models are based on first principles, and are available in a number of software packages including EnergyPlus (Crawley 2000), DOE-2 (Lawrence Berkeley Laboratory 1982), HVACSIM+ (Clark D R 1985), TRNSYS (Klein S A 1976), DEST (ZHU Y X 2003), etc. Jiang Y (1981) developed state-space method for the simulation of thermal behavior within an air-conditioned room. Hong T Z (1997) presented a new multizone model which is an improvement on the state space model. Detailed physical models are time consuming and always need suitable simplification and assumptions. Therefore a simplified physical model for estimating the average air temperature in multi-zone heating system for use in an inferential boiler control scheme was developed by Liao (2004). An alternative approach is to use building performance data and statistical methods. Lethernman (1982) utilized experimental data based on pseudrandom binary sequences of the input to determin the heat dynamics. ARMAX models were discussed by Crawford (1985), who considerd a single-family residence with electric heating. A statistical approach, the grey box modeling method, was applied by Madsen (1995) in order to drive a total model for the heat dynamics of a building with a single test room. Andersen (2000) utilized collected building performance data and statistical methods to obtain a system of stochastic difference equations for the heat dynamics in a residential building. Braun and Chaturvedi (2002) developed an inverse gray box thermal network model for transient building load prediction. Wang S W (2006) presented the building internal mass with a thermal network structure of lumped thermal mass and estimated the lumped parameters using operation data. The main drawbacks of statistical models are that they require a significant amount of training data and may not always reflect the physical behaviors.

Defferent models concentrate on different aspects according to their intention. A special problem of most exited models is that they focus much on buildings characteristic but little on detailed hydraulic heating system, e.g., the TRVs dynamic control process and consumers' adjustment behavior is always not take account in, which may be especially important in analyzing control strategies. Furthermore, the models always based on a single-family residence or occupied office building, heat transfer through neighborhood consumers such as occurred in Chinese multi-family buildings can not be considered.

In view of what mentioned above and based on state space model of room dynamic performance, the main purpose of this paper is to derive a total model for analysis, computation and simulation on the dynamic behavior of hydraulic heating system with the control of TRVs in multi-room building, which is done by treating buildings and the systems as complete entities. Dynamic models for room, radiator and TRVs are derived. Then the suggested models are formulated as a whole system. Multizone model for the simulation of building thermal performance is complicated and will be more difficult when considering dynamic process of radiator and TRVs, Thus the heat transfer between neighboring rooms is simplified. Finally, it is demonstrated that the whole model gives a reasonable description of dynamical behavior of the experimental building.

THE MODELING APPROACH

The multizone model is improved from the state space method (Yi Jiang 1981). Instead of treating all of a building's node together as a state space, it treats a building as separate zones, and each zone constructs a sub state space with all its nodes together.

Room model

The main heat disturbances that influence the room air temperature are solar radiation, indoor casual gains, out door temperature, heat input from radiators, air temperature of adjacent zones, infiltration or ventilation through openings. First three of the heat disturbances values mentioned above are known or can be directly calculated. The long wave radiation exchange between an external surface of a zone with the internal surfaces of the adjacent zone is simplified into the convective heat transfer between the external surface of this zone and the air of the adjacent zones. According to the sub state space model of each zone and the feature of each heat disturbance, the room temperature can be calculated as:

$$\begin{aligned} T_{\mathrm{a},k}(t) = {} & T_{\mathrm{bz1},k}(t) + \sum_j \psi_{j,0,k} T_{\mathrm{a},j}(t) + \sum_j \psi_{j,1,k} Q_j(t) \\ & + \psi_{\mathrm{rad},0,k} Q_k(t) + \psi_{\mathrm{v},k} c_p \rho V_{\mathrm{out},k}(t)[T_{\mathrm{out}}(t) - T_{\mathrm{a},k}(t)] \\ & + \sum_j \psi_{\mathrm{v},k} c_p \rho V_{j,k}(t)[T_{\mathrm{a},j}(t) - T_{\mathrm{a},k}(t)] \end{aligned} \tag{1}$$

where $T_{\mathrm{bz1},k}(t)$ represents the air temperature of room k without considering the influence of heat transfer between thermal zones, the heat input from radiator and infiltration at time t; $\psi_{j,0,k}$ 、 $\psi_{j,1,k}$ 、 $\psi_{\mathrm{rad},0,k}$ 、 $\psi_{\mathrm{v},k}$ separately represents the influence coefficient of the adjacent zones air temperature $T_{\mathrm{a},j}$ 、 heat emit from adjacent zones Q_j and calculation zone Q_k 、 natural ventilation $V_{\mathrm{out},k}$ and adjacent ventilation $V_{j,k}$ to the room temperature at time t.

Yi Jiang (1981) Gives detailed calculation method of these influence coefficients. The only difference is that Jiang discussed a residential space-conditioning system for which air conditioning influence the room temperature only through convection, while this paper focuses on hydraulic heating system for which heat transfer from the radiators not only to the air through convection but also to the internal surfaces of envelope through radiation.

Considering the control process of TRVs, the sampling time is chosen based on a priori estimate of the smallest time constant, e.g., when time constant of TRVs is 10min, 5min is taken as the sampling time. Room temperature will be changed little during two calculation step, therefore the previous calculation result of neighbour room temperature and radiator emit are used to approximate the influence of neighbour disturbance. Equation (1) can be approximated as

$$\begin{aligned} T_{\mathrm{a},k}(t) = {} & T_{\mathrm{bz1},k}(t) + \sum_j \psi_{j,0,k} T_{\mathrm{a},j}(t-1) + \sum_j \psi_{j,1,k} Q_j(t-1) \\ & + \psi_{\mathrm{rad},0,k} Q_k(t) + \psi_{\mathrm{v},k} c_p \rho V_{\mathrm{out},k}(t)[T_{\mathrm{out}}(t) - T_{\mathrm{a},k}(t)] \\ & + \sum_j \psi_{\mathrm{v},k} c_p \rho V_{j,k}(t)[T_{\mathrm{a},j}(t-1) - T_{\mathrm{a},k}(t)] \end{aligned} \tag{2}$$

This approximation is essential to simplify the coupling between one zone and its adjacent zones, thus the state space for the building can be decomposed into sub state spaces for each zone. Equation (2) can also be written as

$$T_{\mathrm{a},k}(t) = T_{\mathrm{bz},k}(t) + \psi_{01,k}(t) Q_k(t) \tag{3}$$

Where

$$\begin{aligned} T_{\mathrm{bz},k}(t) = {} & \frac{T_{\mathrm{bz1},k}(t) + \sum_j [\psi_{j,0,k} T_{\mathrm{a},j}(t-1) + \psi_{j,1,k} Q_j(t-1)]}{1 + \psi_{\mathrm{v},k} c_p \rho [V_{\mathrm{out},k}(t) + \sum_j V_{j,k}(t)]} \\ & + \frac{\psi_{\mathrm{v},k} c_p \rho [V_{\mathrm{out},k}(t) T_{\mathrm{out}}(t) + \sum_j V_{j,k}(t) T_{a,j}(t-1)]}{1 + \psi_{\mathrm{v},k} c_p \rho [V_{\mathrm{out},k}(t) + \sum_j V_{j,k}(t)]}, \end{aligned}$$

$$\psi_{01,k}(t)=\frac{\psi_{\mathrm{rad},0,k}}{1+\psi_{\mathrm{v},k}c_p\rho[V_{\mathrm{out},k}(t)+\sum_j V_{j,k}(t)]}$$

Radiator model

The power from the radiator is not known completely and has to be modeled as well. The radiator emits heat to the ambient through both convection and radiation. For a given type of radiator, the proportion of convection and radiation can be treated as constant (Zhang X 1996). It has been considered in the calculation of influence coefficient. Introducing effective coefficient ε, dynamic equation of radiator can be written as

$$C_{\mathrm{rad},k}\frac{dT_{\mathrm{rad},k}(t)}{dt}=C_{\mathrm{w}}q_{\mathrm{m},k}(t)\varepsilon_k(t)[T_{\mathrm{s},k}(t)-T_{\mathrm{a},k}(t)]$$
$$-K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}[T_{\mathrm{rad},k}(t)-T_{\mathrm{a},k}(t)]\,, \qquad (4)$$

$$Q_k(t)=K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}[T_{\mathrm{rad},k}(t)-T_{\mathrm{a},k}(t)]\,. \qquad (5)$$

where

$$T_{\mathrm{rad},k}(t)=\frac{T_{\mathrm{s},k}(t)-T_{\mathrm{re},k}(t)}{\ln\frac{T_{\mathrm{s},k}(t)-T_{\mathrm{a},k}(t)}{T_{\mathrm{re},k}(t)-T_{\mathrm{a},k}(t)}}+T_{\mathrm{a},k}(t)\,, \qquad (6)$$

$$K_{\mathrm{rad},k}(t)=\alpha(T_{\mathrm{rad},k}-T_{\mathrm{a},k})^{\beta}\Big|_{t-1}\,, \qquad (7)$$

$$\varepsilon_k(t)=\frac{T_{\mathrm{s},k}(t)-T_{\mathrm{re},k}(t)}{T_{\mathrm{s},k}(t)-T_{\mathrm{a},k}(t)}=1-\exp[-\frac{3.6K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}}{C_{\mathrm{w}}q_{\mathrm{m},k}(t)}]\,. \qquad (8)$$

α、β are characteristic coefficients of radiator gained from standard experiment. Subscript rad represents radiator, w represents water, s represents supply water, re represents return water.

TRVs model

Sense temperature

In the process of room temperature fluctuation, the temperature of TRVs sense can not be the same as the room temperature at once because of its thermal capacity. It can be expressed as

$$C_{\mathrm{sen}}\frac{dT_{\mathrm{sen},k}(t)}{dt}=K_{\mathrm{sen,a}}A_{\mathrm{sen}}[T_{\mathrm{a},k}(t)-T_{\mathrm{sen},k}(t)]\,. \qquad (9)$$

Define following variable

$$\tau_{\mathrm{sen}}=\frac{C_{\mathrm{sen}}}{K_{\mathrm{sen}}A_{\mathrm{sen}}},$$

Equation 4 will become

$$\tau_{\mathrm{sen}}\frac{dT_{\mathrm{sen},k}(t)}{dt}+T_{\mathrm{sen},k}(t)=T_{\mathrm{a},k}(t)\,. \qquad (10)$$

where C is heat capacity, T is temperature, t is time, K is heat transfer coefficient, A is surface area, τ is time constant; subscript sen represents sense, a represents air.

Take Δt as calculation step, the relation between $T_{\mathrm{a},k}(t)$ and $T_{\mathrm{a},k}(t-\Delta t)$ may approximately be described as zero-rank.

$$T_{\mathrm{a},k}(t)=T_{\mathrm{a},k}(\eta)=T_{\mathrm{a},k}(t-\Delta t)\,,\quad t\le\eta\le t-\Delta t \qquad (11)$$

Then the discrete solution of Eq (10) will be

$$T_{\mathrm{sen},k}(t)=\mathrm{e}^{-\frac{\Delta t}{\tau_{\mathrm{sen}}}}T_{\mathrm{sen},k}(t-\Delta t)+(1-\mathrm{e}^{-\frac{\Delta t}{\tau_{\mathrm{sen}}}})T_{\mathrm{a},k}(t-\Delta t)\,. \qquad (12)$$

Flow control

The radiator thermostat will always respond to changes in room temperature by controlling the flow-rate of radiator. The calibrated pressure in the bellows corresponds to the temperature of the sensor. This pressure is balanced by the force of a regular spring. On a rise in ambient temperature the pressure rises in the bellows, moving the valve cone towards the closed position until equilibrium exists between the bellows and the spring. Control equations of TRVs can be set up based on the characteristic curves gained from the test according to CEN EN215 standard (2004), with a pressure drop across the valve at 0.1 bar. Assuming that the pressure drop across the valve maintains Δp under operating situation, the flow control characteristic can be discribed using Eq (13). Coefficients A, B and C in Eq (13) can be gained from the curves by using least - square fitting.

$$q_{\mathrm{m},k}(t)=\begin{cases}\sqrt{\Delta p_k}/\sqrt{0.1}\left[A_k\Delta T_k^{\,2}(t)+B_k\Delta T_k^{\,2}(t)+C_k\right], & \Delta T_k(t)>0;\\ 0, & \Delta T_k(t)\le 0\,.\end{cases} \qquad (13)$$

where

$$\Delta T_k(t)=T_{\mathrm{cls},k}(t)-T_{\mathrm{sen},k}(t). \qquad (14)$$

q_{m} is quality flow-rate , T_{cls} is closing temperature determined by set value of temperature selector.

Formulation of a total model

The models of room, radiator and TRVs are not independent. The variables in one model always interact with those in other models. Some approximate measures are taken as decoupling, e.g., dealing with the influence of neighbour disturbance as mentioned above. The variables such as radiator power and room temperature are still coupling, which should be simultaneously resolved by equations.

From Eq(3) and Eq(5), Eq(15) will become

$$T_{\mathrm{a},k}(t)=\frac{T_{\mathrm{bz},k}(t)+\psi_{01,k}(t)K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}T_{\mathrm{rad},k}(t)}{1+\psi_{01,k}(t)K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}}\,. \qquad (15)$$

Put Eq(15) into Eq(4), Eq(4) can be transformed to

$$\frac{dT_{\mathrm{rad},k}(t)}{dt}=B_{2,k}+B_{1,k}T_{\mathrm{rad},k}(t)\,. \qquad (16)$$

where

$$B_{1,k}=\frac{\psi_{01,k}(t)K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}[K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}-C_{\mathrm{w}}q_{\mathrm{m},k}(t)\varepsilon_k(t)]}{[1+\psi_{01,k}(t)K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}]C_{\mathrm{rad},k}}-\frac{K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}}{C_{\mathrm{rad},k}}$$

$$B_{2,k}=\frac{C_{\mathrm{w}}q_{\mathrm{m},k}(t)\varepsilon_k(t)\ T_{\mathrm{s},k}(t)}{C_{\mathrm{rad},k}}+\frac{[K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}-C_{\mathrm{w}}q_{\mathrm{m},k}(t)\varepsilon_k(t)]\ T_{\mathrm{bz},k}(t)}{[1+\psi_{01,k}(t)K_{\mathrm{rad},k}(t)A_{\mathrm{rad},k}]\ C_{\mathrm{rad},k}}\ .$$

Resolve differential equation (16), the main temperature of radiator can be calculated as

$$T_{\mathrm{rad},k}(t)=\mathrm{e}^{B_{1,k}\Delta t}T_{\mathrm{rad},k}(t-\Delta t)-\frac{B_{2,k}}{B_{1,k}}(1-\mathrm{e}^{B_{1,k}\Delta t})\ . \qquad (17)$$

The model takes weather parameter, supply water, indoor casual heat gains, setting point of TRVs and characteristic value of each component as input. For the total model every room’s air temperature and radiator power are both unknown, however, in every calculation step for the calculating room *k*, temperature and radiator power of neighbor rooms are transformed to known values through proper approximation. Supposing that the time variant ventilation scheme is known, and flow rate can be calculated using room temperature at time t-1 according to flow control model, the unknown value left are air temperature and radiator power of room *k*, which can be obtained from Eq (17), Eq (15) and Eq (5). The return temperature of radiator can also be got from Eq(8). So at time *t* all of the rooms radiator flow rate, water return temperature, power and air temperature can be calculated one by one. Finally, time series respond of total water flow and return temperature in the building can be gained based on the quality and heat quantity conservation.

$$q_{m,\mathrm{tot}}(t)=\sum_k q_{m,k}(t) \qquad (18)$$

$$T_{\mathrm{re,\,tot}}(t)=\sum_k\frac{T_{\mathrm{re},k}(t)q_{m,k}(t)}{q_{m,\mathrm{tot}}(t)} \qquad (19)$$

model validation

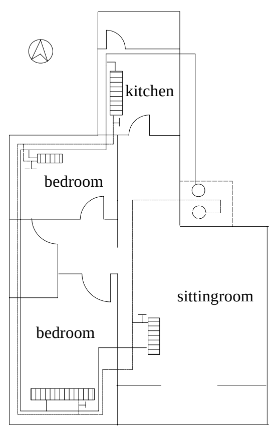

Fig.1 heating system in the room

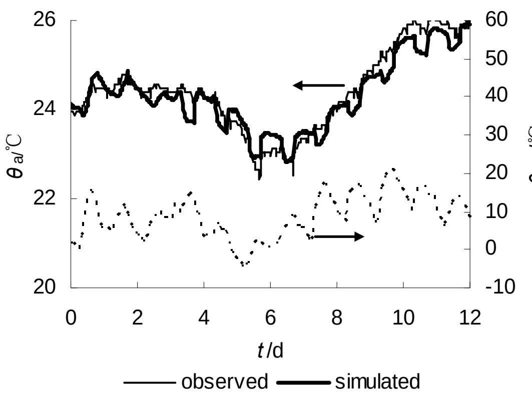

Fig.2 measured and calculated room temperature

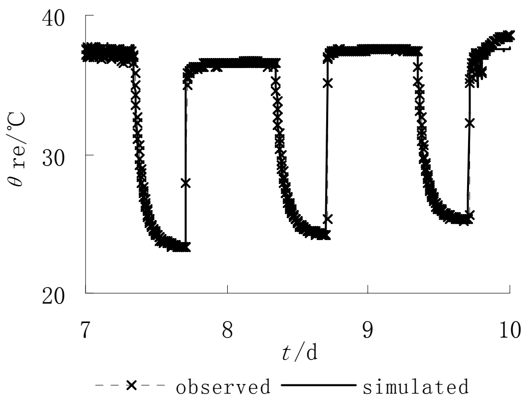

Fig.3 measured and calculated return water temperature

For testing the model, some district heat-metering system in Beijing was investigated during 2006-01—2006-03. The flow in each radiator is controlled by a thermostatic valve (Fig1). Regulate the valve according to schedule during 03-10—03-20. Put the setting point of the valves to antifreezing position during am 8:20—pm 17:00, and to maximal value at other time. Taking north bedroom as main study object, temperature self-record meters which can record the value per 5min were installed in the room, all of its neighbor rooms, outside the room, and at the outlet/inlet of the radiators. Solar radiation and indoor casual heat gains can be ignored in the northern empty tested room. The experimental measured neighbor room temperature, outdoor temperature and supply temperature are used as input to the model, then the measured air temperature and return water temperature are compared with the calculated values.

In figure 2 and figure 3, the agreement between simulated and measured values is quite good. The result shows that the maximal simulation deviation of return temperature and room temperature are both less than 1℃. Some of the differences must be attributed to three factors. One is experimental error;second, the accurate values of heat transfer coefficient of the envelope is hard to obtained; third, the influence of the wind speed is not taking into consideration.

CONCLUSIONS

A total model is formulated which can serve as a reasonable approximation of the heat and hydraulic dynamics of multi-family building under the TRVs control. Brief descriptions of models for several components such as room, radiator and TRVs are given. The sub-models are not treated independently but formulated as a whole model through simultaneously resolving the equations. An approximate method is used to simplify the coupling between one zone and its adjacent zones in the building. Comparisons between simulant and experimental data indicate that the model is suitable for detailed simulation.

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