Performance and Control Strategies of Heating Systems in Residential Buildings

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ABSTRACT

Purposes of the control of heating system are to keep the room air temperature variance in minimum for energy economic reasons and to maintain thermal comfort conditions in room spaces. There is no chance to reach these aims, if the whole heating system including control system is not designed, dimensioned and made with care.

To be able to compare different control strategies some criterion must be found. There are two possibilities; to compare energy consumption with optimal energy consumption or to calculate variance of indoor air temperature. The requirements in the ASHRAE and DIN Standards concerning thermal comfort conditions are not valid for evaluating the performance of heating system.

According to computer simulation and measurements in experimental and pilot buildings, the control loop should always be closed. In water radiator heating a closed control loop is obtained using well-dimensioned thermostatic radiator valves, linear / on-off magnetic valves controlled by the room air temperature. If microprocessors are used, either traditional PI-/PID-controllers of self-tuning algorithms can be used. Furthermore, extra compensators like wind and solar-air temperature compensators do not bring any improvement into the control results, if only weather compensation (outdoor air compensation) is used. Results of measurements in residential houses with open / closed loop control system are also given.

In direct electricity heating and warm air heating systems the temperature and heating power of each room can be controlled individually. A time proportional control strategy has been applied in both heating systems. The controlling of the heating power of each room separately is optimal, but unfortunately heating and control devices are not as sophisticated.

According to our field measurements we can conclude that the energy consumption of residential buildings with different heating and control systems does not differ significantly, but the room air variance does.

Some practical aspects concerning the design and dimensioning of heating system in relation to controllability are also given.

Les performances et les stratégies de contrôle des systèmes de chauffage des immeubles résidentiels

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MOTS CLEFS

Systèmes de chauffage, Immeubles résidentiels, Stratégies de contrôle, Critère de la performance, Simulation

SOMMAIRE

La raison de contrôler les systèmes de chauffage est de garder les variations de température au minimum pour l'économie d'énergie et de maintenir les conditions thermiques confortables dans les lieux habités. Ces buts ne sont pas accomplis sans la conception, le dimensionnement et la réalisation avec soin de l'ensemble du système de chauffage contenant le système de contrôle.

Pour pouvoir comparer les différentes stratégies de contrôle il faut d'abord choisir le critère. Il y a deux possibilités; soit la comparaison de la consommation d'énergie dans le cas optimal, soit le calcul de la variance de la température intérieure. Les exigences des normes ASHRAE et DIN concernant les conditions thermiques confortables ne sont pas valides dans l'évaluation de la performance d'une système de chauffage.

D'après les simulations par ordinateur et les mesures dans des bâtiments expérimentals et pilotes, le circuit de contrôle devrait toujours être fermé. Dans le cas de chauffage par circulation d'eau dans le radiateur, un circuit de contrôle fermé est obtenu en utilisant des soupapes de radiateur thermostatiques proprement dimensionnées, des soupapes magnétiques linéaires / on-off contrôlées par la température de l'air intérieur. Avec les microprocesseurs on peut utiliser soit des contrôleurs traditionnels PI/PID, soit des algorithmes réglant soi-même. En outre, les compensateurs supplémentaires pour compenser par exemple l'effet du vent et de la température de l'air solaire n'améliorent pas les résultats de contrôle, si on utilise seulement la compensation d'état du temps (compensation de plein air). Des résultats des mesures dans des immeubles résidentiels munis de système de contrôle à circuit ouvert / fermé sont aussi présentés.

Avec les systèmes de chauffage électrique direct et de chauffage par circulation d'air chaud, la température et le chauffage peuvent être contrôler séparément dans chaque pièce. Une stratégie de contrôle proportionnelle à temps a été appliquée dans ces deux systémes de chauffage. Le contrôle du chauffage de chaque pièce séparément est optimal mais malheureusement les appareils de chauffage et de contrôle ne sont pas aussi sophistiqués.

D'après nos mesurages en terrain nous pouvons conclure que la consommation d'énergie des immeubles résidentiels ne varie pas beaucoup selon les différents systèmes de chauffage et de contrôle, mais la variance de la température de l'air intérieur le fait.

Aussi, quelques points de vue pratiques concernant la conception et le dimensionnement des systèmes de chauffage relatifs à la contrôlabilité sont présentés.

INTRODUCTION

In many cases, if the control result is not acceptable, it claimed that the control system does not work. This is not, however, a right conclusion. Control problems arise from the process or from the control strategy more often than from the controller. For example, microcomputer - based controllers and supervision systems with direct digital control applying complicated control algorithms have become rather frequent while the research and development of heating and air-conditioning processes have been neglected.

Purposes of the control of heating systems are to keep the variance of room air temperature in minimum for energy economic and thermal comfort reasons. This means that heating energy is saved; heat gains are exploited; and better thermal comfort conditions are achieved.

In this paper, the performance of heating systems will be discussed. Also some aspects of the design of the whole heat distribution system will be introduced based on computer simulation and field / laboratory experiments.

EVALUATION OF CONTROL RESULT

The evaluation of the performance of heating and control systems is somewhat problematic. One possibility is to compare the energy consumption of a real system with the theoretical consumption:

$$\eta_s = \frac{\int^t \phi_{opt}(t)\ dt}{\int^t \phi_a(t)\ dt} , \qquad (1)$$

where the subindexes opt and a denote the theoretical and actual energy consumption, respectively.

In Equation (1), there is not taken into account the restrictions on indoor temperature in relation to thermal comfort and thus it is not alone a reasonable basis to evaluate heating and control systems.

An other approach to evaluate the control efficiency is to calculate the variance of indoor / operative temperature for a certain period

$$J = \frac{1}{n} \sum_{i=1}^{n} (T_{o,i} - \tilde{T}_o)^2 , \qquad (2)$$

where $T_{o,i}$ is indoor air / operative temperature at time i
$\tilde{T}_o$ set point of the operative / indoor air temperature
n number of measurements.

This approach is resonable only, if heat gains are smaller than heat demand, because indoor air temperature will rise even if the heating system is switched off (there is no cooling power in ordinary heating systems in residential buildings).

In the ASHRAE-Standard 55-81, there are some requirements on the thermal comfort conditions applicable in the evaluation of the performance of heating and control systems. In non-steady state, if the peak variation in operative temperature exceeds 1.1 K, the rate of temperature change shall not exceed 2.2 K/h. There are no restrictions on the rate of temperature change, if the peak to peak is 1.1 K or less.

According to our field measurements in residential houses, these requirements can not be fulfilled: indoor air temperature variation was usually ∓ 2 K. There was not, however, a significant difference in energy consumption in different heating systems. Measurements in our test house and test room showed that the indoor air temperature variation with cyclic heat gains was on an average ∓ 1 K. Neither in these cases, the ASHRAE requirements were fulfilled.

In the ASHRAE-Standard 55-81, there is also demand for temperature drifts or ramps. Slow rates of operative temperature change (approximatelly 0.6 K/h) during the occupied period are acceptable. The temperature must not, however, extend beyond the comfort zone by more than 0.6 K and for longer than one hour.

THE CONTROL SYSTEM IS A PART OF A WHOLE

The control system is operating under the influence of several things: heating process; design and dimensioning; workmanship; and inhabitant behavior. There is no chance to achieve an acceptable control result, if the whole heating system (including the control system) is not designed, dimensioned and made with care.

In water radiator heating with thermostatic radiator valves both heat distribution network and thermostatic valves affect the control result. According to computer simulation, primary heating load is increased if the proportional band, hysterisis or the heating effect of supply water is increased or if the valve authority is decreased (Table 1). Correspondingly, the indoor air variance is increased.

Test room measurements (Fig. 1) showed that if the inlet temperature is rised, the level of mass flow rate decreases but the oscillation of mass flow rate increases (the oscillation frequency doubled). The operation conditions of the thermostatic valve get worse because the characteristic curve of a nearly closed valve is indefinite. The temperature of the sensor of the thermostat increases and the indoor air temperature decreases, correspondingly. A temperature difference 0.3 K of the sensor correlated with a temperature difference 0.2 K of the indoor air.
A heat gain of 200 W (67 % of the heat demand) was brought into the test room between 7.00-8.00 and 18.00-22.00. The outside temperature was kept constant. The "gaps" in the inlet temperature curve are due to cooling of the water in the piping when the mass flow rate decreases.

The authority of thermostatic radiator valves can be kept nearly constant (0.6-0.8) and the distribution network hydraulically stabile, if pipes are dimensioned for low (50-100 Pa/m) friction losses and thermostatic radiator valves for high (2-4 kPa) pressure drop and using pressure difference or by-pass valves in columns. Correspondingly, supply air terminals in warm air heating systems should be dimensioned for the pressure drop of 50 Pa.

ASPECTS OF THE CONTROL OF HEATING SYSTEMS

Some general aspects concerning the design of the control system of heating systems can be given based on simulation and field / laboratory measurements. Control system should always be closed; extra compensators (wind, solar-air) should not be used because of difficulties in tuning; heating power of each room space should be individually controllable; self-tuning (microprocessor-based systems) can have advantage over traditional analog systems also in the control of heating system; inhabitants should have possibility to change the thermal comfort conditions according to their pleasure.

Using microprocessors it is possible to apply more sophisticated control algorithms than in analog techniques. Unfortunately, almost all commercial DDC-controllers are based on the traditional PID-algorithm. Also the tuning of control systems, often failed, can be left for the controller itself in adaptive systems. Another possibility to make use of sophisticated (adaptive) control algorithms is emulation of controllers with fixed parameters. In other words, the fixed parameters are determined by using an adaptive control algorithm instead of the conventional algorithm. The emulation should be carried out, at least, when the plant is started and when the operation conditions of the heating system are changed.

If sophisticated control algorithms are used, also heating systems and their components (process) must be technically at the same level.

In water radiator heating a closed control loop is obtained using well-dimensioned thermostatic radiator valves or linear / on-off magnetic valves controlled by the room air temperature.

In water radiator heating the feedback of indoor air temperature can be obtained also from the extract air. This information can be used as a restriction, i.e., the weather compensation curve is in a band. According to field measurements, a better thermal performance is obtained with thermostatic radiator valves than with extract air compensation in a heating system, where the supply water temperature is weather-compensated.

According to computer simulations, extra compensations in water radiator heating are energy efficients, but in practice they can spoil the whole control system, because it is very difficult to tune them. The only possibility to get use of the extra compensators is to apply predictor models, which are, however, more reasonable in closed loop control system, where all disturbances can directly be taken into account.

In direct electric heating each heat emitter can be controlled individually. Controllers are based either on traditional P-control or time proportional control strategy. Thus there exists always a difference between the set point and actual value, and heating power is on, if the actual value is with the proportional band. We should also note that temperature sensors should be placed on a wall surface in order to avoid the drift of set point, which can be, according to measurements, as high as 7 K.

To aim to control heating power and thermal conditions individually in each room space means that there is a heating coil with control devices in each room in warm air heating systems.

Figure 2 shows a warm air heating system developed at our laboratory. Terminal heaters can be electric or water coils. Heating power of electric/water terminal heaters can be controlled by thermostats; time-proportional/thermostatic; time-proportional magnetic valves, respectively.

Unfortunately, only periliminary tests have been carried out, but the results so far have been very encouraging. We should note that there is also cooling capacity in this kind of air heating system.

A warm air heating system was also tested in an occupied small house. The commercially available controller based on a self-tuning PID-algorithm with sample time of 20 seconds. In the first experiment, the control loop was open, i.e., the supply air temperature was dependent on the outdoor temperature. The indoor air temperature was swinging significantly. The controller itself worked according to the algorithm. At the second stage, the correcting range of the control system was restricted; heating was switched off/on, if the indoor air temperature was over +22 °C / below +20 °C. The control result was better than with pure weather compensation.

In the last experiment carried out in spring time, heating power was controlled directly by the indoor air temperature. Although heating power was switched on only for short periods the indoor air temperature rised owing to heat gains. If open loop control system were used, heating power should have been on. Figure 3 gives results of the three experiments.

CONCLUSIONS

Requirements and evaluation of the control result, design and dimensioning as well as the thermal performance of heating systems in residential buildings was discussed.

The evaluation of control result can be based either on energy or thermal comfort aspects. From the theoretical point of view, the variance of indoor air/operative temperature in relation to the set value is a reasonable criterion in evaluation of control result. There is, according to our field measurements, also a correlation between the room air temperature variance and energy consumption.

Procedures and criterions should be developed for testing the performance of heating and control systems. Only this will guarantee the development of process, control systems and devices to a sufficient high level.

The building, HVAC-system and it's control system are inseparable parts of a whole. The design and dimensioning of those parts should be made with care. It is not a problem to spoil the operation possibilities of the control devices with bad design and installation work.

Closed - loop control should be used in heating systems, and each room space should be controlled individually. In water radiator heating closed - loop control can be achieved by using thermostatic / magnetic radiator valves. In direct electric heating, each heat emitter can be controlled individually, but because of set point drift the control will work well enough only if the sensors are placed on a wall surface. In warm air heating the heating power should be controlled directly by the indoor air temperature.

Annual energy consumption in heating systems (water radiator, direct electric, warm air heating) do not differ significantly if differences in the overall k-value of envelope and in ventilation rate as well as in indoor air temperature are taken into account in the nomination of annual energy consumption. The exploitation of heat gains like the control result differ, however, significantly.

Microprocessor based controllers and supervision systems have become rather frequent. This development make the integrated control of HVAC-systems possible, which should be the aim in long term.

TABLE 1

Influence of thermostatic radiator valve on the control result

PROPERTY	EXPLOITATION OF HEAT GAINS	CONTROL RESULT	
		ROOM AIR TEMPERATURE VARIANCE	MEAN ROOM AIR TEMPERATURE, °C
Hysteresis 0 → 1 K	Decreases significantly	9,54	21,25
Valve athority 1,0 → 0,2	Decreases	9,70	21,5
Proportional band 2 K → 3 K	Decreases significantly	10,40	21,75
I d e a l*		9,61	21,3

* Hysteresis 0, valve authority 1, proportional band 2 K .

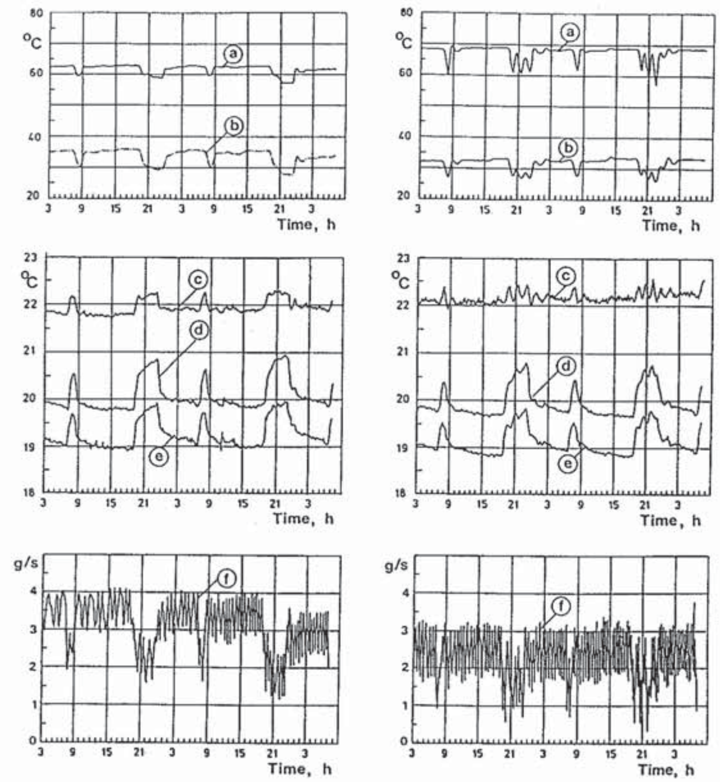

Fig. 1. The effect of inlet temperature rise to the performance of water radiator network and indoor air temperature.

(T_{inlet} = 62,5 °C on the left and T_{inlet} = 68 °C on the right)

a) inlet temperature, °C
b) outlet temperature, °C
c) temperature of sensor, °C
d) indoor air temperature, 1500 mm above floor, °C
e) indoor air temperature, 50 mm above floor, °C
f) mass flow rate, g/s

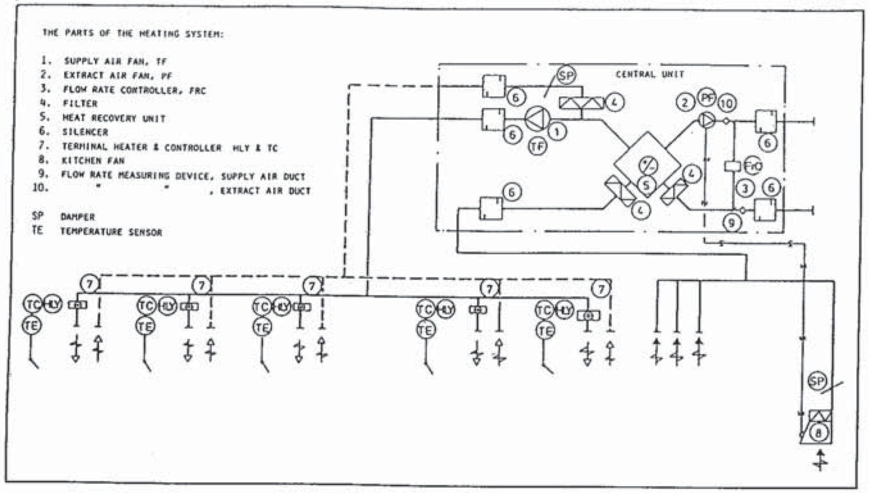

Fig. 2. A warm air heating system developed in the Laboratory of Heating and Ventilating, VTT.

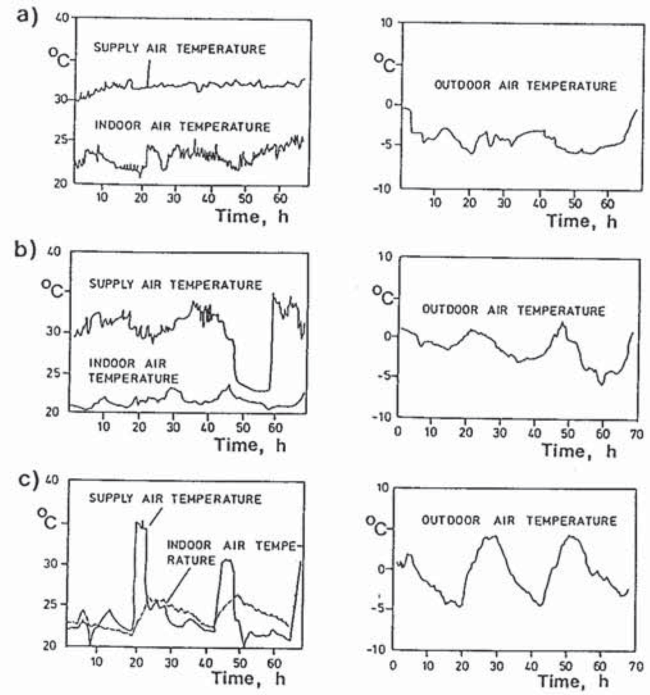

Fig. 3. Indoor, outdoor and supply air temperature in warm air heating.

a) open loop control
b) open loop control with correcting range
c) closed loop control