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DECENTRALIZED CONTROL OF AIR DISTRIBUTION FOR INDIVIDUAL AREA ENERGY MANAGEMENT

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ABSTRACT

Air distribution systems form the predominant mode of energy distribution for environmental conditioning in homes and small buildings, especially in North America. Most existing buildings employ a single heating/cooling source based ducted distribution system designed to provide a balanced energy distribution to the entire structure. Thus, temperature control of the entire structure, or in some cases entire zones, can only be accomplished. Efficient energy management methodologies, such as occupancy based environmental conditioning, depend upon the ability to control temperatures of individual areas to reduce heat loss or gain from setback zones. Such control requires unbalancing the distribution. The unbalancing has the potential for further improving energy efficiency by directing conditioning air flow to only those non-setback areas that need conditioning. In this paper we investigate the problem of retrofitting conditioning air distribution control, to provide individual area environmental conditioning in an existing structure designed with a balanced distribution, and to improve building ventilation.

KEYWORDS Room Airflow, Energy Conservation, Distributed Control

INTRODUCTION

Space conditioning accounts for significant energy usage in the United States. The high cost of fuels has led to increased efforts for conserving this mode of energy usage. Rickelton (1988) has shown that variable-air-volume (VAV) systems provide an effective way of reducing energy in buildings. Using simulations Mutammara and Hittle(1990) showed that proportional plus integral (PI) control strategy to be the most effective for reducing energy costs in VAV systems.

Reducing electronic processing and control hardware costs have made it economically viable to introduce VAV systems in small residential forced air conditioned buildings. Nungester and Rhodes (1989) have investigated conversion of original constant volume single-zone systems into multi-zone VAV systems. Their investigation focused on the ability of the system to maintain a minimum airflow across the heat exchanger without the use of a bypass damper. Minimum airflow is necessary to prevent burning up or freeze up of the heat exchanger tubes. The use of bypass dampers negatively impacts energy savings. They simulated the operation of a seven zone retrofit system to study the effects of damper positioning on heat exchanger airflow. Their study concludes that motorized dampers can be installed and used to control airflow without recourse to an inefficient bypass damper arrangement.

Individual area control can be used to effect energy management. Gajjar (1976) has shown that control point setback based on occupancy and projected occupancy of individual zones can provide significant energy savings by reducing building envelope energy loss and gain. McKee and Falcigno (1991) have shown the implementation of a communication protocol to effect such control using a single chip microprocessor network using carrier signals over the house power line. In this paper we consider the problem of retrofitting air distribution control to provide individual area environmental conditioning in an existing single-zone building with a balanced distribution. Using a simplified model we develop a simple control heuristic for implementing the control.

System Description

Cost minimization and ease of installation are important considerations in system design for retrofit applications. A large majority of existing residential heating/cooling systems employ bang-bang controls since they are robust. Furnace actuation is controlled by the room and over-temperature thermostats. Furnace operation is cycled to provide bonnet deck-air temperature within a few degrees of the cut-in temperature. Air distribution is controlled directly by sensing the deck-air or plenum temperatures. An important factor in ease of installation and cost minimization is to make as much use of existing control actuation as possible.

The modelled system is designed to interface directly with existing heating system actuation. When the system controls furnace operation, it provides cycling of the furnace to appropriately regulate deck-air temperature. The other installation modifications to the existing system consist of replacing existing registers with control actuated registers that operate either open or shut, with the unactuated normal position being open. The registers are connected to zone control and sensing modules that sense zone temperature and occupancy, and communicate to a central controller. Occupancy information is used to provide setback control or for correction in predictive implementations.The controller in turn communicates control commands to the zone control modules and to a furnace control module that interfaces to the furnace thermostat terminals.

The system operation is essentially open-loop except for zone temperature and set point feedback. These are logically related to the on-off control actuation of zones. Further, furnace operation control is only logically related to the zone feedback. Otherwise, plant operation is controlled by its inherent robust bang-bang control. VAV control is achieved through unbalancing the air distribution by means of damper control at the registers. Such control results in heat exchanger air flow control due to variation in back pressure at the distribution side of the bonnet, which in turn affects operating point on the fan curve. Following Nungester and Rhodes (1989), we note that any control methodology must ensure a minimum airflow rate of 73% of system maximum through the heat exchanger. From Figure 2 of their simulation, it should be noted that if only one zone is active, its flow rate will be up to three times the system balanced flow rate and the total airflow will drop below the minimum limit. Hence it is important to determine the impact of overflow on dynamics of the active zone. The simplified model developed below is useful in approximating the dynamics.

Model Development

Several different modelling approaches have been used to represent the complex interaction between the heating/cooling system and transients due to radiation, convection and conduction in rooms. The simplified approach undertaken here is guided by formulations of Anders (1977) and Athienitis et. al (1990). Several assumptions are made to reduce model complexity:

1. lumped properties are assumed for thermal transfer processes,
2. humidity changes are neglected,
3. volume specific heat of air c_v is assumed to be independent of temperature,
4. radiant heat transfer is simplified using a linear approximation, and
5. room air is assumed to be fully mixed.

After dividing by c_v, the mass and energy balance relations, for active air flow into the room can be expressed as:

$$F_{eq} T_{eq} = V_R \frac{d T_R}{d t} + F_{eq} T_R + K T_R \qquad (1)$$

where

$F_{eq} = (F_A + F_i)$, is the equivalent room air flow rate (m^3/sec.)

T_{eq} is its equivalent temperature expressed as $(F_A T_A + F_i T_i)/(F_A + F_i)$ (°K)

V_R represents an air volume with heat capacity equivalent to room capacity (m^3)

T_R is the room temperature (°K), and

K is an equivalent flow rate representative of heat loss to the exterior building mass and intra-zone infiltration

F_A and F_i respectively represent system supplied and infiltration flow rates, and T_A and T_i represent their respective mean temperatures. The second term on the right hand side represents displacement ventilation, i.e. excluding direct room infiltration. The system time constant can be expressed as: $\tau = V_R / (F_{eq} + K)$. If we define the steady state temperature by: $T_{SS} = F_{eq} T_{eq} / (F_{eq} + K)$, the room temperature starting from an initial value of T_{RI}, can be expressed as:

$$T_R(t) = T_{SS} - (T_{SS} - T_{RI}) \exp\left(-\frac{(t+\Delta)}{\tau}\right) \quad (2)$$

In the above Δ represents the total of the sensing time constant, the mixing lag, the heat exchanger storage time constant, and transport lag through the duct. The above approximation represents the dynamic behavior from the commencement of airflow into the room up to its cessation due to room demand being satisfied. With Δ set to zero the equation represents idealized room temperature. Temperature overshoot can be estimated by first calculating the time for the idealized value to reach the set point and using that value for t in equation 2.

RESULTS AND DISCUSSION

The effects of increased flow due to unbalancing the dynamics were simulated using the approach described. The simulation parameters were representative of those used by Nungester and Rhodes (1989), i.e. a residential structure with seven zones and a 29 kW furnace and a maximum air flow rate of 0.4 m^3/s. Figure 1 shows the room response from a setback temperature of 10 °C for various flow rates. The curves marked 1,2,3,and 4 respectively correspond to one, two, 2.5 and three times the normal room flow rate with all dampers open. Figure 2 shows the temperature overshoot over the setpoint as a function of system lag time (Δ).

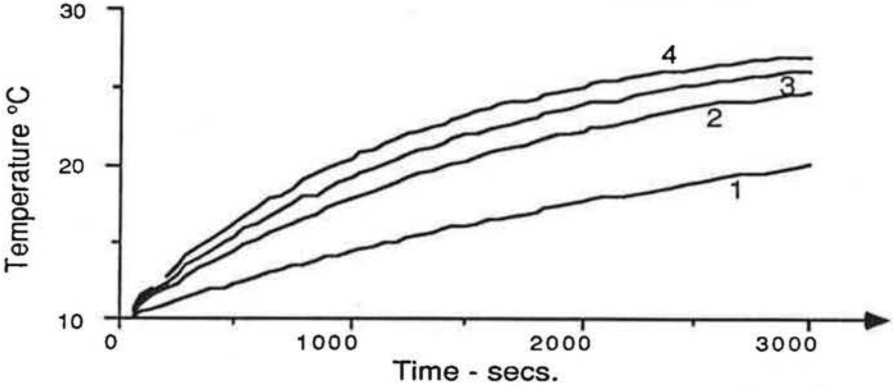

***Figure* 1** *Room response from a setback temperature of 10 °C*

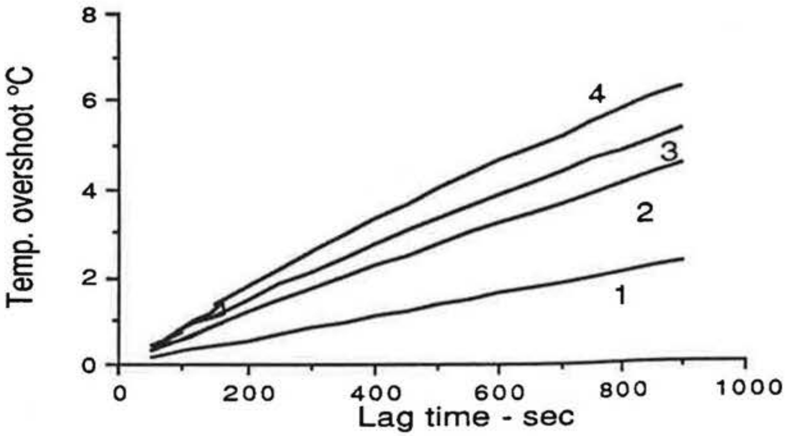

Figure *2 Temperature overshoot as a function of system lag time.*

The results compare favorably with those obtained by Anders 1977. The need for permitting 35% damper opening suggested by Nungester and Rhodes (1989), translates in the present system to ensuring that approximately one-third of the zones need to be active whenever the furnace is operating. At a minimum one of these is the one causing furnace actuation. In the worst case the remaining zones will have to be time-shared for this duration. This time-sharing provides pulse width modulation operation, which approximates PI control. The need to provide maximum setback in unoccupied zones leads to the following operation heuristic and sets up a hierarchy of zones that are preferred.

1. Zones that are demanding conditioning.
2. Occupied zones that have not been satisfied to the upper cut-off set point, and
3. Unoccupied setback zones to be time-shared.

It should be intuitively clear that for the most part, the first two levels of the hierarchy will be needed in a majority of situations. Major exceptions to this will occur when only one zone is occupied or when occupancy shifts from one zone to another.

Impact on Ventilation

The control methodology represented by occupancy based individual area energy management can also be employed to provide an efficient ventilation environment by mixing fresh air to the blower fan input. Two major benefits accrue from this mode of operation. On one hand occupied zones, due to their increased heat loss or gain, will receive more frequent actuation and concomitant improved ventilation. Ventilation of unoccupied zones, where it is not needed, will be less frequent.

The second benefit results from the fact that for the most part air circulation will be provided only to a few zones at a time. The flow rate into the active zones will be usually substantially higher than that obtained by flow to the entire structure, especially where the total flow rate is constrained by turning down all dampers to reduce air flow in all zones. This will result in more efficient mixing in and scavenging of the active zones while at the same time utilizing a minimum amount of external air.

CONCLUSIONS

The results of our simulation show that the approach to retrofitting existing forced air conditioned residences, using occupancy as a criteria for control of individual areas, will serve to both reduce energy consumption and to improve air quality, while at the same time utilizing a minimum amount of external air to effect ventilation. More detailed modelling and verification are suggested by our results. The approach has the potential to be effectively used in hotels and office buildings to provide efficient ventilation and improved energy utilization.

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