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Technologies toward Thermal Comfort-based and Energy-efficient HVAC Systems: A Review

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***Abstract*—This paper reviews thermal comfort based control strategies for modern commercial buildings with heating, ventilating, and air-conditioning (HVAC) systems. In order to make HVAC systems more energy-efficient, better system operations and control algorithms for HVAC systems are demanded. Research conducted predominately within the last decade suggests that commercial building HVAC significantly influences the health, satisfaction, and productivity of the building occupants. This paper also projects the use of Wireless Sensor Networks (WSNs) to enhance energy efficiency of HVAC systems as well as provides comfortable environment to assure occupants' productivities.**

***Keywords*— Heating, ventilating, and air-conditioning (HVAC), Control, Wireless Sensor Networks, Wireless Sensors**

I. INTRODUCTION

Heating, ventilating, and air-conditioning (HVAC) systems are applied in modern commercial buildings to maintain a reasonable level of thermal comfort while limiting energy consumption and cost. As shown in Figure 1, a typical HVAC system consists of two major parts: in-building part and out-building part. The features of HVAC systems in a given building rely on several variables including [1]:

- the age of a building
- climate
- building codes in effect at the time of the design
- budget that is available for the project
- planned use of the building
- owners and designers' individual preferences
- subsequent modifications

HVAC systems provide buildings with heating/cooling function, filtered outdoor air and proper humidity level, thereby reducing the outside environmental impacts on buildings and their occupants. Well-designed efficient systems achieve this with minimal non-renewable energy and air/liquid pollutant emissions.

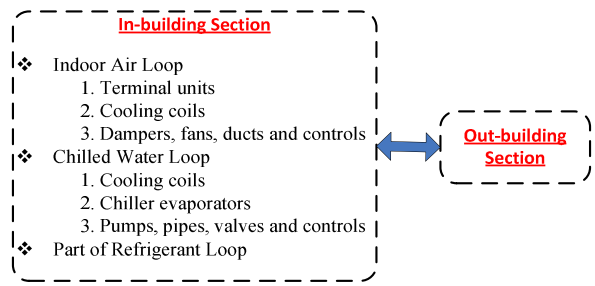

Figure 1 Block Diagram of a HVAC System

The major objectives of HVAC control systems are to maintain occupant comfort at a minimal energy use. Research conducted in the last decade suggests that HVAC systems can greatly affect the thermal comfort, health, satisfaction, and productivity of building occupants. Meanwhile, they play a huge part in a building's overall energy consumption. According to the US Department of Energy, they account for 40 to 60% of the energy used in US commercial and residential buildings [2]. As reported by the U.S. Energy Information Agency, world energy consumption was projected to grow by 71 percent from 2003 to 2030 [3]. Two-thirds of the primary energy use in the US is electrical and about two-thirds of all electric power is used in buildings [4]. Within HVAC systems, water heating is responsible for a significant percentage. According to some assessments, energy consumption in buildings could be reduced 20-40% through appropriate control strategies [5]. A typical centralized HVAC system is shown in Figure 2. A large portion of building energy consumption comes from the components of the in-building section [6]. A small increase in their operating efficiency can result in substantial energy savings.

Some current HVAC control strategies, however, are weak in achieving occupant comfort requirements while leading to significant energy cost. People sometimes have to stay in uncomfortable work environments, or attend a meeting in a conference room that is too hot or cold. Most of the current HVAC systems cannot meet comfort requirement and save energy simultaneously. Although the HVAC maintenance cost increases by millions of dollars annually in commercial buildings, occupants never stop complaining about their uncomfortable working environment [7]. Much energy is wasted through the inappropriate or out-of-date temperature control strategies.

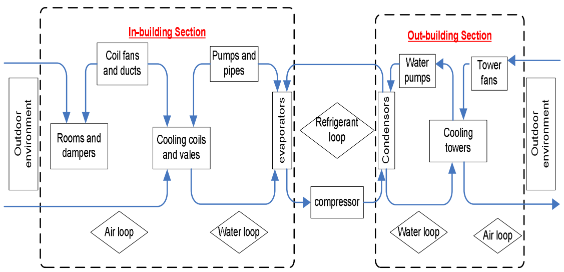

Figure 2 A Typical centralized HVAC System

The remainder of the paper is organized as follows. Conventional Proportional, Integral and Derivative (PID) control in HVAC systems is discussed in Section II. Section III reviews the advanced thermal comfort-based methodologies applied in HVAC systems including neural network and fuzzy logic-based intelligent control strategies. Challenges and future research issues of deploying WSNs in building HVAC systems in order to save energy and reach the highest comfort requirements of occupants are presented in Section IV. The last section concludes this review paper.

II. Conventional PID Control in HVAC Systems

Most of the conventional controllers commissioned in HVAC systems are of PID control [8]. Several types of PID controllers are used in HVAC systems [9]. Their main advantage lies in their relatively simple structures, which can be easily understood and implemented in practice. Their cost and failure risk are both low since they are mature technologies. They are thus more acceptable than advanced controllers in practical applications.

In HVAC control, there is one controlled variable --typically a temperature or pressure point, and one controlled device --valve, damper, motor speed, etc. in each control loop that is modulated to maintain the controlled variable at a specific value (set point) using a feedback circuit to compensate for changes in external conditions. PID calculations adjust motor speed as necessary to maintain a set point as shown in Figure 3 [10]. By adjusting cooling-tower-fan-motor speed, the speed of a cooling-tower fan and the temperature of water discharged from the cooling tower can be controlled to maintain a desired temperature set point. This control strategy leads to low initial cost and a simple system structure. However, to obtain a set of workable PID controller parameters, requires an accurate model of a process and an effective controller design rule. The tuning procedure can be a time-consuming, expensive and difficult task [11,12]. It may take a control engineer up to three days to search for a proper PID controller setting for an air pressure loop in a building [13]. The situation is even worse, if re-tuning is needed which is true for many large HVAC systems. It is also realized that many loops in practice are poorly tuned due to lack of process knowledge. Therefore, it is highly desirable to develop workable PID autotuning technology for HVAC industries. Autotuning has been widely and successfully applied to many industrial fields [14]. Nesler [15] developed a computer-based autotuning and selftuning controller, where the open loop step test of Ziegler and Nichols methods was used to derive the process model and controller.

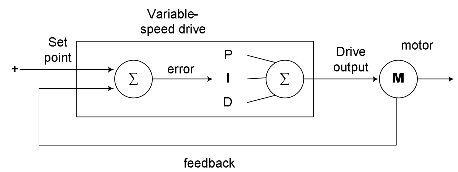

Figure 3 A typical PID control concept.

Although a network that connects all PID controllers has sophisticated features that provide much greater flexibility, most systems still operate with fundamental problems. The most serious one associated with the use of PID control in HVAC systems is inefficient system operation [16]. Conventional PID control loops are not directly associated with energy optimization, thus routinely attempts to adjust the temperature/pressure set points for energy optimization are ineffective and leads to unacceptable outcomes. Most of PID control requires a compromise in energy efficiency and stable control. Therefore, modern HVAC systems have to embody an ever widening range of technologies to achieve the increasing demands of occupants.

III. Thermal Comfort-Based Advanced Control

A. *Thermal Comfort Index*

Continued use of standalone PID control techniques, however, seriously undermines the performance, stability, efficiency and reliability of these modern building HVAC systems. Creating thermal comfort for occupants while consuming less energy is now a primary goal of the HVAC industry. Regarding the first part of this goal, there has been considerable work in the formulation of thermal comfort models that can be used to control HVAC systems [17- 20]. In order to yield a desired condition for human comfort, real-time determination of human thermal comfort is desired. However, thermal comfort is a very vague and not easily defined term, and it is influenced by both physical environment and individual's physiology or psychology. To overcome these problems at least partially, an indicator of human thermal comfort, predicted mean vote (PMV), was technically proposed and defined as the thermal comfort index as early as in 1972 by Fanger.

The value of the PMV index is from (-3, 3) as shown in Figure 4, which corresponds to the human's feeling from hot to cold. The null value of the PMV index means neutral. It is used to predict the mean thermal sensation vote on a standard scale for a large group of persons.

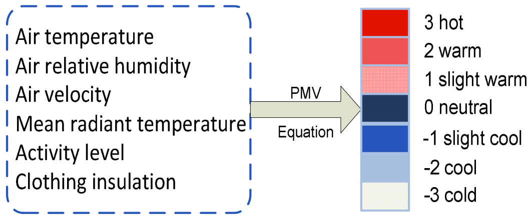

Figure 4 Fanger's PMV Model

PMV [17] is a function of the following variables:

T_i	Indoor air temperature *(°C)*
T_{mrt}	Mean radiant temperature *(°C)*
M	Human activity *(kcal/hm2)*
v	Relative air velocity *(m/s)*
P_v	Vapor pressure in the air *(mmHg)*
I_{cl}	Thermal resistance of clothing *(clo : 1 clo = 0.18°Cm2h/cal)*
h_c	Convective heat transfer coefficient *(kcal/m2h°C)*
f_{cl}	Ration of the surface area of the clothed body to the surface area of the nude body
T_{cl}	Outer surface temperature of the clothing *(°C)*
RH	Relative humidity in percent *(%)*
P_s	Saturated vapor pressure at a specific temperature *(pa)*

Because PMV is nonlinear with its variables, its calculation is complex. Some algorithms have been derived to simplify it. Fanger and ISO proposed in [21] to use tables and diagrams to simplify the calculation of the thermal comfort sensation in practical applications. This method necessitates manual selection of the environmental variable set points that create optimal indoor thermal comfort. From a practical point of view, this solution is difficult to use because it requires detailed knowledge of the HVAC control techniques. Other studies proposed simplified models of calculating the thermal comfort index to avoid an iterative process. Such simplified model-based controllers are proposed in [18]. A comprehensive fuzzy evaluation model is developed based on fuzzy logic to estimate the thermal comfort level as presented in [22]. Li and Zhang [23] develop a new thermal comfort degree softsensor model based on CMAC (Cerebellar Model Articulation Controller) neural network to calculate PMV. Because the algorithm is simple and has a quick learning speed, the model can be built more easily compared to the conventional Fanger model, as shown in Figure 5.

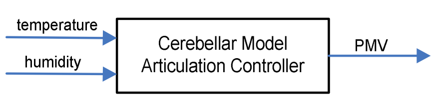

Figure 5 A Softsensor Model

B. Thermal Comfort -based and energy efficient HVAC System Design

Since the evaluations of thermal comfort are accurately defined by PMV index, to provide healthy and comfortable interior conditions to maintain occupants' high productivity becomes more realistic. More advanced controllers should be designed to reach good tradeoff between minimizing energy consumption and maximizing occupants' comfort metrics based on the PMV index.

1) Neural Network (NN) based HVAC System Control

HVAC systems are multiple-input multiple-output (MIMO), nonlinear and time-varying systems. A difficulty in HVAC system parameter estimation is they have multiple time varying parameters. Some intelligent approaches, such as NN, are appropriate for controlling HVAC systems. The application of intelligent control to HVAC systems is proposed by Shoureshi and Rahmani [24]. Curtiss *et al.* [25] discuss the results of applying NN for both local and global HVAC system control. Some thermal comfort sensing systems and controllers based on PMV design are proposed in [26-29]. Liang and Du [30] propose an NN-based thermal comfort control of HVAC to overcome the ever-increasing pressure of energy saving. Instead of using the simple on/off control or conventional PID control, their NN-based control strategy is similar to comfort index regulators control but with more powerful functions, as shown in Figure 6. This model shows that the PMV values of the conventional temperature control can fluctuate between (-0.5, 0.5) under ambient disturbance. Therefore, this new strategy can help to achieve higher comfort level. However, some limitations still exist. For example, as we mentioned before, there are two human conditions in Fanger model, human activity and clothing insulation. These two individual dependent variables cannot be measured and are currently set as a constant with respect to the season. Therefore, their approach can be improved by using sensors to measure and use these data directly.

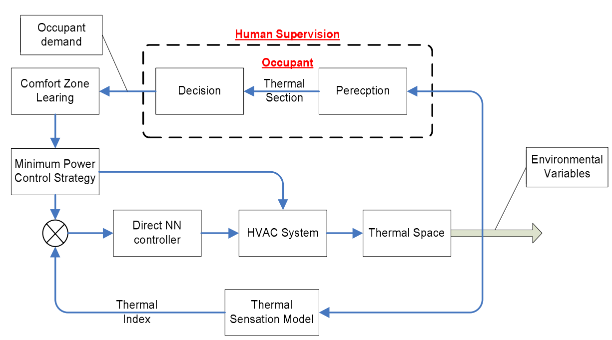

Figure 6 Neural Network-based control for HVAC system

2) Fuzzy Logic Based HVAC Systems Control

Fuzzy set theory was first proposed by Zadeh in [31] and is an extension of the classical set theory. It deals with fuzziness of the real world and simulates a human's subjective thinking by incorporating the inherent imprecision of the human thought process. A fuzzy controller is used to make decisions in which approximate reasoning is required, such as the estimation of human comfort.

Guo et al. [32] proposed fuzzy logic control to be an excellent alternative. Since it is based on the operational experience of human experts, the system is robust to changes in environment. Compared to traditional control approaches, its advantage resides in the fact that no mathematical modeling is required.

The design process of the fuzzy logic based HVAC systems control is mainly based on the human knowledge of the system behavior [22]. The proposed architecture of their TCL (Thermal Comfort Levels)-based fuzzy control system, as shown in Figure 7, has two main advantages. First, it is equipped with an online comfort verification process; second, the operation of the HVAC system can be set to follow occupant personal preferences. These characteristics could be of importance in the development of modern HVAC systems by using thermal comfort sensors to quantify the user's degree of thermal comfort/discomfort. So et al. in [33] developed a fuzzy controlled air handling unit (AHU) controller.

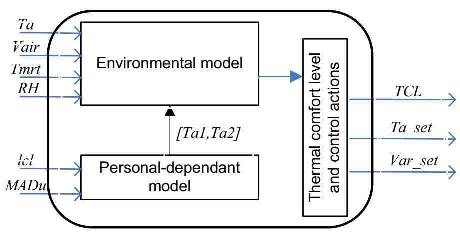

Figure 7 TCL-based fuzzy systems

However fuzzy control needs expert experience to lay down linguistic rules as well as identify all fuzzy membership functions. Meanwhile it is often difficult to express human experience exactly using linguistic rules in a simple form. Sometimes there is no experience that can be used to construct control rules. Due to the above problems, it is necessary to design and develop a more efficient control approach to obtain optimal performance and reduce energy usage of HVAC systems. Fuzzy logic should be applied to the evaluation of the air velocity and the air temperature set points that function as the input to the HVAC system in order to create indoor thermal comfort.

The design of the thermal comfort-based fuzzy system is realized by extracting knowledge from Fanger's thermal comfort model. The above proposed control systems allow easier evaluation of the indoor climate by using linguistic description of the thermal comfort sensation which make it simpler to understand and to process than having to solve iteratively a complex mathematical model. Few HVAC systems perform as well in practice as originally intended. There is a considerable potential for achieving better performance by means of acquiring large amounts of time series temperature data through wireless sensor technology.

IV. WIRELESS SENSOR NETWORK FACILITATED HVAC CONTROL

Wireless Micro-Electro-Mechanical Systems and Complementary metal oxide semiconductor sensors used for measuring common environmental variables, such as temperature, humidity, light level, and pressure have become available in the commercial market. The self-forming, self-healing, and battery operable attributes of a sensor network make it ideal for HVAC system monitoring in a wide range of facilities. Abundant real time data can be captured through temperature, humidity sensors, etc which can be used to design and operate HVAC systems better. The most obvious reason to use wireless sensor networks (WSNs) in controlling the HVAC systems is the significant potential cost saving. Wireless technology eliminates the cable or wiring cost, saving from 20% to 80% of the installation cost of control [34] compared to a hardwired network infrastructure. And occupants' comfort may be improved as well. Energy cost is certainly to be reduced if appropriate HVAC controllers are deployed in the entire system design.

A technology installation review describes an implementation of using wireless temperature sensors to improve HVAC control systems [35]. Such sensors are used to measure and supply primary zone temperatures to HVAC controllers. In this experiment, the wireless sensor solution comes from Inovonics Wireless Corporation [36]. The operating frequency is 902 to 928MHz and the technology employs spread spectrum frequency-hopping techniques to enhance the robustness and reliability of the transmission [37]. 37 temperature sensors, three repeaters, one receiver and one integration module are installed and integrated into the U.S. Environmental Protection Agency facility. These temperature sensors are installed at each office and hallways. The transmitters are attached to the walls to measure supply air temperatures. The higher spatial resolution of the zone temperatures provides valuable insights into the HVAC operations. Fault diagnosis capabilities of the existing thermostats, temperature sensors and control are improved. With a wireless temperature sensor at every office, the air temperature zone is monitored. The ability to observe zone temperatures office-by-office is the key motivator to the control strategy and leads to improved energy efficiency. Through the data collected from the 37 wireless temperature sensors, a high spatial resolution is available for the control system.

Multi-sensor control of HVAC systems is presented in [38]. A simple, ad hoc sensor network method used to control a set of rooms is investigated and a new optimization procedure is designed. Each room has its own sensor that comprises the ad hoc sensor network. After determining the maximum number of rooms that can be put into the comfort zone, the method then aims to optimize the rooms that are outside the comfort zone. If all of the rooms outside the comfort zone are too cold, the hottest room can be moved to the upper limit of the comfort zone, thereby minimizing the discomfort of the rooms outside the comfort zone. Only when all rooms can be put within the comfort zone, the energy consumption issue can be solved. This is the first limitation of this control strategy. In order to simplify the complex relationship between environmental factors and comfort, they make assumptions that all environmental factors other than temperature and clothing are constant. Clothing adjustment is made based on limited seasons. These assumptions become the important limitation of this control strategy.

Many residential HVAC systems treat the house as a single zone. Single zone control consists of one thermostat, in a central area of the house that controls the HVAC operation. In a single zone system all of the vent registers are open, distributing air into all areas of the house at once. Single zone control leads to wasted energy for two reasons; one is that all rooms are conditioned even when they are not occupied. The other reason is that occupied rooms are often conditioned to a temperature that is not comfortable for the occupants. Watts et al. [39] describe an application of wireless sensor networks that implement an automated vent louver system to solve the above problems in heating homes. Instead of using traditional temperature sensors, they install wireless controlled louvered vents in each room. Their simulation results show that optimal HVAC energy savings are achieved when taking the average of distributed temperature sensors within the area being conditioned.

Applying WSNs in HVAC system design is still at an early stage. Multiple wireless sensors allow HVAC systems to use more real-time data of buildings and their environment to meet the highest occupant comfort requirement as well as save energy. The use of a WSN can certainly provide benefits to all the control technologies and their resultant HVAC systems. Wireless sensor technology relies on accurate and reliable sensors and has the ability to help ensure the accuracy of sensors through improved sensing methods and intelligence built into the sensor for self diagnostics. Research on these topics has shown huge improvements of the low-power wireless sensor and actuator networks to be used in building control systems. To calculate occupants' thermal comfort level index, we can apply wireless sensor network and information technology to capture the real-time data of all individuals inside the building. The building HVAC system controller can schedule appropriate control actions to prevent high demands of energy. By applying this method, the energy consumption should be decreased. However, many technical issues remain unsolved.

A. Communication Protocol

A wireless sensor network is comprised of a number of wireless sensors. Each sensor node is basically composed of a sensing part, a wireless antenna and a power supply. For relaying data, each of them has to be equipped with a routing function. The configuration of a network becomes complex as more sensors are deployed. Methods for networking the large system of sensors will be needed to make the best use of collected sensor data.

B. Interference

Wireless interference originates from other users of the same frequency band. The most notable interferers for IEEE 802.15.4-based devices that operate in the 2.4 GHz frequency band are Wi-Fi transceivers. Most interferers will not fully block out an IEEE 802.15.4 device, but will cause some wireless packets to get lost. Therefore, it is necessary to take into consideration the effect of radio interference when sensor networks are installed.

C. Battery

The devices of HVAC systems are dispersed over a large area. The majority of the sensors used are still battery-powered; these batteries require regular changing and/or recharging. Due to the high node count in WSNs, doing so every few days makes WSN solutions infeasible. In addition, reintegrating failed nodes after battery maintenance further increases maintenance cost. Thus, efficient schemes for powering the instruments must be developed.

D. Security

With the wireless transmission of data, there is always a danger of data leaks and tampering. Building privacy and security in the initial HVAC design should ensure that all necessary or required controls exist to protect access to and dissemination of personal information over the entire WSNs. WSNs must be able to protect them from attack [40].

The potential of incorporating sensor networks that capture dynamics of occupants' activity into HVAC system control is enormous. Through good prediction algorithms, sensor networks can provide more accurate information about the situation within a space.

V. FUTURE RESEARCH CHALLENGES

Providing the highest comfort level for building occupants and optimizing the system operation to reduce energy consumption are two critical issues. Natural ventilation, solar control, passive temperature control and day light are applied as common approaches to save energy, and other novel air-conditioning systems such as under floor air distribution and displacement ventilation are mainly employed to increase the occupant comfort level. Advanced control strategies for increasing occupant comfort and decreasing energy consumption in buildings are required to meet these two requirements simultaneously.

Sensor and control needs for buildings span a broad range of technical activities. Sensors at sufficiently low cost are needed for measuring temperature and humidity as well as power consumption. Any advanced control strategy for increasing occupant comfort, decreasing energy consumption, and ensuring safety in buildings relies on accurate and reliable sensors. New technologies may help to ensure the accuracy of sensors through improved sensing methods and intelligence built into the sensor for self diagnostics.

VI. CONCLUSION

This paper reviews the thermal comfort-based control strategies of HVAC systems for modern commercial buildings. If better system operations and control algorithms are applied, HVAC systems can be operated in an energy saving mode as well as provide a favorable environment to occupants. Intelligent technology-based HVAC control can enhance conventional HVAC control by providing a more comfortable environment to occupants. Application of a wireless sensor network in HVAC control can achieve both human comfort level and energy saving requirements with more flexibility. More real-time environmental data such as temperature, air velocity, humidity and human activity level can be collected and applied in the system design. It can greatly save energy while offering high comfort level to occupants. It is clear that much more research and development is needed to fulfill this vision.

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