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MOBILE THERMOSTAT FOR CLIMATE CONTROL IN RESIDENTIAL BUILDINGS

Alexander L. Burd, Ph.D., P.E., member ASHRAE, Advanced Research Technology, LLC., USA

& Galina S. Burd, M.S., Advanced Research Technology, LLC., USA.

Summary

The objective of the investigation was to evaluate the performance of a new control device - the wireless mobile thermostat. The mobile thermostat's prototype system was manufactured, installed and tested during one year in a two-story residential townhouse with a central furnace and forced-air system. The modes of operation of space heating and space cooling systems with stationary and mobile thermostats were compared and analyzed. Control of the heating/cooling systems with a stationary thermostat leads to significant vertical air temperature variations between the second and the first floors as well as horizontal temperature variations within a floor. The mobile thermostat has the authority to override control from the stationary thermostat in order to optimize climate control strategy resulting in better comfort conditions. Potential annual energy savings for heating and cooling are estimated at about 5% with a simple payback for the new device in approximately 3 years.

Introduction

Typically, apartments in residential buildings and individual residential houses with central forced-air space heating/cooling systems employ one stationary thermostat located in the living room. Other rooms do not have thermostats; therefore, a tenant can directly control the air temperature only in the living room by changing the stationary thermostat's set point temperature.

The air temperature in other rooms of the apartment can only be controlled indirectly by resetting the stationary thermostat's set point with the anticipation that the temperature in various rooms of the apartment would correlate with the temperature at the stationary thermostat's location.

This system is very popular in the United States where nearly 70 millions households are equipped with central forced-air heating and cooling installations. In addition, some of the households are equipped with central steam and heat pump heating systems which also have only one centrally located stationary thermostat to control air temperature in the buildings. Based on publications of the United States Department of Energy, one household on the average annually consumes about 52 x 10^3 MJ (49.3 x 10^6 Btu) for space heating and about 5.3 x 10^3 MJ (1,465 kWh) for space cooling, respectively.

One of the objectives of the study was to investigate how the temperature in different rooms of the apartment varies depending on the set point temperature maintained at the stationary thermostat's location. Another objective of the study was to test the new device - the mobile (wireless) thermostat prototype - in order to analyze its ability to maintain the set point temperature at a given location as well as to evaluate potential climate control improvements in the apartment and to evaluate associated energy and cost savings.

Residential Apartment Heating and Cooling Equipment and Loads

The residential apartment - a two bedroom, two-floor townhouse located in the state of Connecticut - has approximately 92.9 m^2 (1,000 ft^2) of total area. The height of each floor is 2.44 m (8 ft). The apartment has a kitchen and a living room on the first floor and two bedrooms on the second floor (one of the bedrooms is also used as a study room). In addition, the apartment has a full basement (which is used as a storage area) where the forced-air furnace and associated ductwork are located. The apartment is situated in the middle of the four-unit residential building and has easterly and westerly oriented outside exposures. The residential building was built in 1986.

Natural gas is used for space heating and electricity for space cooling. The furnace has an evaporator (cooling coil); the compressor and condenser units of the cooling system are located outside the apartment. The air treated in the furnace (heated or cooled) is delivered throughout the apartment via ductwork, supply diffusers and registers, and, - then, is returned to the furnace via return grills and ductwork.

The heat transfer coefficient of the apartment's roof and outside walls is 0.284 $W/m^2 \cdot K$ (0.05 $Btu/hr \cdot ft^2 \cdot {}^0F$) and 0.91 $W/m^2 \cdot K$ (0.16 $Btu/hr \cdot ft^2 \cdot {}^0F$), respectively. The heat transfer coefficient of the windows is 4.6 $W/m^2 \cdot K$ (0.81 $Btu/hr \cdot ft^2 \cdot {}^0F$). The furnace input and output heating capacity is 14,655 W (50,000 Btu/hr) and 11,140 W (38,000 Btu/hr), respectively; at the design capacity the furnace is 76% thermally efficient. The cooling coil capacity is 5,803 W (19,800 Btu/hr), the cooling system COP=3.25 (EER=11.1).

The furnace blower is capable of delivering 0.388 m^3/s (825 ft^3/min) of air at an external static pressure of 124.5 Pa (0.5 inch of water). The apartment's space heating load at the design outdoor dry-bulb air temperature of -16.7^0 C (2^0 F) is 8,620 W (29,400 Btu/hr). For the load calculations the design indoor dry-bulb air temperature during heating period was assumed to be 20^0 C (68^0 F). The apartment space cooling load at the design outdoor dry-bulb and wet-bulb temperatures of 31.3^0 C (88^0 F) and 22.2^0 C (72^0 F), respectively, is 5,745 W (19,600 Btu/hr). For the load calculations, the design indoor dry-bulb air temperature and relative humidity during cooling period was assumed to be 23.9^0 C (75^0 F) and 50%, respectively.

Three people live in the apartment. The apartment has one non-programmable thermostat located in the living room, which services both heating and cooling loads. The first and the second floor plans of the townhouse are shown in Figure 1.

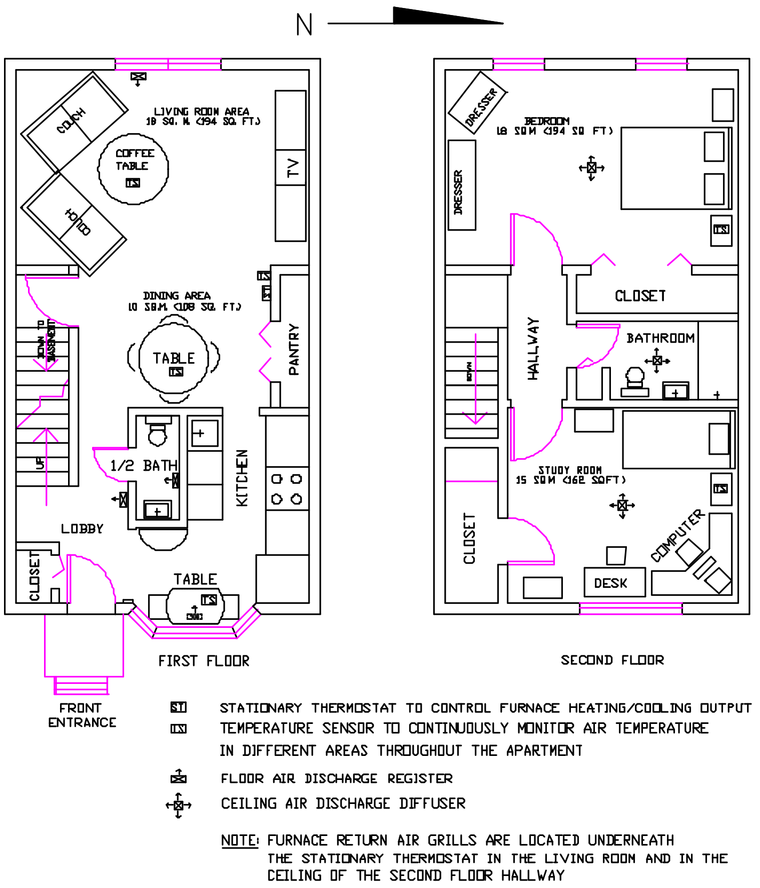


FIGURE 1. TOWNHOUSE FLOOR PLANS, AIR DISTRIBUTION TERMINALS AND TEMPERATURE SENSORS LOCATION

The annual average magnitude of the townhouse thermal energy intensity for space heating during 1997 and 1998 was about 458 MJ/m^2 (40.2 x 10^3 Btu/ ft^2). The annual average magnitude of the townhouse electrical energy intensity for space cooling during 1997 and 1998 was about 54.3 MJ/ m^2 (1.4 kWh/ft^2). The annual gas and electrical energy intensity indicators for space heating and space cooling were found by subtracting constant energy consumption components imposed by different loads (such as domestic hot water and lights, etc.) from monthly gas and electricity consumption and by summing up the results of the calculations during the course of the year. The results of the calculations were divided by the total area of the apartment.

Air Temperature Monitoring System

The air temperature was continuously monitored throughout the apartment. Air temperature sensors were installed in the living room, in the study room and in the bedroom. The air temperature sensors - data loggers - have an accuracy of $\pm$ 0.7^0 C ($\pm$ 1.25^0 F). The air temperature sensors were placed on various surfaces such as on the coffee table and dinner table in the living room and on the kitchen table at about

0.41 m (16 inch), 0.74 m (29 inch) and 0.86 m (34 inch) above the floor, respectively, as well as on the nightstand at about 0.6 m (24 inch) above the floor in both the bedroom and in the study room.

Another air temperature sensor was installed about 0.15 m or 6 inch away from a discharge diffuser of one of the branches of the ductwork in the basement. An air temperature sensor was also installed at the stationary thermostat location 1.5 m (59 inch) above the floor level as well as at the mobile thermostat locations, when space heating/cooling control was implemented by the mobile thermostat. The space heating/cooling air distribution terminals and the location of temperature sensors are also shown in Figure 1. In addition, the outdoor air temperature was also monitored. The monitoring data were collected during predetermined time intervals that varied for different tests from 2 to 15 minutes. The doors in the study room and in the bedroom on the second floor were kept open during the entire experiment so the air could freely circulate throughout the apartment.

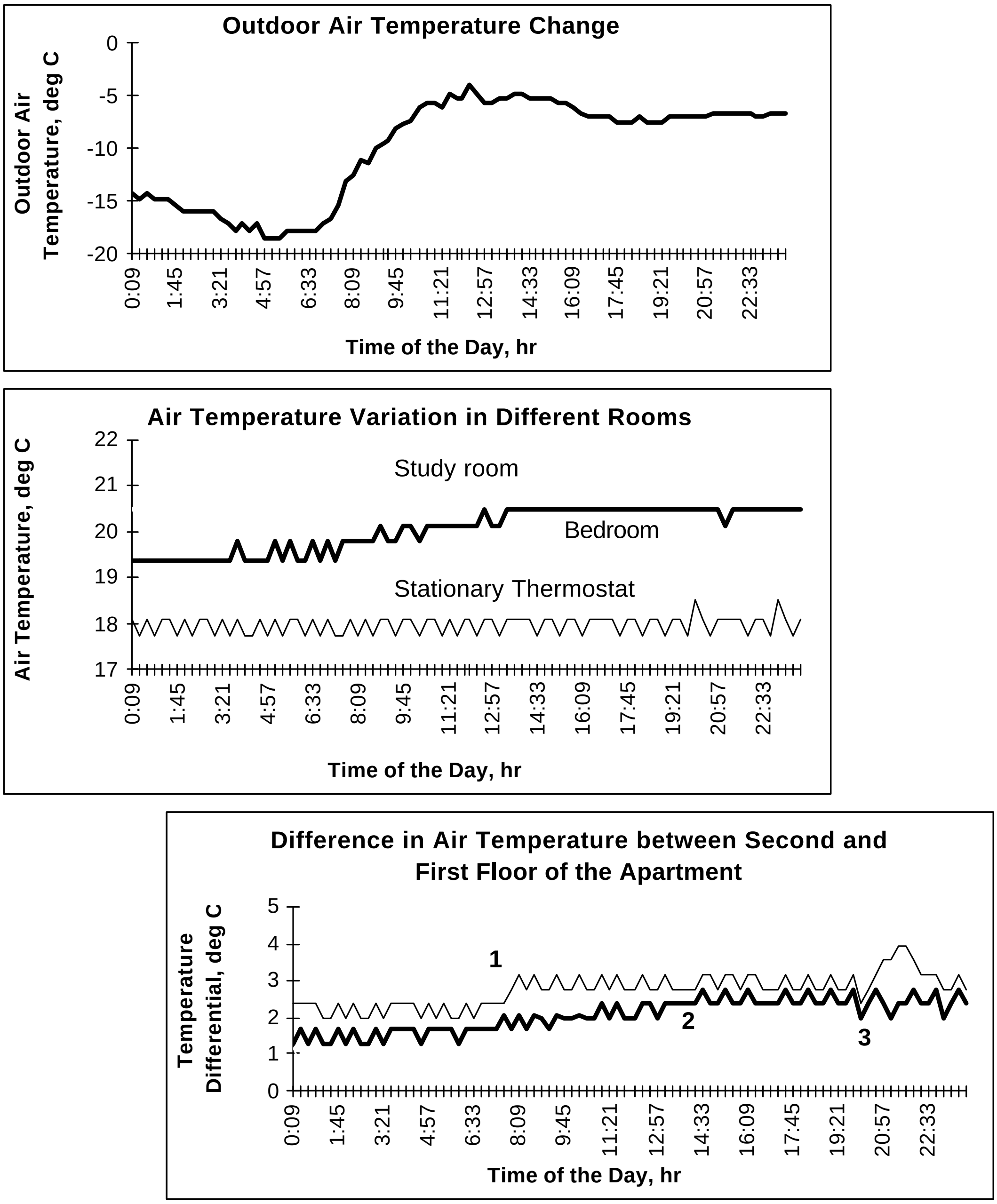
Stationary Thermostat Operation and Air Temperature Variations in Residential Buildings

We have investigated how the air temperature in different rooms of the apartment varies while the control is implemented by the stationary thermostat in the living room.

1. Stationary Thermostat Operation During Heating Mode

The modes of the stationary thermostat operation and variation in the apartment's air temperatures during one day in February 1999 are introduced in Figure 2.

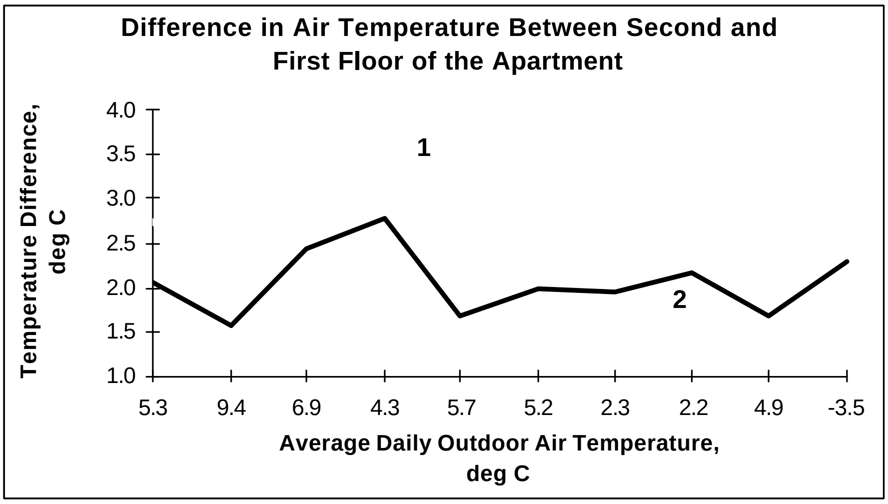
The outdoor air temperature (shown in the upper portion of the graph) during this day changed from -18^0 C (-0.4^0 F) to about -4^0 C (24.8^0 F). The study room air temperature was slightly higher than the bedroom temperature (the middle portion of the graph). The stationary thermostat set point was maintained at 18^0 C (64.4^0 F). The air temperature at the thermostat location varied from 17.7^0 C (63.9^0 F) to 18.6^0 C (65.5^0 F). The air temperature in the apartment is subjected to a significant vertical variation between the first and the second floors. This variation is due to natural air convection (1). For this particular day, the temperature in the study room (see the lower portion of the graph) exceeded the living room temperature at the stationary thermostat location by 2^0 C (3.6^0 F) to 4^0 C (7.2^0 F). The temperature in the bedroom was also higher than in the living room by 1.5^0 C (2.7^0 F) to 2.8^0 C (5^0 F).



1. Difference in air temperature between the study and living room
2. Difference in air temperature between the bedroom and living room
3. Difference in air temperature between the study and bedroom.

Figure 2. Stationary Thermostat Operation and Vertical Temperature Variation in the Apartment (Heating Mode).

The results of processing air temperature monitoring data during 10 consecutive days in winter 1999 (when the heating in the apartment was controlled by the stationary thermostat) are shown in Figure 3.



1. Difference in air temperature between the study and living room
2. Difference in air temperature between the bedroom and living room

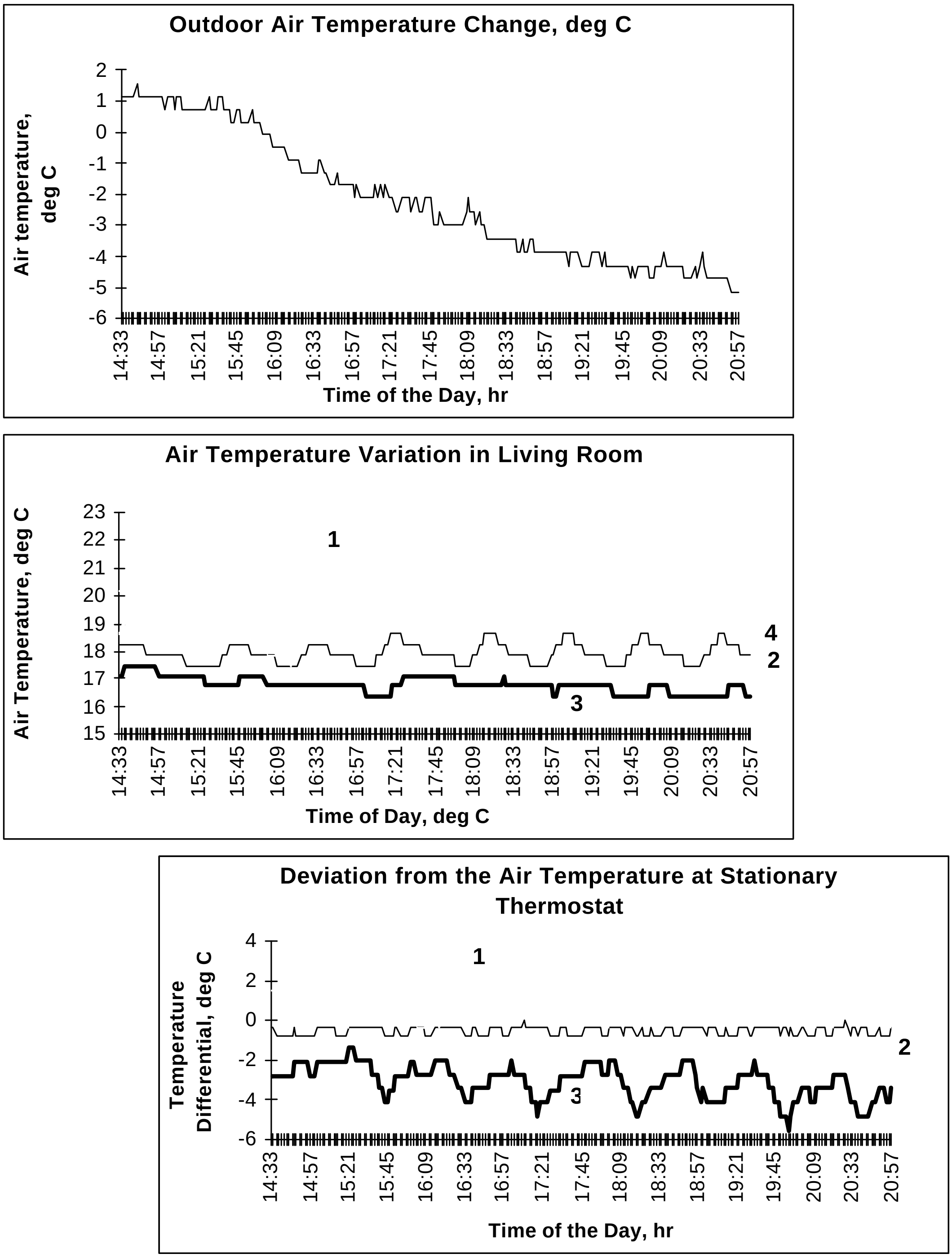
Figure 3. Vertical Variation of Air Temperature Distribution in Apartment (Heating Mode) at Different Outdoor Air Temperatures.

The air temperatures were monitored and processed during the 12-minute intervals and, then averaged over the course of the day. The average daily outdoor air temperature for the considered period varied from -3.5^0 C (25.7^0 F) to 9.4^0 C (49^0 F). The air temperatures shown in Figure 3 represent the difference between the temperatures upstairs (in the study room and in the bedroom) and temperatures downstairs (in the living room). The air temperature upstairs was consistently higher than the air temperature downstairs. The air temperature in the study room was higher than the air temperature in the living room by 2^0 C (3.6^0 F) to 3.6^0 C (6.5^0 F). The air temperature in the bedroom exceeded the temperature in the living room by 1.6^0 C (2.9^0 F) to 2.8^0 C (5^0 F). On average, the air temperature in the study room and in the bedroom during these 10 days was higher than the temperature at the stationary thermostat in the living room by 2.7^0 C (4.9^0 F) and by 2.2^0 C (4.0^0 F), respectively.

The data in Figure 3 show that the temperature difference between the apartment's upstairs and downstairs rooms is not constant and fluctuates significantly for the considered days. The temperature difference between the study room and the bedroom is more moderate and varies from 0.5^0 C (0.9^0 F) to 1^0 C (1.8^0 F). The study room has higher air temperature when compared to the bedroom because of heat gains from the office equipment in the study room (such as the computer and printer).

We have also investigated the variation of the air temperatures in the living room which is interconnected with the kitchen. To do this, we compared the air temperature at the stationary thermostat location to the temperatures at the frequently occupied places such as the coffee table, dinner table and kitchen table

(Figure 1 shows the location of the air temperature sensors in the living room during the conducted tests). The upper portion in Figure 4 indicates that the outdoor air temperature during the considered day in January 1999 varied from 1^0 C (33.8^0 F) to -5^0 C (23^0 F).



1. Coffee table. 2. Dinner table. 3. Kitchen table. 4. Stationary thermostat.

Figure 4. Stationary Thermostat Operation and Horizontal Temperature Variation in Different Areas of Living Room (Heating Mode)

The results of the air temperature monitoring during the 2-minute intervals shows that in addition to the vertical variation of air temperature in the apartment, a substantial horizontal variation in air temperature is also occurring. Figure 4 indicates that the air temperature in various areas of the living room differs and depends on the specifics of the particular location.

For instance, the air temperature at the dinner table was just slightly lower than the temperature at the stationary thermostat (middle portion of the graph). However, the air temperature at the kitchen table, which is located next to the window, was 2^0 C (3.6^0 F) to 5^0 C (9^0 F) less than the temperature at the stationary thermostat location (lower portion of the graph).

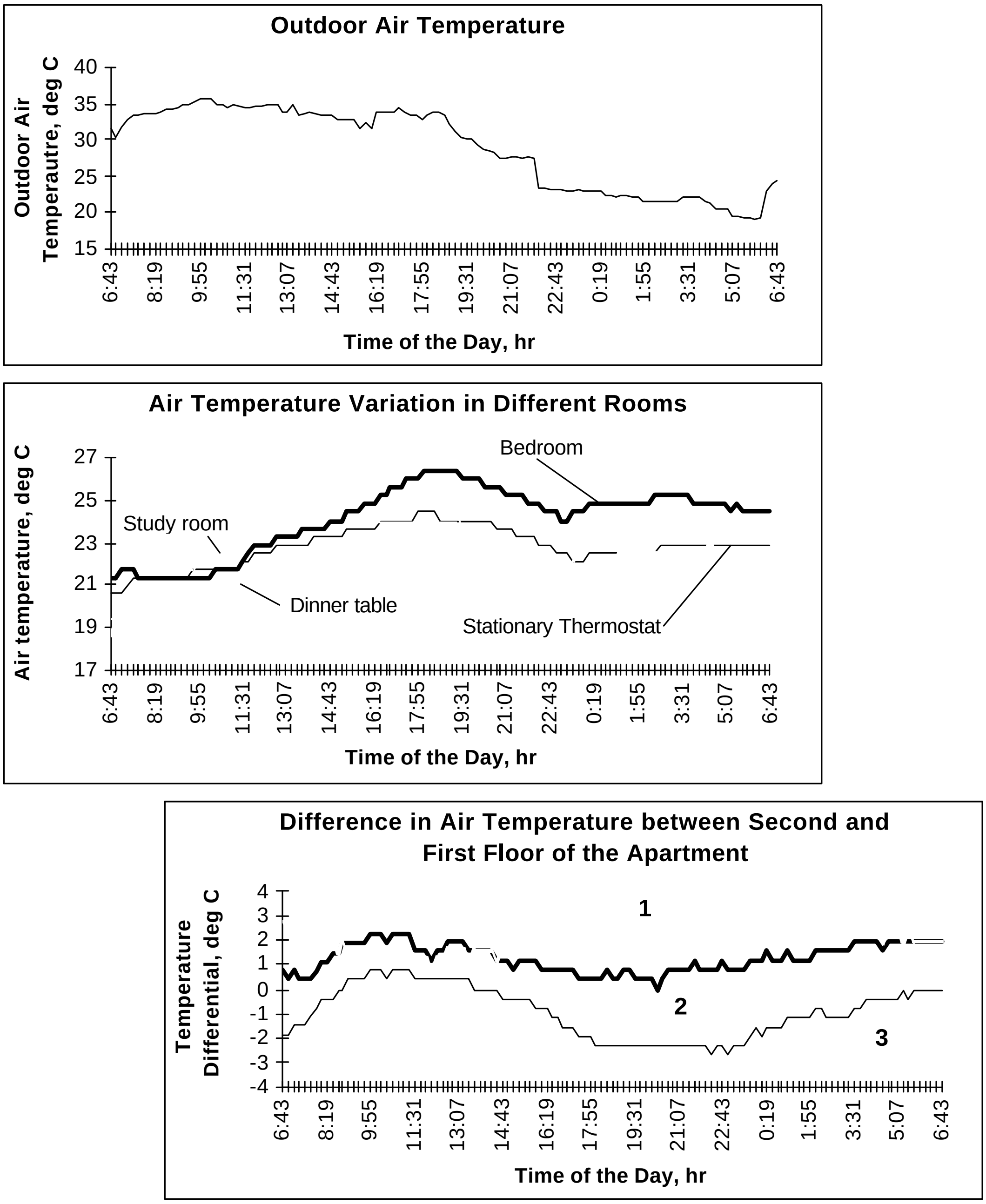
On the other hand, the air temperature at the coffee table, which is located close to the floor air discharge register, is 1^0 C (1.8^0 F) to 2^0 C (3.6^0 F) higher when compared to the temperature at the stationary thermostat location (lower portion of the graph). Therefore, the air temperature inside the same room is also subjected to a noticeable change.

2. Stationary Thermostat Operation During Cooling Mode

The modes of the stationary thermostat operation in July 1999 are introduced in Figure 5. The outdoor air temperature (shown in the upper graph) during the day changed from 35^0 C (95^0 F) to 18^0 C (64.4^0 F). At 6:45 the stationary thermostat set point temperature (not shown on the graph) was initially set at 21^0 C (69.8^0 F). At approximately 12:00 it was raised to 23^0 C (73.4^0 F), and then at about 23:00 it was reduced to 22.5^0 C (72.5^0 F).

The middle part of the graph indicates that the stationary thermostat maintained the given set point temperature within the range of $\pm$ 1^0 C ($\pm$ 1.8^0 F). During the day, the bedroom had the highest temperature of 26.5^0 C (79.7^0 F) in the apartment. This was a result of intensive solar radiation into the room. As seen from the lower part of the graph, the air temperature in the bedroom for the considered day was higher than in the living room (at the dining table) by 1^0 C (1.8^0 F) to 3^0 C (5.4^0 F). The air temperature in the study room was also higher than in the living room by 0.5^0 C (0.9^0 F) to 1.8^0 C (3.2^0 F). The air temperature in the living room (at the dining table) was lower by 0.5^0 C to 2^0 C (0.9^0 F to 3.6^0 F) than the temperature at the stationary thermostat location (see the middle part of the graph).

The investigation of air temperature variation at the frequently occupied places in the living room during cooling mode of operation showed that the air temperature fluctuates considerably. For instance, for the day in July 1999, when the outdoor air temperature changed from 23^0 C to 35^0 C (99^0 F to 120^0 F), the air temperature at the kitchen table exceeded the air temperature at the stationary thermostat by 1^0 C to 2^0 C (1.8^0 F to 3.6^0 F). The air temperature at the coffee table was higher or lower than the air temperature at the stationary thermostat by + 1^0 C to -1.5^0 C ($+1.8^0$ F to -2.7^0 F). The air temperature at the dinner table was lower than the air temperature at the stationary thermostat by 1^0 C to 2^0 C (1.8^0 F to 3.6^0 F).



1. Difference in air temperature between the bedroom and living room
2. Difference in air temperature between the study room and living room
3. Difference in air temperature between the study room and bedroom

Figure 5. Stationary Thermostat Operation and Vertical Temperature Variation in Apartment (Cooling Mode)

Therefore, the conducted analysis indicates that the space heating/cooling control with the stationary thermostat leads to a substantial fluctuation of air temperature in the different rooms. A temperature differential between the various locations in the rooms is a function of many variables (such as the distance to the heating/cooling outlets and to the windows, occupancy level, heat gains from the appliances, wind direction, orientation towards the sun, etc.) and therefore, is difficult to predict.

Thus, one can come to the conclusion that the stationary thermostat is capable of maintaining (with reasonable predictability and accuracy) a given temperature set point only in close proximity to the thermostat location. In this capacity, the stationary thermostat operation is well suited for the application when nobody is at home. On the other hand, when people are at home, a more accurate temperature control is necessary in order to enhance controllability and flexibility of the heating/cooling system and maintain a customized air temperature at a certain time and at a certain location in the apartment on demand. This can be done by utilizing the mobile thermostat -- a wireless device that can be moved to different locations throughout the apartment on an as needed basis.

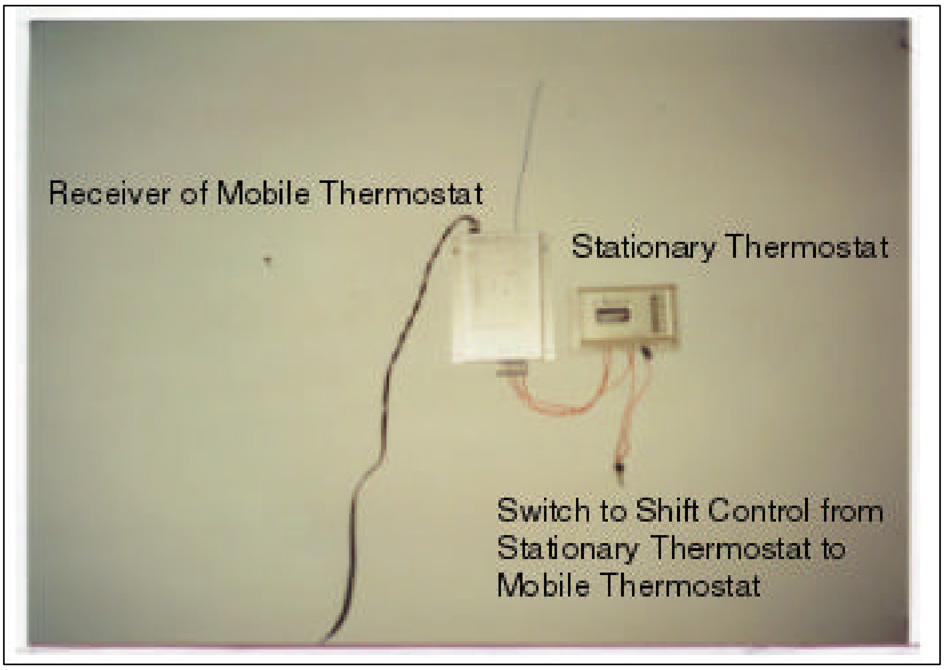
Multistage Temperature Control and Mobile Thermostat Prototype Description

The accuracy of maintaining a desired air temperature in the building greatly depends on the control system. Usually, when more stages of control are used, more factors which impact the indoor air temperature value could be considered, resulting in less deviation of the air temperature from its targeted value.

For instance, the quality of the control from the central heating substation or hot water boiler plant could be improved if a reset water flow rate or temperature control is implemented following the outdoor air temperature measured with the mass thermometer rather than following an instantaneous outdoor air temperature value (2,3,4). This additional stage of control allows consideration of the specifics of the building exposure’s materials and their thermal properties which provides a closer match between the building’s heat loss and heat supply, and thus improves the controllability of the system and reduces its energy consumption.

At the same time, the closer the location of the control device is to the area where the targeted temperature value is critical to maintain, the more accurate the control becomes. Obviously, the best and most precise control could be achieved by combining various stages of control and eventually, by utilizing a final (ultimate) control stage when the control device is located at the place where a particular air temperature has to be maintained. The mobile thermostat is a battery-operated and electrically-powered device which facilitates implementation of this final stage of control to accurately balance heat loss and heat supply to maintain a desired air temperature in a particular area of the house.

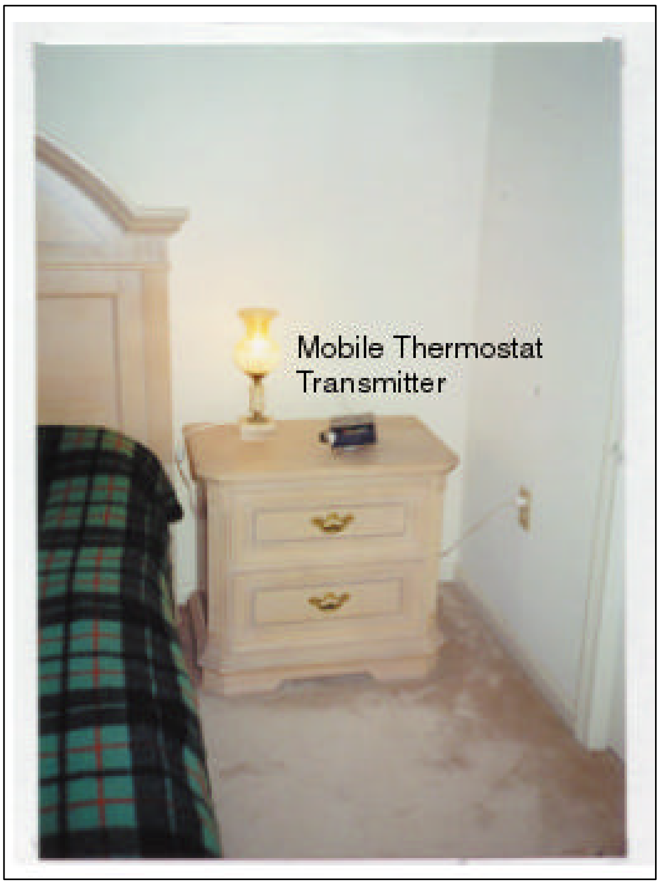
A prototype of the mobile thermostat was manufactured in compliance with the United States Patent (5) specification to conduct testing of the thermostat’s performance. The prototype consists of two parts: a receiver and a transmitter. The prototype was installed in the townhouse. Picture 1 shows the existing stationary thermostat connection to the receiver of the mobile thermostat. Picture 1 also shows a switch to shift control from the stationary thermostat to the mobile thermostat and vice versa.



Picture 1. Mobile Thermostat (Receiver) Connection to Stationary Thermostat

Pictures 2 and 3 show the location of the mobile thermostat's transmitter (remote element) in different areas throughout the apartment (in this case, in the bedroom and living room).

Picture 2. Mobile Thermostat (Transmitter) Location in the Living Room



Picture 3. Mobile Thermostat (Transmitter) Location in the Bedroom

The transmitter of the mobile thermostat is capable sending a remote radio signal to the receiver, which in turn activates or deactivates the furnace's heating or cooling systems to maintain a set point temperature at the thermostat's transmitter location.

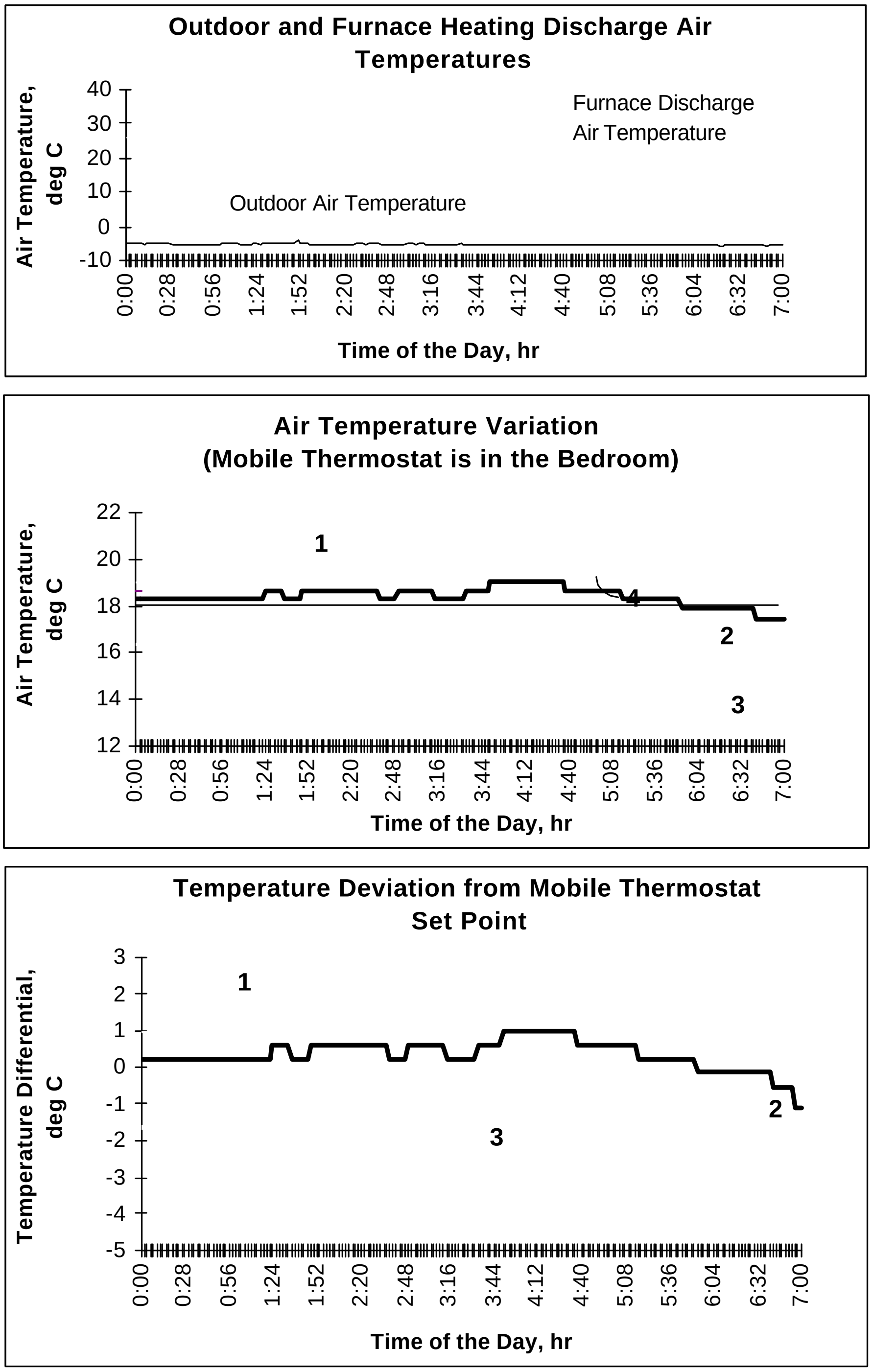
1. Mobile Thermostat Operation During Heating Mode

The results of the mobile thermostat's operational tests in December 1998 are shown in Figure 6 and Figure 7. The upper part of the graph of Figure 6 demonstrates the performance of the mobile thermostat during a nighttime period when the outdoor air temperature was near - 6.5^0 C (20^0 F). The maximum value of the furnace's discharge air temperature measured in the basement was near 30^0 C (86^0 F).

The lower temperature value (approximately 13^0 C or 55^0 F) during each cycle corresponded with the air temperature value in the basement at the end of the period when the furnace was not running. As soon as the furnace's heating mode is resumed, the discharge air temperature gradually increased above its lower temperature until it peaked at 30^0 C (86^0 F).

The mobile thermostat was located on the nightstand in the bedroom, and its temperature set point was 18^0 C (64.5^0 F). The middle part of the graph shows that the temperature in the bedroom was maintained close to the thermostat set point (maximum deviation did not exceed + 1^0 C or 1.8^0 F and -0.5^0 C or

0.9^{0} F). The mobile thermostat overrode the stationary thermostat control and turned the furnace on and off as necessary (as shown in the upper portion of the graph) to maintain required temperature at the mobile thermostat's transmitter location.



1. Study room. 2. Bedroom. 3. Living room (dinner table). 4. Thermostat temperature set point.

Figure 6. Mobile Thermostat Operation during Nighttime (Heating Mode).

While the temperature in the bedroom (as well as in the study room) closely followed the mobile thermostat temperature set point, the temperature in the living room was maintained at a substantially lower magnitude.

The lower part of the graph represents the temperature differential between the air temperatures in the bedroom, study room and living room on one side and the mobile thermostat temperature set point on the other side.

The air temperature difference between the bedroom and the study room is not quite noticeable and does not exceed -1^0 C to $+1^0$ C (-1.8^0 F to $+1.8^0$ F). Conversely, the air temperature in the living room was significantly lower, by 1^0 C to 4^0 C, or by 1.8^0 F to 7.2^0 F, than the temperature at the mobile thermostat location. This demonstrates the ability of the mobile thermostat to save energy for space heating by maintaining the desired temperature in the occupied rooms upstairs while maintaining a lower temperature on the first floor when it is not occupied.

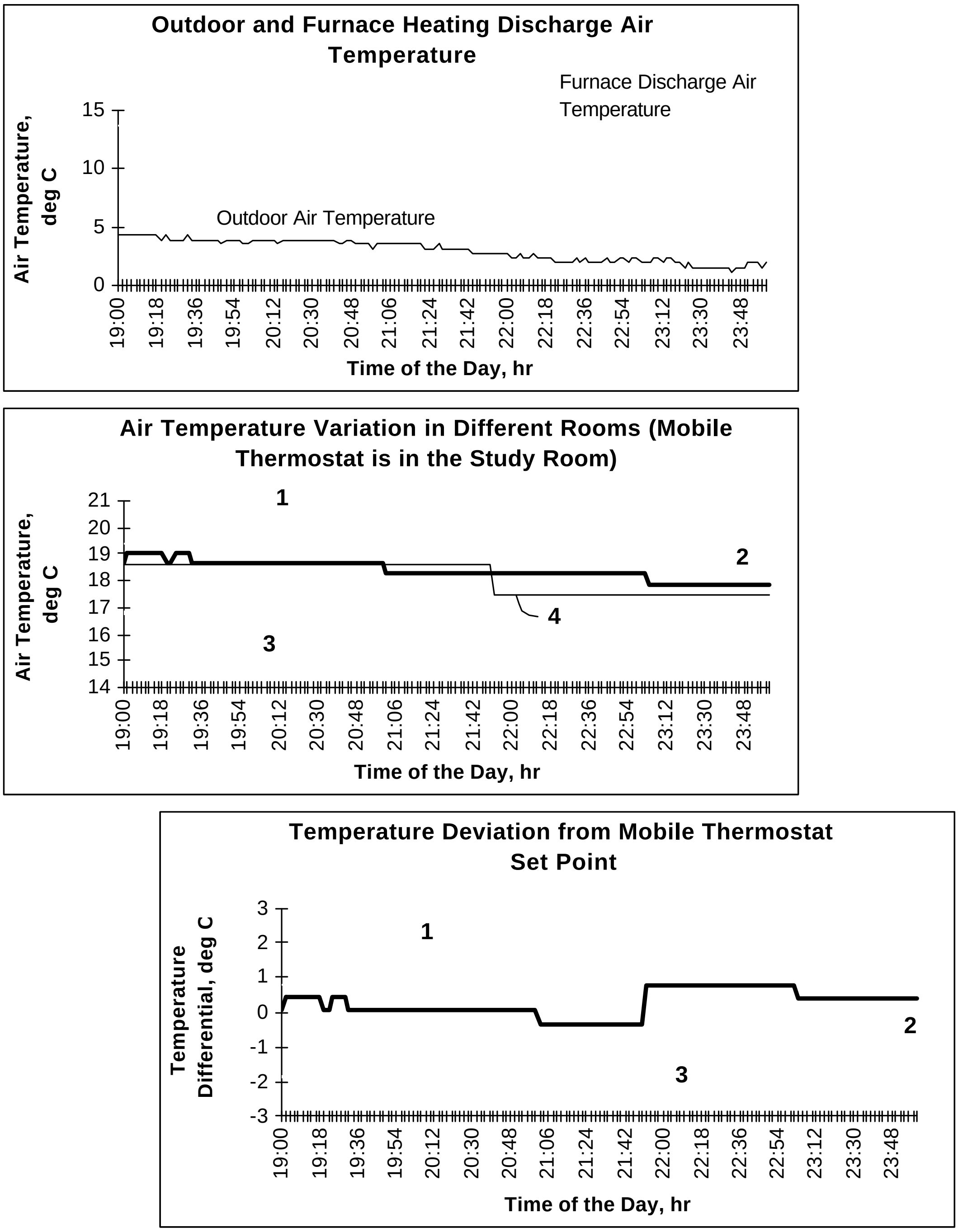
The operation of the mobile thermostat during the evening is shown in Figure 7. The outdoor air temperature changed from 4^0 C to 1^0 C, or 39.2^0 F to 33.8^0 F (the upper portion of the graph). The mobile thermostat was in the study room and its set point temperature was reduced at approximately 22:00 from 18.6^0 C to 17.5^0 C, or 65.5^0 F to 63.5^0 F (the middle portion of the graph). Since the actual temperature in the study room during the considered period was higher than the mobile thermostat set point, the thermostat did not turn the furnace on.

The air temperature in the study room during the period from 19:00 till 22:30 exceeded the temperature in the bedroom by approximately 2^0 C to 2.5^0 C (3.6^0 F to 4.5^0 F) because the computer, printer, and scanner were also turned on, thus, generating additional heat gains in the study room.

The upstairs air temperatures in the study room as well as in the bedroom were consistently higher than the downstairs air temperature in the living room. The air temperature difference between the upstairs and downstairs rooms varied: about 2.1^0 C to 2.5^0 C (3.8^0 F to 4.5^0 F) for the bedroom and 2.5^0 C to 4^0 C or 4.5^0 F to 7.2^0 F for the study room (see the middle portion of the graph).

The lower portion of the graph shows the temperature deviation from the mobile thermostat set point in various rooms of the apartment. On average, the temperature upstairs was higher than the mobile thermostat set point by 0.5^0 C to 1.5^0 C (0.9^0 F to 2.7^0 F). The air temperature downstairs was lower than the mobile thermostat set point by 1.2^0 C to 2.8^0 C (2.2^0 F to 5^0 F).

The mobile thermostat enabled tenants to take advantage of maintaining the desired temperature in the occupied upstairs rooms while keeping the temperature lower on the first floor when it was not occupied. The conducted investigation of the mobile thermostat operation clearly indicates its ability to reduce energy consumption for space heating in the residential apartment while maintaining comfortable conditions and desired air temperature for the tenants.

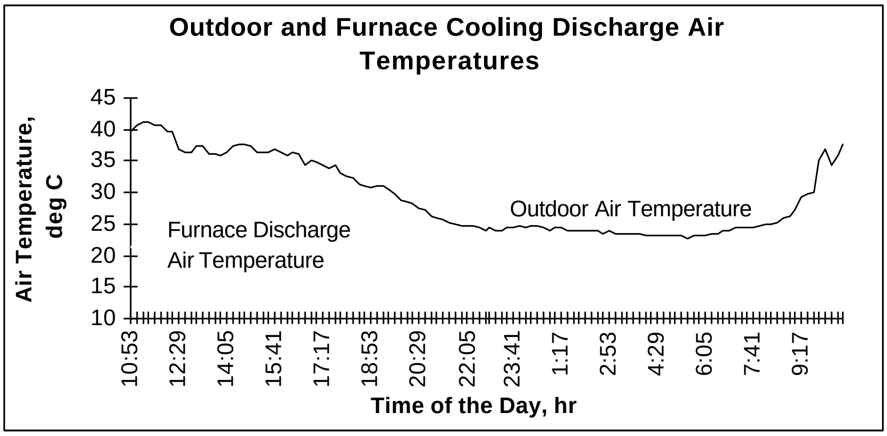


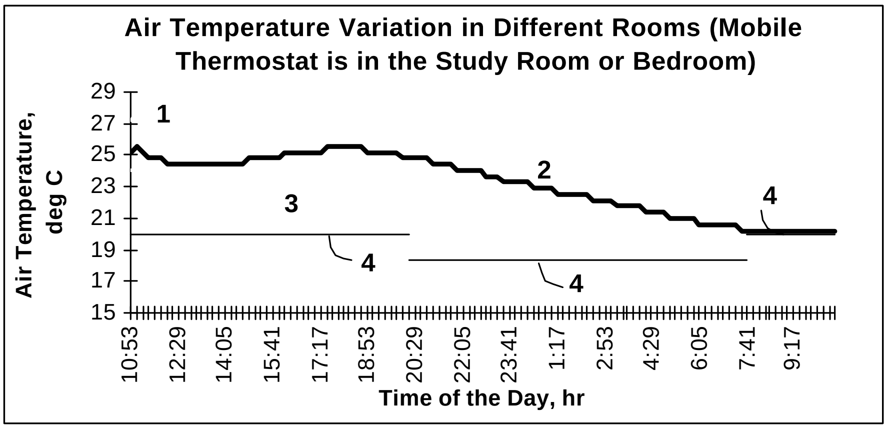
1. Study room. 2. Bedroom. 3. Living room (dinner table). 4. Thermostat temperature set point.

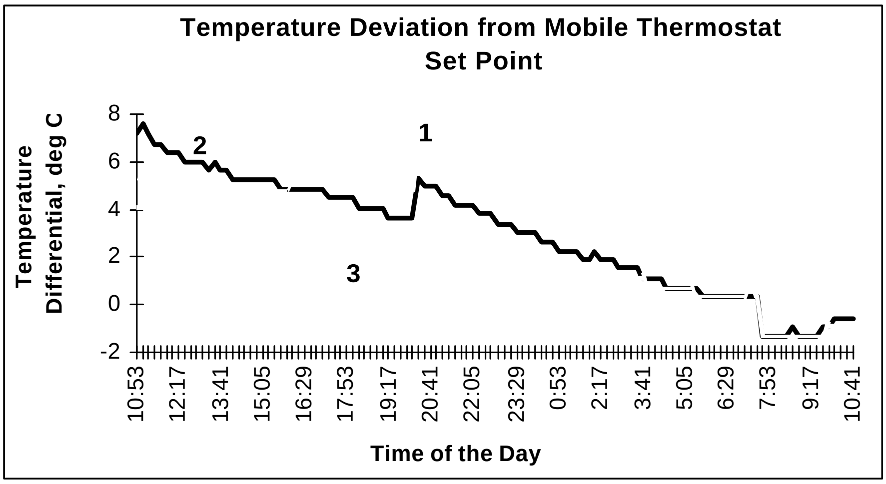
Figure 7. Mobile Thermostat Operation during Evening Time (Heating Mode).

2. Mobile Thermostat Operation During Cooling Mode

Operation of the mobile thermostat during one day of cooling mode in June 1999 is shown in Figure 8.







1. Study room. 2. Bedroom. 3. Living room (dinner table). 4. Thermostat temperature set point.

Figure 8. Mobile Thermostat Operation During a Day (Cooling Mode).

The upper portion of the graph indicates that the outdoor air temperature for the considered day changed from 41^0 C to 23^0 C (105.8^0 F to 73.4^0 F). The dry-bulb outdoor air temperature during this day was significantly higher than the design cooling outdoor air temperature of 31.3^0 C (88^0 F) which was determined by the 99th percentile frequency of occurrence during summer months. The furnace was on cooling mode all day long and its average discharge air temperature (measured in the basement) was close to 15^0 C (59^0 F).

From 10:53 till 19:55 the mobile thermostat was in the study room. At 19:55 the mobile thermostat was moved from the study room to the bedroom and then at about 7:30 was returned to the study room. The mobile thermostat set point temperature was changed during the day first from 20^0 C (68 ^{0} F) to 18^0 C (64.5^0 F) and then back to 20^0 C (68^0 F).

The maximum temperature difference between the second and the first floor of the apartment for the considered day (the middle portion of the graph) changed from 2.7^0 C or 4.9^0 F (the temperature differential between the air temperature in the study room and the living room) at the beginning of cooling to 0.6^0 C (1.1^0 F) at the end of cooling (the temperature differential between the bedroom and the living room).

At the beginning of the considered period, the air temperature in the apartment was significantly higher, by 4^0 C to 7.8^0 C, or by 7.2^0 F to 14^0 F than the mobile thermostat's set point (the lower portion of the graph). At the end of the considered period, the maximum deviation of the air temperature in the apartment from the mobile's thermostat set point did not exceed 1^0 C (1.8^0 F).

The mobile thermostat has demonstrated its ability to control cooling system operation by bringing and maintaining the air temperature upstairs close to its targeted value. This avoids overcooling the apartment which could occur if the cooling mode is controlled with the stationary thermostat since the temperature change on the second floor is difficult to predict based on the set point temperature maintained at the stationary thermostat location. Under these circumstances, it is likely that a tenant would set-back excessively the stationary thermostat set point temperature to ensure the tenant's satisfaction with the climate upstairs.

Projected Annual Energy Savings Resulted from the Use of Mobile Thermostat

The use of the mobile thermostat would allow for more accurate air temperature control in the required location, and would result in improved comfort conditions and substantial energy savings. In our calculations, we evaluated potential annual energy savings due to the utilization of the mobile thermostat to control space heating and space cooling in the townhouse (which is similar to one considered in the paper) located in the city of Hartford, Connecticut.

A simplified model which assumes that the heating and cooling requirements are proportional to the difference between the average house air temperature and average outdoor air temperature was utilized in the calculations.

The specific annual energy savings (SAES) due to a lowering or increasing a thermostat's set point temperature by $\pm$ 1^0 C ($\pm$ 1.8^0 F) during heating or cooling mode of operation was calculated by the formula:

$$SAES = [\Delta t / (HCS - t_{avoutHC})] \times 100\%$$

Where:

Δt = the magnitude of lowering or increasing of a thermostat's set point temperature, ^{0} C (^{0} F);

HCS = current heating or cooling set point temperature, ^{0} C (^{0} F);

$t_{avoutHC}$ = average outdoor air temperature during heating or cooling season, ^{0} C (^{0} F).

Potential Savings During Heating Mode of Operation

The following assumptions were used to compute the savings for space heating:

- an average outdoor air temperature during a heating season in winter, 1.3^0 C (34.4^0 F), corresponds to the space heating balance temperature of 12.8^0 C (55^0 F), based on the assumption that space heating will be necessary when the outdoor air temperature is lower than 12.8^0 C (55^0 F)
- based on the results of temperature monitoring, the mobile thermostat will reduce the air temperature in the apartment by Δt = 2.2^0 C (4^0 F), when it is occupied and the occupants are on the second floor
- an average downstairs air temperature in the house during the time when the downstairs area is not occupied and controlled by the stationary or mobile thermostat is 20^0 C (68^0 F) or 17.8^0 C (64^0 F), respectively
- an average upstairs air temperature in the house during the time when the upstairs area is occupied and controlled by the stationary or mobile thermostat is 22.2^0 C (72^0 F) or 20^0 C (68^0 F), respectively
- average daily time the apartment is occupied and not-occupied during a typical week is 14.4 hours (60% of the time) and 9.6 hours (40% of the time) a day, respectively
- 30% and 70% of the occupied time in the house is spent downstairs and upstairs, respectively
- SAES per 1^0 C (1.8 ^{0}F) of air temperature set-back from 20^0 C (68^0 F) is about 5.3%
  per 1^0 C [(1^0 C /(20^0 C-1.3^0 C)) x100%] or 3% per 1^{0}F.

Annual energy savings (ES) for space heating (assuming the assumptions listed above) are calculated by the formula:

ES = SBAT x SAES x RHO x RUOH

Where:

SBAT = set back in air temperature in the house due to the utilization of the mobile thermostat, 2.2^0 C (4^0 F);

RHO = ratio of weekly occupied hours in the house to the total weekly hours, 0.6;

RUOH = ratio of the upstairs weekly occupied hours to the total house weekly occupied hours, 0.7.

Therefore, the annual energy savings will be:

ES = 2.2 ^{0} C x 5.3%/1^{0} C x 0.6 x 0.7 = 4.9%

Potential Savings During Cooling Mode of Operation

The following assumptions, in addition to those stated previously, have been used to compute savings:

- the average outdoor dry-bulb air temperature during a cooling season in summer is 27.7^{0} C (81.9^{0} F), we assumed that the apartment's cooling would be necessary when the outdoor air temperature exceeds 23.9^{0} C (75^{0} F)
- the mobile thermostat will allow the air temperature in the apartment to increase by Δt = 0.55^{0} C (1^{0} F) when it is occupied and the occupants are on the second floor
- the average downstairs air temperature in the house during the time when the downstairs area is not occupied and controlled by the stationary or mobile thermostat is 22.8^{0} C (73^{0} F) or 23.3^{0} C (74^{0} F), respectively
- the average upstairs air temperature in the house during the time when the upstairs area is occupied and controlled by the stationary or mobile thermostat is 23.3^{0} C (74^{0} F) or 23.9^{0} C (75^{0} F), respectively.

Annual energy savings (ES) for space cooling (assuming the assumptions listed above) are calculated by the formula:

ES = SFAT x SAES x RHO x RUOH

Where:

SFAT = set forward in air temperature in the house due to the utilization of the mobile thermostat, 0.55^{0} C

(1^{0} F).

SAES per 1^{0} C (1.8^{0} F) of the increased air temperature is about 26.3 %/1^{0} C [(1^{0} C / (27.7^{0} C - 23.9^{0} C)) x 100%] or (14.6%/1^{0} F).

ES = 0.55 ^{0} C x 26.3%/1^{0} C x 0.6 x 0.7 = 6.1%.

According to the statistical information from the publications of the United States Energy Information Administration, an average household in the United States pays about $545 and $123 per year for space heating and space cooling, respectively. Thus, annual energy cost savings for space heating will be approximately $545 x 0.05 ≅ $27, while annual energy cost savings for space cooling will be $123 x 0.06 ≅ $7.

We anticipate that a unitary mass production cost of the mobile thermostat system (including the cost of the mobile and stationary thermostats) would be approximately $75 to $100. Therefore, the simple payback for a mobile thermostat utilization in a residential townhouse would be close to 3 years. The above savings would result in an annual reduction of energy intensity for a residential townhouse in the United States of approximately 22.9 MJ/m^2 (2.0 x 10^3 BTU/ft^2) and 3.3 MJ/m^2 (0.085 kWh/ft^2) for heating and cooling, respectively.

Presently, accurate control of the room air temperature can only be maintained in a close proximity to the stationary thermostat. This means that the air temperature in a particular location in the room (where an occupant happens to be at the moment) will always be kept higher (in heating mode) or lower (in cooling mode) than its desired value by so called “safety factor” to guarantee an occupant’s satisfaction with the climate in the house.

In our opinion, the mobile thermostat would also save an appreciable amount of energy for space heating and space cooling (even when located in the same room where the stationary thermostat is) by allowing reduction of this “safety factor”, and thus decreasing the difference between the thermostat’s set point and the desired temperature in a particular location of the room. In addition, the mobile thermostat would allow implementation of optimized nighttime set-back temperature control on the second floor of the apartment (assuming that the nighttime air temperature is reduced when compared to the upstairs air temperature during the rest of the day) and realize related additional energy savings. However, at this time we do not have sufficient information to quantify these two categories of potential savings.

Conclusion and Future Directions

The control of the heating/cooling systems in residential townhouses utilizing a stationary thermostat leads to a significant vertical air temperature variations between the second and the first floor as well as horizontal temperature variations within open areas of the first floor in the living room.

The vertical air temperature variations between the second and the first floors during the heating mode of operation ranged from 1.5^0 C to 4^0 C (2.7^0 F to 7.2^0 F). The horizontal air temperature variations during the heating mode of operation within the living room on the first floor ranged from $+2^0$ C to -5^0 C ($+3.6^0$ F to -9^0 F) as compared to the temperature at the stationary thermostat.

The vertical air temperature variations between the second and the first floors during the cooling mode of operation ranged from 0.6^0 C to 2.7^0 C (1.1^0 F to 4.9^0 F). The horizontal air temperature variations within the living room on the first floor during the cooling mode of operation ranged from + 2^0 C to -2^0 C ($+3.6^0$ F to -3.6^0 F) as compared to the temperature at the stationary thermostat.

It should be noted that the air temperature variations observed in our investigation are not uniquely related only to the townhouse type of residential buildings. We have also monitored the air temperature variations in a two-bedroom ranch residential house located in the state of Wisconsin. The house has approximately

111.5 m^2 (1,200 ft^2) of total area. The house has a central furnace and forced-air system. The stationary thermostat is in the living room. The temperature differential between the air temperature at the thermostat location and in the bedrooms during the heating mode of operation ranged from 1.1^0 C to 2.8^0 C (2^0 F to 5^0 F).

The air temperature variations are a function of multiple variables, and therefore, are difficult to predict and to determine the required set point temperature at the stationary thermostat location. An additional control stage is necessary to adequately address vertical and horizontal temperature differences in residential houses.

The mobile thermostat - an innovative wireless control device - suggests a solution to the problem. The mobile thermostat employs advanced control technology and is designed to provide customized air temperature control throughout the building. The mobile thermostat consists of the receiver (stationary part) and the transmitter (movable part). The transmitter is capable of sending a remote radio signal to the receiver to turn on/off a furnace's heating or cooling system in order to maintain a set point temperature at the transmitter's location. The investigation of the mobile thermostat's prototype model operation in a residential apartment during heating and cooling modes has been conducted. The mobile thermostat has successfully demonstrated its ability to control the air temperature in any location of the apartment and at any time on demand.

The mobile thermostat is recommended for application in combination with the stationary thermostat. The stationary thermostat will continue to implement heating/cooling control when the apartment is not occupied. The mobile thermostat could be utilized when the house is occupied. In this capacity, the mobile thermostat would give a tenant the tool to enhance comfort in the apartment as well as to save about 5% in annual energy for space heating and cooling.

The next step will include manufacturing a group of mobile thermostats to investigate their performance in various types of residential buildings situated in different geographical locations. The baseline energy consumption for the building's heating and cooling with stationary thermostats shall be compared to the energy consumption of the buildings equipped with the combined control system including mobile and stationary thermostats. This would allow verifying and quantifying potential energy conservation benefits associated with utilization of the mobile thermostats.

The mass application of the mobile thermostat, considering the scale of energy consumption in residential buildings which consume more than 20% of the total energy use (6) including residential, commercial, agricultural and transportation sectors, could be an important step in the conservation of energy resources. Obviously, the use of the mobile thermostat is not limited exclusively to residential buildings and might be beneficial for different kinds of buildings and end-uses.

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