Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 95 (2016) 358 – 365

Energy Procedia

International Scientific Conference “Environmental and Climate Technologies”, CONECT 2015, 14-16 October 2015, Riga, Latvia

Automation of monitoring the thermal conditions in a room

Nadezhda Petrova*, Aleksandr Vershinin, Stanislav Abramchuk, Aleksey Pugovkin

Tomsk State University of Control Systems and Radioelectronics, 40 Lenina Prospect, Tomsk 634050, Russia

Abstract

Monitoring of thermal conditions in a separate room and a building is one of the most important practical tasks on the stage of building commissioning. The task can be solved by in-situ temperature measurement of and the results are calculated by a simple mathematical model. The model is a system of balance differential equations for average temperatures of a heater, air and internal boundary.
The parameters of equations are heat-transfer coefficients of heaters, heat-transfer coefficients of internal and external boundary and heat capacitance of objects in a room. These parameters are calculated in a reverse problem. Non-steady-state situations appear with temperature changes in a room. The target values are calculated through the analysis of temperature dependence.
The automated complex for this algorithm consists of a system of temperature sensors, a microcontroller, a radio data link and a hosting server. The system was tested in residential and production buildings, and the monitoring proved to be low-cost.
The system also allows to measure heat energy input to high precision according to individual characteristics of a room and a heater. The accuracy is provided by experimental study of heat-transfer coefficients of heaters and statistical data analysis.

Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment.
Keywords: energy efficiency; thermal comfort; thermal performance; heat transfer; monitoring; simulation; experiment

1. Introduction

Energy efficiency is one of the most important tasks of society. The problem of rational heat consumption is current because heating systems in residential buildings are the most power-intensive engineering systems in many countries. Control and monitoring of indoor thermal conditions represent an important task with the aim of ensuring suitable working and living spaces to people [1–5].These tasks include investigations of heater efficiency [6, 7] and effective

* Corresponding author. Tel.: +8-952-886-6995
E-mail address: n.muslimova@mail.ru

Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment.
doi:10.1016/j.egypro.2016.09.022

heat-retention lagging of the room [8, 9], instrumentation and automation for measurement and control of thermal conditions and power consumption.

The measurement of heat energy input to high precision in one flat in an apartment building with a vertical heat supply system is an important problem. The problem is still relevant, despite the huge number of heat energy metering systems [10–15]. An apartment-level heat meter [14], which measures the mass flow rate of a heat-transfer fluid, cannot be used in this block of flats because of high costs, poor precision and other major deficiencies. The heat cost allocators for the determination of the consumption of room heating radiators [15] are also not widely used in Russia, because these heat cost allocators only allow the determination of the heat consumption of each radiator in a flat as a share of the total heat consumption of the block of flats or a user group. It is not possible, with the heat cost allocators to calculate heat consumption in one flat, individually. The main problem is that such systems cannot be applied in the old housing stock, where the problem of energy saving is particularly important. The heat cost allocators [10–13, 15] have substantial defects: some characteristics of a room and a heater are not measured and taken into account by correction factors measured in the laboratory. The heat cost allocators do not take into account the individual characteristics of a room and a heater.

The problem can be solved by in-situ temperature measurement of objects and the results are handled by a simple mathematical model. The proposed approach also allows to measure heat energy in SI units input to a high rate of precision in one flat. The measuring device is mounted on the heater surface in order to record the time integral of the temperature difference between the heater surface and the room. In addition, the proposed approach also permits monitoring of thermal conditions in a separate room and to assess the effective heat-retention lagging of the room in real time without additional financial costs. This is possible because the same temperature sensors are used for monitoring and heat metering.

Many studies have focused on mathematical models of thermal conditions in buildings [16–20]. On the one hand, mathematical models of thermal conditions in buildings [16] provide a comprehensive discussion of the theory and practice of a mathematical simulation method for studying the thermal behaviour of rooms and buildings. However, this scientific approach uses many calculations. These mathematical models can be used for power supply engineering and construction and predict room temperature, but they are difficult and costly for technical feasibility.

On the other hand, building energy analysis programs can predict energy use and cost for all types of buildings [17–20]. As a rule, these programs use the national normative documents and the hidden mathematical models, which form the basis of their algorithms of calculation. This approach is not developed enough to be applied in practice for energy audit and heat energy measurement.

Based on the above, the main requirements of a mathematical model for monitoring thermal conditions in a separate room and a building is simplicity, quick operation and high precision.

The scientific novelty of this work is in the method of measuring the heat-transfer coefficients of heaters and the approach of measuring heat energy according to individual characteristics of a room and a heater. Automation of monitoring includes automated data collection from the temperature sensors and data communication to the hosting server by radio data link. The results are handled by a mathematical model on the hosting server. The automation systems of the control and the monitoring of indoor thermal conditions are widely used [1–5]. In particular, there are many opportunities to build wireless monitoring systems using ZigBee [2]. However, the use of the technology ZigBee leads to higher prices of finished products. In this regard, we have developed a radio modem operating at 868 MHz.

In the present paper the following goals are set:

- Monitoring thermal conditions in a room: investigations of heater efficiency and effective heat-retention lagging of the room;
- Model analysis of thermal conditions in a separate room with account of behaviour of temperatures of a heater, air and an internal boundary;
- Model analysis with account of the condition of a heater when its characteristics and its temperature change under external impacts;
- Energy audit and measurement of heat energy using the same system of temperature sensors;
- The proposed mathematical model can form the basis of the algorithm and the software of automatic control systems of heat supply in a separate room and a building.

Nomenclature

h_a	heat transfer coefficient of ambient air
h_2	heat transfer coefficient of internal boundary
h_3	heat transfer coefficient of a heater
h_{adj}	heat transfer coefficient of adjacent rooms
T_1	indoor air temperature
T_a	ambient air temperature
T_2	temperature of internal boundary
T_{adj}	temperature of adjacent rooms
T_3	temperature of a heater
ΔT	$\Delta T = T_3 - T_1$ the time-dependent thermal gradient between environment and heater
Ts	supply temperature
Tr	return temperature
G	mass flow rate of a heat-transfer fluid
C_1	heat capacity of indoor air
C_2	heat capacity of internal boundary
C_3	heat capacity of a heater
τ_1	time constant of air in room
τ_2	time constant of internal boundaries
τ_3	time constant of a heater
Q	thermal energy

2. Model formulation

2.1. Mathematical model of the thermal and air conditions in a room

The basis of mathematical modeling is a system of balance differential equations for average temperatures of a heater, air and the internal boundary. This approach does not consider some characteristics of the current process. However, the main processes of heat transfer are described in the following paragraphs.

The mathematical model is considered for a separate room that contains internal and external boundaries, a heater and has adjacent rooms. The increase in thermal energy is due to a heater, and its loss due to heat transfer to the external environment and the adjacent rooms. The thermal energy is a dependent variable in balance differential equations.

The first equation considers the change of thermal energy of air Q_1 in a room:

$$\frac{dQ_1}{dt} = h_3 \cdot (T_3 - T_1) - h_2 \cdot (T_1 - T_2) - h_a \cdot (T_1 - T_a) \tag{1}$$

The second equation for the internal boundary is documented. The temperature of adjacent rooms is not equal to the temperature of the internal boundaries of the room in question:

$$\frac{dQ_2}{dt} = h_2 \cdot (T_1 - T_2) - h_{adj} \cdot (T_2 - T_{adj}) \tag{2}$$

We introduce the ratio: $Q_1 = C_1 \cdot T_1$, $Q_2 = C_2 \cdot T_2$. The system of equations can be written as:

$$\begin{cases} C_1 \cdot \dfrac{dT_1}{dt} = h_3 \cdot (T_3 - T_1) - h_2 \cdot (T_1 - T_2) - h_a \cdot (T_1 - T_a) \\ C_2 \cdot \dfrac{dT_2}{dt} = h_2 \cdot (T_1 - T_2) - h_{adj} \cdot (T_2 - T_{adj}) \end{cases} \quad (3)$$

These equations must be supplemented by the initial conditions, for example, indoor air temperature and temperature of the internal boundary in the initial instant t=0. The ambient air temperature and temperature of a heater are dependent variables. The coefficients h_a, h_2, h_3 included in the equation, are of integral character and can be found experimentally.

2.2. Equations for a heater

The thermal conditions in a room provide a heater the temperature of which was set constant in the preceding discussion. But in fact the temperature of a heater is changed during operation.

The equation for a heater in dynamic rating is written down:

$$\frac{dQ_3}{dt} = G \cdot (T_s - T_r) - h_3 \cdot (T_3 - T_1) \quad (4)$$

This equation considers inert properties of a heater, speed of heat transfer fluid and other parameters. The increase in thermal energy is due to a heating medium supply, and its loss due to heat transfer to the indoor air.

In the first approximation, we consider that the flow temperature and the surface temperature of the heater are proportional to each other with the correction coefficient $Q_3 = C_3 \cdot T_3$.

In a real situation, the temperature of the heater is a function of time. Therefore, the system of Eq. 3 should be supplemented by the Eq. 4. Below, we write the system of equations describing the thermal conditions in a room:

$$\begin{cases} C_1 \cdot \dfrac{dT_1}{dt} = h_3 \cdot (T_3 - T_1) - h_2 \cdot (T_1 - T_2) - h_a \cdot (T_1 - T_a) \\ C_2 \cdot \dfrac{dT_2}{dt} = h_2 \cdot (T_1 - T_2) - h_{adj} \cdot (T_2 - T_{adj}) \\ C_3 \cdot \dfrac{dT_3}{dt} = G \cdot (T_s - T_r) - h_3 \cdot (T_3 - T_1) \end{cases} \quad (5)$$

This system can be applied to calculation of the thermal conditions of rooms in stationary and dynamic conditions.

Some assumptions were accepted:

- The time constant τ_3 is the parameter characterizing the inertial properties of a heater. The time constant τ_3 is much less than time constants of air in a room τ_1 and of internal boundaries τ_2. We accept that temperature of air equal to temperature of an internal boundary. Therefore, the equation for a heater in a system (1) can be solved independently of the system (1);
- If the temperature of a heater is constant, the equations of air and an internal boundary can be solved independently of the third equation in the system (1);
- The heat transfer coefficient of a heater is an integral quantity which takes into account the heat transfer surface area.

The parameters of equations are heat-transfer coefficients of heaters, heat transfer coefficients of internal and external boundaries and heat capacitance of objects in a room. These parameters are calculated in a reverse problem.

Non-steady-state situations appear with temperature changes in a room. The target values are calculated through the analysis of temperature dependence.

We considered the third equation in system (1) for a heater. If the speed of heat transfer fluid is equal to zero, heat-transfer coefficient of a heater is calculated as:

$$h_3 = \frac{C_3 \cdot \dfrac{dT_3}{dt}}{T_3' - T_1'} \tag{6}$$

According to Newton's law of cooling, the thermal energy of a heater can be defined by using the equation:

$$Q = \sum_i h_3^i \cdot (T_3^i - T_1^i) \cdot \Delta t \tag{7}$$

Known h_3 value allows to find the remaining parameters of the Eq. 5. The thermal conditions in a room is a steady-state ($dT_1/dt = 0$). The ambient air temperature does not change. Some assumptions were accepted: $T_1 = T_2$. Basic data for calculation were selected from one point of the time: T_a, T_3, $T_1 = T_{adj} = T_2$. Substituting these data and the known value of h_3 in the first equation (5) can be found h_a:

$$h_a = \frac{h_3 \cdot (T_3 - T_1)}{(T_1 - T_a)} \tag{8}$$

The system of equations (5) establishes a relationship of heat transfer coefficients in the whole chain of summing up, transformation and scattering of thermal energy, namely heat-transfer fluid - heater - air - boundary. Evaluation of each of these relations in the conditions determines the influence of the parameters *ha*, h_2, h_3 on the heat exchange process.

3. Results and Discussion

3.1. Model check

To check the mathematical model adequacy (5) and to investigate heating processes in a room, we simulated the reference value parameters taking into account real thermo-technical characteristics of external boundaries (the given resistance of heat transfer and air permeability).

3.1.1. Heating of cooled air in a room

We can simulate the heating of cooled air in a room. Let’s imagine that the air and the walls in a room are cooled by the cold air from the outside (open window). Because of response delay, the walls are cooled less than the air. Then the room system was stabilized and the air and the walls were heated by the heaters.

The parameter values $h_3/C_1 = 5{,}15 \cdot 10^{-5}$, s^{-1}; $h_a/C_1 = 2{,}78 \cdot 10^{-5}$, s^{-1}; $h_2/C_1 = 0{,}56 \cdot 10^{-3}$, s^{-1} with the equation system (3) allow us to conduct simulation in MatLab. The initial data for the equations are: the average air temperature in the beginning is equal to 8 °C, the temperature of internal boundaries is 12 °C.

The established conditions:

- Temperature of a heating source 45 °C;
- Outside temperature –17 °C;
- Temperature of communicating rooms 17 °C.

The gained temperature dependences are given in Fig. 1.

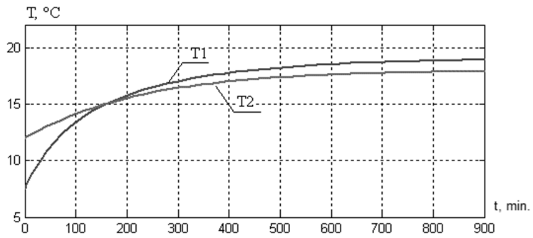

Fig. 1. Time dependences of air temperature T1 and room boundaries T2.

Figure 1 shows that in the beginning the wall and air temperature are different and the air temperature in the room is less than the temperature of the room boundaries.

The dependences are exponential with the phase of rapid air temperature grow and much slower grow of the room boundaries temperature. Both dependences stabilize after a while. The time of the transition process is a very important characteristic because it allows to measure the response delay in heating or cooling of a room. Figure 1 also shows the crossing of two curves at one point.

3.1.2. Self-cooling mode of a heater

In this case, the heating medium supply is interrupted G=0 at the initial time t=0. The results of the simulation are given in Fig. 2 the parameter is the value of the heat capacity of a heater.

The analysis of the gained results is quite clear: the temperature decrease is exponential and the time constant (the rate of decay) depends on the heat capacity of a heater).

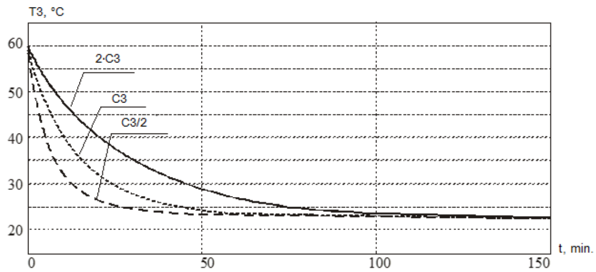

Fig. 2. Self-cooling of a heater depending on its heat capacity.

3.2. Automated system monitoring and field experiment

The experiment was made in a room of an apartment building. The floor area of the room is 14 sq.m. There is a window, a cast iron radiator of a MS-140-500 series with six sections, isolating valves and internal and external boundaries in the room.

The ADT7410 digital temperature sensor of high accuracy measures the temperature of a heater and indoor air. The third sensor measures the temperature of ambient air. The data from sensors is transferred to the computer.

To collect the data from heat and energy meters we developed a wireless modem with ONEwire, I2C, RS485, RS232, UART, etc [21]. The wireless modem parameters: input voltage 3,7 – 6,0 V; input current – not more than 35 mA in transmission mode, in sleeping mode – less than 1 uA; battery supply is possible, operating frequency – 433/868 MHz. To choose the frequency range we conducted a series of experiments in noise measurement in those ranges.

Data Acquisition and Transmission Devices provide wireless communication of meters connected to the wireless modem and the server. The Data Acquisition and Transmission Devices and the servers are connected by Ethernet or GSM/GPRS. The wireless modem RF433/868 can combine all the connected devices and the Data Acquisition and Transmission Devices in a MESH network with the possibility of data transfer to the server.

Figure 3(a) shows the results of the field experiment during the cooling process of a heater with six sections. The heat transfer coefficient of a heater is calculated in Eq. 6.

The measurement procedure for measuring heat transfer coefficient consists of the following actions. The temperature of a heater as a time function is measured in the cooling rate in Fig. 3(a). The air temperature is measured. A simple moving average is used with time series data to smooth out short-term fluctuations. The rate of temperature change in a heater as a time function is found on a segment of the cooling curve. This segment consists of *n* of points. *n* is the minimum number of indication when the heater temperature falls to the value not less than 3 K. The heat transfer coefficient of a heater is calculated in Eq. 6. The heat capacity of a heater is reference data. The approximation by linearization is applied for the heat transfer coefficient as a ΔT function. It is necessary to find the slope of the curve at two points (h и ΔT).

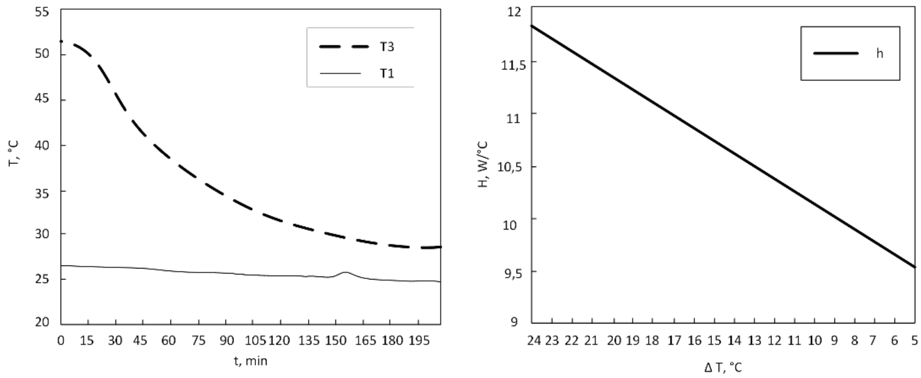

Fig. 3. Field experiment (a) Temperatures of a heater and air as a time function is measured in the cooling conditions; (b) Heat transfer coefficient as ΔT function.

Known h_3 value allows to find the remaining parameters of the Eq. 1. The second experiment was carried out to investigate the heat transfer coefficient of ambient air. The measurements were taken for 24 hours. The thermal conditions in a room is steady-state. The ambient air temperature does not change. Some assumptions were accepted: $T_1 = T_2$. Basic data for calculation were selected from one point of the time: T_a = - 14,11 °C; T_3 = 50 °C; $T_1 = T_{adj} = T_2$ = 26 °C. Fig. 3(b) helps us calculate the value of h_3 = 11,85 W/°C when ΔT = 24 °C. These data are added in Eq. 8 and we get the result h_a = 7,09 W/°C.

The known value of the heat transfer coefficient of ambient air allows to evaluate a heat leakage through the external boundary in real-time. For example, the thermal outputs of a heater and a heat leakage through the external and internal boundaries, when ΔT = 24 °C, h_3 = 11,85 W/°C, h_a = 7,09 W/°C:

- $P_3 = h_3 \cdot \Delta T$ (W) = 11,85 · 24 = 284,4 W - thermal outputs of a heater;
- $P_a = h_a \cdot \Delta T$ (W) = 7,09 · 24 = 170,16 W - heat leakage through the external boundaries;
- P_2 = 284,4 – 170,16 = 114,24 W - heat leakage through the internal boundaries.

Thus, we see that according to Eq. 1 in the steady-state when the air in the room does not change (window and door closed), the whole thermal capacity of the heater should be spent through the external and internal boundaries. We can assess the condition of external and internal boundaries and take the necessary measures to improve energy efficiency for a known value of thermal outputs.

4. Conclusion

We presented the mathematical model that can form the basis of the algorithm and the software of automatic control systems of heat supply in a separate room and a building. The scientific novelty of this work is in the method of measuring the heat-transfer coefficients of heaters and the approach of measuring heat energy according to individual characteristics of a room and a heater. The system of balance differential equations establishes interrelation of the heat transfer coefficient of ambient air, the heat transfer coefficient of internal boundary and the heat transfer coefficient of a heater. The assessment of each of these ratios in specific operating conditions allows to define the influence of various parameters of the heat exchange process. The known value of the heat transfer coefficient of ambient air allows to evaluate heat leakage through the external boundary in real-time.

The proposed approach also allows to measure heat energy input to high precision according to individual characteristics of a room and a heater. The automated complex for this algorithm consists of a system of temperature sensors, a microcontroller, a radio data link and a hosting server. Accuracy is provided by an experimental study of heat-transfer coefficients of heaters and statistical data analysis. The approach also allows to perform the energy audit and measurement of heat energy using the same system of temperature sensors. The offered approach also allows to perform the monitoring of thermal conditions in a separate room and a building whole at the stage of building commissioning.

Acknowledgements

This work is financially supported by the Ministry of Science and Education of the Russian Federation, contract no. 02.G25.31.0107.

References

[1] Principi P, Di Perna C, Ruffini E. Laboratory Experimental Method to Measure Thermal Fluid Dynamic Parameters Characterizing the Climatised Office Room. Journées de Thermique 2001;183–188.
[2] Noh SK, Kim KS, Ji YK. Design of a Room Monitoring System for Wireless Sensor Networks. International Journal of Distributed Sensor Networks Volume 2013;1–7.
[3] Calvino F, Gennusa ML, Rizzo G, Scaccianoce G. The control of indoor thermal comfort conditions: Introducing a fuzzy adaptive controller. Energy and Buildings 2004;36:97–102.
[4] Chung WY, Oh SJ. Remote monitoring system with wireless sensors module for room environment. Sensors and Actuators B 2006;113:64–70.
[5] Xianzhe H. Room temperature and humidity monitoring and energy-saving system. Presented at the 6th International Conference on Computer Science & Education (ICCSE 2011) Singapore, 2011;537–540.
[6] Tabunschikov Y, Brodatch M. Optimal control of energy consumption for heating. ASHRAE Journal 2006;48:26–31.
[7] Pukhkal V. Experimental estimate of the heat flow parameters of heating appliances. J of Applied Engineering Science 2014;12:19–22.
[8] Balajia NC, Monto Manib, Venkatarama Reddyc BV. Discerning heat transfer in building materials. Energy Procedia 2014;54:654–668.
[9] Vasilyeva GP, Lichmana VA, Peskovb NV. Simulation of heat and moisture transfer in a multiplex structure. Energy and Buildings 2015;86:803-807.
[10] Nikitina SV. Individual account of thermal energy in buildings with vertical distributing heating systems. Legislative and applied metrology 2014;5:31–34.
[11] Heat cost allocator. The proven technology for metering heat consumption. Available: https://www.ista.com/corporate/solutions/technology/heat-cost-allocator.
[12] Ziemele J, Pakere I, Blumberga D, Zogla G. Economy of heat cost allocation in apartment buildings. Energy Procedia 2015;72:87–94.
[13] Techem Italy to install and service 25.000 radio heat cost allocator and thermostatic valves on behalf of the City of Rome. Press Release, 2010. Available: http://www.techem.com/fileadmin/attachments/www.techem.com/English/PDF/Press/2010/07_05_10/PI_Techem_Italy_CPL_Ater_May2010_engl_.pdf
[14] Danfoss Products. Energy Meters. Available: http://products.danfoss.com/productrange/heatingsolutions/energy-meters/
[15] Heat cost allocators for the determination of the consumption of room heating radiators. European Standard EN 834; 1994.
[16] Tabunschikov YA. Mathematical Models of Thermal Conditions in Buildings. English edition. CRC Press; 1993.
[17] U.S. Department of Energy. Energyplus energy simulation software 2015. Available: http://apps1.eere.energy.gov/buildings/energyplus/?utm_source=EnergyPlus&utm_medium=redirect&utm_campaign=EnergyPlus%2Bredirect%2B1.
[18] ESP-r. Modelling tool for building performance simulation. Available: http://www.esru.strath.ac.uk/Programs/ESP-r.htm.
[19] Danish building research institute. BSim - Building Simulation. Available: http://www.sbi.dk/en/bsim.
[20] The home of DOE-2 based building energy use and cost analysis software. Available: http://www.doe2.com/.
[21] Boll SR. Analog Interfacing to Embedded Microprocessors. Publishing house Dodeka-XXI; 2007.