Experimental study of transient processes in the elements of climatic systems

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Abstract. Transition processes for different modes of functioning of elements of the climate system model are experimentally investigated and analyzed. The following elements have been selected as the objects of experimental research: the air heater and the fan as the main elements that are part of each climate system. The system under study consisted of the following sequential elements: air heater-fan-room. The relative excess heat is proposed as a dimensionless parameter in the analysis and normalization of experimental data. First, the relative excess heat takes into account changes in temperature, moisture content and flow rate of humid air, and secondly, allows identifying similarities in the processes of change over time of the thermodynamic state of the air when passing through the climate system elements for different operating modes of the fan and air heater. Analysis of the evolution of relative excess heat during transient changes in the parameters of the flow of humid air, as in case of abrupt changes in performance of a heater but with a fixed performance of a fan and in case of abrupt changes in performance of a fan, but with a fixed power of the air heater. The regularities of the evolution of relative excess heat in the flow of moist air and its most important qualitative types when passing through the elements of the model climate system are shown. It was found that the types of behavior of relative excess heat depend only on the state in which the elements of the system are located during the transition process, and not on the element itself as a physical object.

1 Introduction

Providing thermal conditions in buildings for various purposes requires stabilization of the specified parameters of the microclimate at a certain level. This requires, on the one hand, certain material and energy resources. On the other hand, this is connected with the concept and development of climate systems, which should compensate for the constantly changing external and internal disturbances of the heat and moisture flows, etc.

External and internal disturbances of microclimate parameters can be periodic (for example, daily, seasonal) or random. This determines the non-stationary thermodynamic mode of climatic systems.

Because of the level of requirements to the quality of the microclimate, the climate system can be functionally quite simple, for example, convection heating and quite complex, for example, the air conditioning system in combination with radiant systems for heating and cooling [1, 2]. No matter how complex the climate system may be, it consists of the main elements: heat and mass transfer devices (heat exchangers, humidifiers and dehumidifiers), pressure lifting devices (pumps, fans, compressors) [2]. But at any level of complexity of climate systems, however, the task is to study transients of changes in the parameters of the state of a stream of humid air as it passes through the elements of the climate system, that is, to study the response of a stream to an external disturbance.

The importance of such research is based primarily on the attention of specialists in the design and development of control systems and automated microclimate quality control. In most cases, thermodynamic and transient processes of heat transfer have been investigated theoretically only [3-10]. In our opinion, the reason is quite obvious. Experimental studies are quite expensive and require a significant amount of time and experimental installation corresponding to real climate systems. In particular, the processes occurring in real conditions should be adequately reproduced.

2 Experimental setup and measurement techniques

Experimental studies were carried out on the installation of standard elements that are used in the design of ventilation and air conditioning systems. The installation was equipped with a computer-controlled information-measuring system (Fig. 1).

The information-measuring system recorded the temperature at the inlet and outlet of each element of the heater-fan-room system: t_1 and t_2 for the air heater, t_2 and t_3 for the fan and t_3 and t_4 for the room. The flow rate (u), the static pressure by the fan (ΔP), and the relative

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humidity in the flow (φ) were also recorded. The measured values of the sensors were recorded equidistant in one second in the control sections. Power control of the system elements was automatic: the air heater was equipped with a triac power regulator *AW*, and the fan - frequency regulator *AF*.

The transition process was started abruptly, by changing the performance of one of the elements of the air heater-fan system, with a fixed air flow of the other. The value of the surge in the air flow of elements varied by a certain amount in fractions of the maximum power of the element and ranged from 0.1 to 0.5 with a step of 0.1.

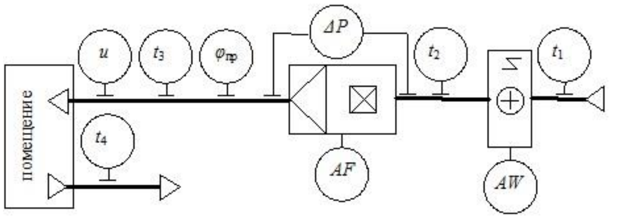

Fig. 1. Schematic diagram of the experimental setup

Registration of parameters was carried out until the stabilization of the air flow temperature. The experiments were divided into series, the number of which was determined by a possible combination of possible modes of operation of the air heater and fan.

3 Measurement result

To generalize and analyze the experimental data of transients in climatic systems, a parameter is required that takes into account both the change in the flow temperature and its velocity. Therefore, we have proposed a relative excess heat, calculated as follows. For the apparent heat generated by the air heater

$$Q_h^r = \frac{Q_h(\tau) - Q_h(0)}{\left|Q_h(\tau_*) - Q_h(0)\right|}, \quad (1)$$

absorbed by the fan

$$Q_f^r = \frac{Q_f(\tau) - Q_f(0)}{\left|Q_f(\tau_*) - Q_f(0)\right|}, \quad (2)$$

and assimilated by the room air

$$Q_r^r = \frac{Q_r(\tau) - Q_r(0)}{\left|Q_r(\tau_*) - Q_r(0)\right|}, \quad (3)$$

where $Q(\tau)$, $Q(0)$, $Q(\tau_*)$ is the heat released by the element into the current τ, the initial τ = 0, and the final τ_* =500s times.

Similarly, the calculated relative excess flow

$$G^r = \frac{G(\tau) - G(0)}{\left|G(\tau_*) - G(0)\right|}, \quad (4)$$

Experimental dependences of the parameters obtained during the processing of experimental data, namely: changes in the flow temperature, velocity and relative values of heat and flow (1) - (4) with a sudden increase in the power of the heater (flow heating) are shown in Fig. 2 and with an abrupt increase in the fan performance (acceleration of the flow) in Fig.3.

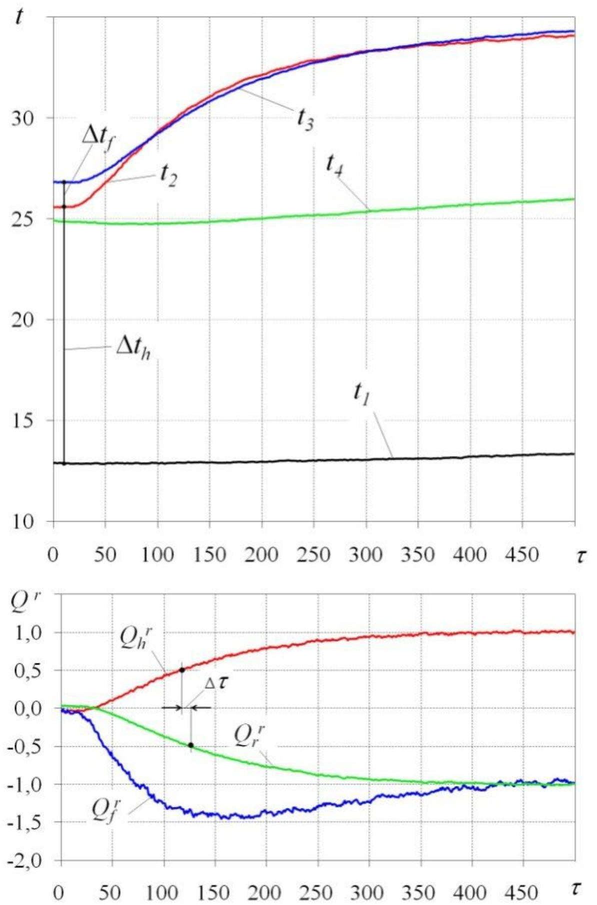

Fig. 2. Experimental dependences of changes in temperature and relative values of heat (1) – (3) on time upon heating of the flow. The mode of operation of the fan 0.9 and air heater 0.5 ÷ 0.8

Consider the behavior of the flow parameters in the process of transition from the initial moment of time to the final. When the flow is heated by the air heater, t_2 will increase, Fig. 2. The experimental data correspond to a constant fan capacity of 0.9 (63 Hz) and an increase in the thermal power of the air heater from 0.5 (6 kW) to 0.8 (9.6 kW). In some series, including this article (Fig. 2), it was found the excess temperature t_2 over t_3 in the time interval from 75 to 300 s. This is due to the high heat capacity of the "body" of the fan, the heat exchange between it and the air that flows it. The higher the fan performance, the more intense the heat exchange between the fan and the flow and the smaller the difference between t_2 and t_3. At high flow rates, this difference may be negative, as shown in Fig. 2. Temperature t_4 characterizes the flow to be removed from the room serviced by the system. It does not a monotonously curve. When heating the stream (τ ~ 75 s), a small minimum is observed. This is due to the volume of air in the room, the value of the fan performance and, therefore, depends on the multiplicity of air exchange. The higher this value, the less the assimilating capacity of the air in the room affects the microclimate parameters.

The evolution in time of the relative excess heat Q^r released by the air heater, absorbed by the fan and assimilated by the air of the room when the flow is heated is shown in the lower part of Fig. 2. When heating the flow, the heat released by the air heater increases Q_h^r. On the contrary, the amount of relative excess heat Q_f^r absorbed by the fan during the heating of the flow increases at the initial stage and reaches a minimum, and then decreases and stabilizes. The extremum of the evolution of the relative excess heat absorbed by the fan is due to the different rates of temperature change before and after the fan (t_2 and t_3) during the transition process.

The evolution of the relative excess heat assimilated by the room Q_r^r air goes in antiphase with a shift Δτ to the heat generated by the air heater. The figure 2 shows fan operation modes at $\Delta\tau \approx 10$ s. With decreasing fan performance, the delay $\Delta\tau$ increases. For example, for fan operation mode 0.4 (28 Hz) Δτ ≈ 16s. What is completely permissible to associate with the rate of air exchange, i.e. with decreasing multiplicity of air exchange, the delay $\Delta\tau$ grows.

The transition process during flow cooling, i.e. with a sharp decrease in the heating capacity of the air heater, is similar to heating, with the only difference that the processes of change Q_h^r, Q_f^r and Q_r^r are practically symmetrical with respect to the time axis.

Fig. 3 shows the data on acceleration of the flow, obtained with a fixed heating capacity of the heater 0.3 (3.6 kW) and fan performance from 0.5 (35 Hz) to 0.8 (56 Hz). When disperse, the t_2 goes down. In this case, t_3 decreases somewhat slower than t_2, which is associated with an increase in productivity and is correlated with a significant increase in the fan's own heat emission. In addition, the larger the sourge of the flow velocity u, the greater the increase of the temperature difference between t_2 and t_3. Temperature t_4 characterizes the flow removed from the room and it does not monotonously curve. When disperse t_4 first increases slightly, and then falls monotonously. The presence of such a phenomenon is mainly associated with the volume of air in the room and the magnitude of the jump in the performance of the fan. The greater the sourge and, accordingly, the greater the increase in the rate of air exchange, the less the assimilation capacity of the air in the room affects the parameters of the microclimate. During the acceleration of the flow, the relative excess heat assimilated by the room air Q_r^r and emitted by the fan Q_f^r increases monotonously.

The relative excess heat of the air heater Q_h^r during the acceleration of the flow has three different sections. At the first stage, there is an almost explosive growth due to a sharp increase in the velocity u of the flow. The duration of the initial phase depends on the time constant setting of the frequency controller *AF*. Then the flow rate u is stabilized and Q_h^r monotonically decreases, which is due to the stabilization of heat exchange between the flow and the surface of the air heater. On the last site Q_h^r practically does not change. This due to the nonlinear dependence of heat transfer between the surface of the air heater and the flow, depending on the growth of the velocity u and the temperature difference between them.

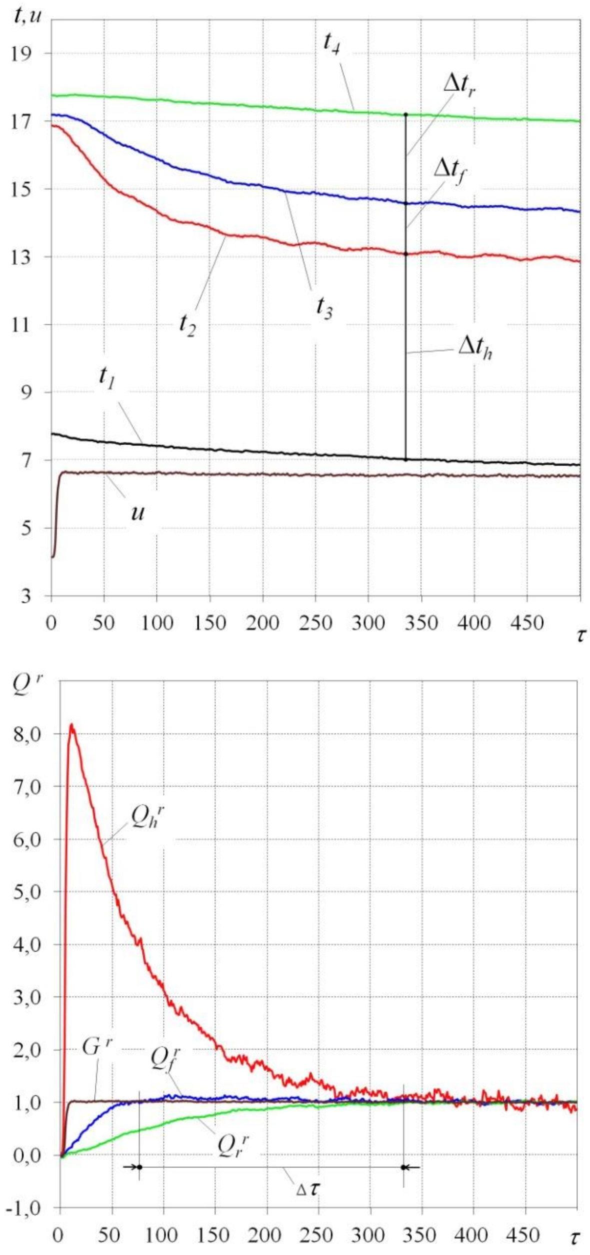

Fig. 3. Experimental dependences of temperature change, flow rate and relative values of heat (1) – (4) on time during acceleration of the flow. The mode of operation of the heater 0.3 and fan 0.5 ÷ 0.8

Evolution Q_f^r characterizes the effect of the fan on the flow at a sourge-like acceleration, depending on its own heat dissipation and heat exchange between its elements and the flow. The fan is a heat-generating element of the system with an internal heat source. As a result, the acceleration of the flow at the initial site (up to

15 s) gradually increases due to a small decrease in t_2 at an almost constant temperature t_3. Therefore, the evolution in this time interval is determined mainly by the explosive growth of the flow velocity.

The transient process of flow deceleration with a sudden decrease in fan performance is similar to heating, with the only difference that the processes of change Q_f^r and Q_r^r occur almost symmetrically with respect to the time axis, and for Q_h^r a decrease in the amplitude of the extremum.

4 Results And Discussions

In our studies, the transient process was considered as a response of the flow state parameters to the discontinuous influence of an element of arbitrary size from the moment of application of this effect to a certain steady state.

The evolution of the relative excess heat of the flow passing through the air heater Q_h^r, the fan Q_f^r and the room Q_r^r shows that their qualitative representation is provided only by the state of the elements of the climate system in which they are during the transition process.

As can be seen from Figs 2 and 3, three basic states of the system element can be distinguished: active, reactive and passive.

The active state is characteristic of the object of regulation with an internal heat source (in Fig. 1 this is an air heater, in Fig. 2 a fan).

Reactive is for an unregulated object, but also with an internal heat source reacting to an external perturbation of the flow by the active element (On Fig.1 is a fan and on Fig. 2 is air heater). And the passive state for the object of control (in both Figures 2 and 3 is a room) that does not have its own sources of heat or cold (except for rooms with enclosing structures with built-in radiant heating-cooling panels), where the microclimate is formed by internal and external sources and heat sinks [11-15].

It should be clarified that objects with internal sources of heat mean objects in which the internal source of heat is an integral part, without which the object cannot perform its functions. For the premises, internal and external sources and flows of heat (heat from people, technological and other climatic equipment, heat losses and heat gain through the enclosing structures, etc.) do not affect the main functions of the enclosing structures, namely protection from direct atmospheric influences.

Let us consider a more detailed effect of the system element on the state of flow parameters and the evolution of relative excess heat. Turning to the active state, the element generates more heat at the end of the transition process during heating or acceleration of the flow than at the beginning. This is indicated by the direction Q_h^r for +1 when heated (Fig. 2) and Q_f^r for +1 at acceleration of a stream (Fig. 3). This is a consequence of growth $\Delta t_h(\tau) = t_2(\tau) - t_1(\tau)$ (Fig.2) and $\Delta t_f(\tau) = t_3(\tau) - t_2(\tau)$ (Fig.3), which determines the positive sign of relative excess heat at the end of the transition process for the active element. The flow rate is always positive, when it is heated it is constant, and during acceleration it quickly grows and stabilizes. In the reactive state, an element with its own source of heat of a certain mass directly influences the evolution of relative excess heat. Moreover, the evolution of the reactive element Q_f^r (Fig.2) develops in the antiphase evolution of the active element, and Q_f^r (Fig.3) - in phase. This is explained by the fact that during the heating of the flow $\Delta t_f(\tau)$ decreases rapidly (Fig. 2) and, therefore, Q_f^r, it tends to -1, and when the flow accelerates, a gradual decrease $\Delta t_h(\tau)$ in the initial part (Fig. 3) is compensated by a sharp increase in the flow rate u Whole Q_h^r tends to +1.

It should also be noted that the elements in the reactive state are characterized by the appearance of the evolution extremum: for the fan Q_f^r (Fig.2) and air heaters Q_h^r (Fig.3). The presence of extrema of evolution is a consequence of different rates of temperature change at the inlet and outlet of the element. For example, the extremum of evolution of Q_f^r (Fig. 2) caused by a faster growth of t_2 than t_3 at the beginning of the transition process, which leads Q_f^r to -1. This behavior is demonstrated by evolution Q_h^r (Fig.3). There is also a significant difference in the rate of temperature change: t_2 decreases faster than t_1, with a sharp increase in the speed u. If the temperature changes rates of t_1 and t_2 were the same, then $\Delta t_h(\tau)$ would remain constant throughout the transition process and the evolution Q_h^r would be similar to the evolution of the relative excess flow rate G^r (Fig.3) without the presence of the extremum.

Evolution Q_r^r under heating of the flow develops in the antiphase evolution of the active element (Fig.2), tending to -1, and during acceleration of the flow behaves in phase to the active element, tending to +1 (Fig.3). This is explained by the fact that the room, having an internal space with a certain mass of air, is a heat-inertial element of the system under study. When the flow is heated by an air heater (Fig.2) the room air absorbs some of the heat and t_4 grows, and during acceleration of the flow fan (Fig.3) gives and t_4 decreases. Thus, $\Delta t_r(\tau) = t_4(\tau) - t_3(\tau)$ when heating the flow increases and decreases during acceleration.

5 Conclusions

The presence of transients in the elements of climatic systems with variable parameters (temperature and flow) of the coolant (air, water, etc.) is characteristic and requires a universal criterion for their analysis, classification and use in the optimization of control processes. As such, the criterion in this paper is the relative excess heat Q^r. This allowed not only to generalize and normalize the obtained experimental data, but also to reveal for the first time the regularities of the evolution of the relative excess heat and the qualitative form of functional relationships between the initial and final flow parameters.

Qualitative identification of the experimental data allows us to further functionally describe the evolution of relative excess heat for a wide class of climatic systems. Thus, the functional and parametric identification of the evolution of the relative excess heat Q^r of the flow passing through the elements of the climate system will make it possible to determine the current parameters of the flow state during the transition process at known initial values. Therefore, it is possible to solve the direct problem, i.e. to predict the reaction of the flow to the disturbance, both for individual elements of the climate system and the system as a whole, and for the room. Since the reaction to the possible disturbance of the moist air flow by the elements of the air heater-fan-room system is predictable in almost all time frames, a real tool for monitoring and controlling the microclimate in the room appears.

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