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Improvement of the Energy Efficiency of Centralised Energy Supply by Means of the Synthesis of a Control System

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Improvement of the Energy Efficiency of Centralised Energy Supply by Means of the Synthesis of a Control System

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Abstract. In this paper, the authors solve the complex problem of analyzing the centralized heat supply management system of a city and suggest ways to improve it. The authors perform the synthesis of combined centralized heat supply systems using two methods and present mathematical calculations.

1. Introduction

The prospects for the development of combined centralized heat supply systems (CCHSS) are determined by the fact that the rational use of natural resources increases and the cost of thermal energy received by CCHSS from CHPPs decreases. This cost is averagely by 40% lower than in district heat supply systems (DHSS) that receive heat energy from boiler houses [1].

As an object of automatic control, they differ in a number of features: input values are the temperature of the heat-transfer fluid entering a heating network and its consumption; output values are the temperature of the heat-transfer fluid returning to a CHPP, and the amount of thermal energy transferred to heat-consuming objects; the main disturbing factor is the outdoor temperature; the control action is determined by the temperature and flow rate of the heat-transfer fluid [2, 6].

The parameters of the heat-transfer fluid at the input of heat-consuming objects determine the quality of heat supply to consumers of thermal energy, and at the output - the efficiency of electricity generation at a CHPP.

CCHSS includes a variety of heat-consuming facilities that are located at different distances from CHP plants, have different heat engineering characteristics and dynamic parameters. The transfer function of control systems of this class is represented as a certain weighted average function corresponding to the conditions of an equivalent (representative) consumer [3, 8].

Automatic control systems of a CCHSS belong to the class of YSF models, so they are looked at from the perspective of interaction of the control system with the environment where the control system is isolated and its relations with the environment are singled out through input and output variables. Taking into account that a disturbing action can be measured, the model is implemented with the help of a perturbation-invariant control system [1, 4].

2. Concept

Fundamentally, such a statement of the question sets the task of synthesizing a model of the control system that provides selective invariance to a disturbing influence with a given control error.

The main purpose of the synthesis is to build a model that satisfies the following requirements: covariance with a task; perturbation invariance; stability and robustness [6]. The means of the problem solution are: choice of the structure of the control system (i.e., elements and topology of the cause-and-effect relationships between them), the structures of the element operators (in particular, controller algorithms) and the values of their parameters (regulator settings).

Satisfaction of the requirements for a behavior of a system determined by the given algorithm is hampered by dynamic properties of the controlled object and other elements of the unchangeable part of the control system, unavailability of complete aprior information about properties of the system



elements and the environment, impossibility of obtaining all current information about the state of the object and disturbances, restrictions on variables of the system and control actions.

Taking into account the fact that the mathematical model of the ASC of a CCHSS does not reflect all the dynamic properties of the control system, and also because of idealization and simplifications inevitable during modeling, as well as inaccuracies in the implementation of controller algorithms and changes in the characteristics of objects and other elements during operation, some restrictions were introduced during the period of modeling. In particular, restrictions concerning the ratio of fast and slow heat losses (heat retention properties of buildings), consideration of buildings as objects with lumped parameters, replacement of the variety of buildings by an equivalent (representative) consumer, change of parameters of a correction device (in order to ensure the stability of the control system) while maintaining the temperature schedule with the given control error.

Operator models of the existing and proposed structures of the automated control system of a CCHSS are presented in Figures 1, 2.

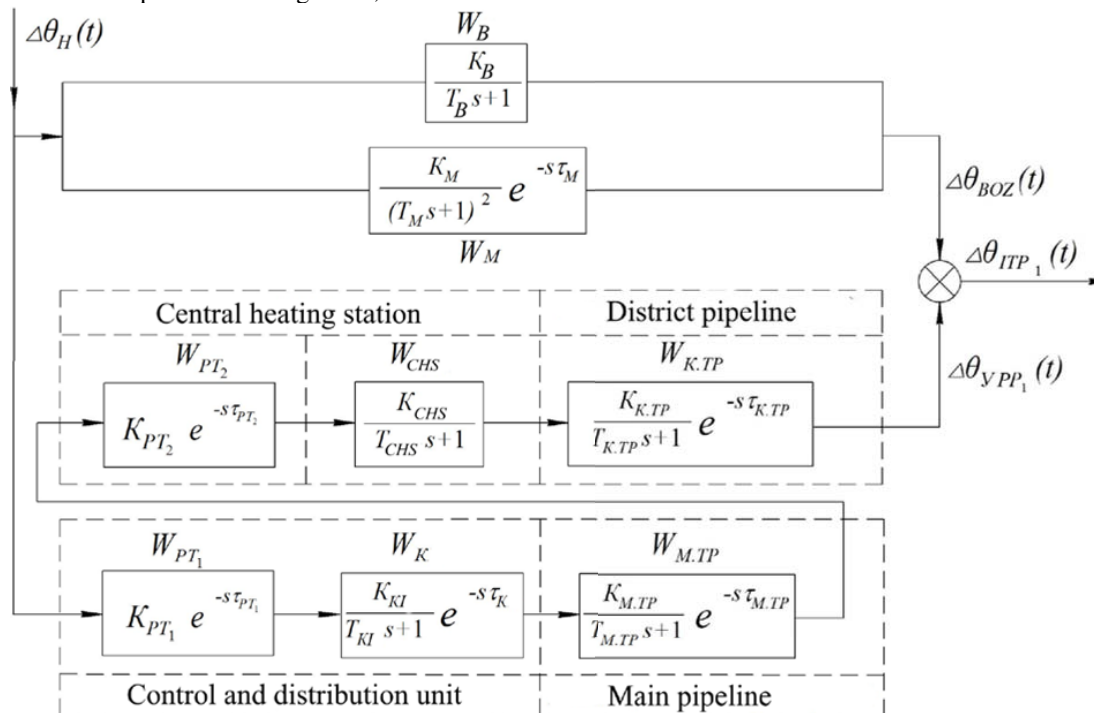


Figure 1. Operator model of the main and local control circuits (subsystem of ACS CCHSS): S – Laplace operator; W_B , W_M , W_{PT1} , W_{PT2} , W_{PT3} , W_{PT4} , W_{KI} , W_{CHS} , $W_{M.TP}$, $W_{K.TP}$, W_{CO} – transfer functions of the channels of fast and slow heat losses, temperature regulators of the cogeneration source, central heat supply station, heating system, hot water supply system; transfer functions of the main pipeline, district pipeline, heating system, hot water supply system; $\Delta\theta_H(t)$, $\Delta\theta_{BOZ}(t)$, $\Delta\theta_{YPP1}(t)$, $\Delta\theta_{ITP1}(t)$, $\Delta\theta_{ITP}(t)$ – temperature deviations of: outside air, disturbing effect, control actions and corresponding temperature increments of the heat-transfer fluid at the inlet and outlet of an individual substation.

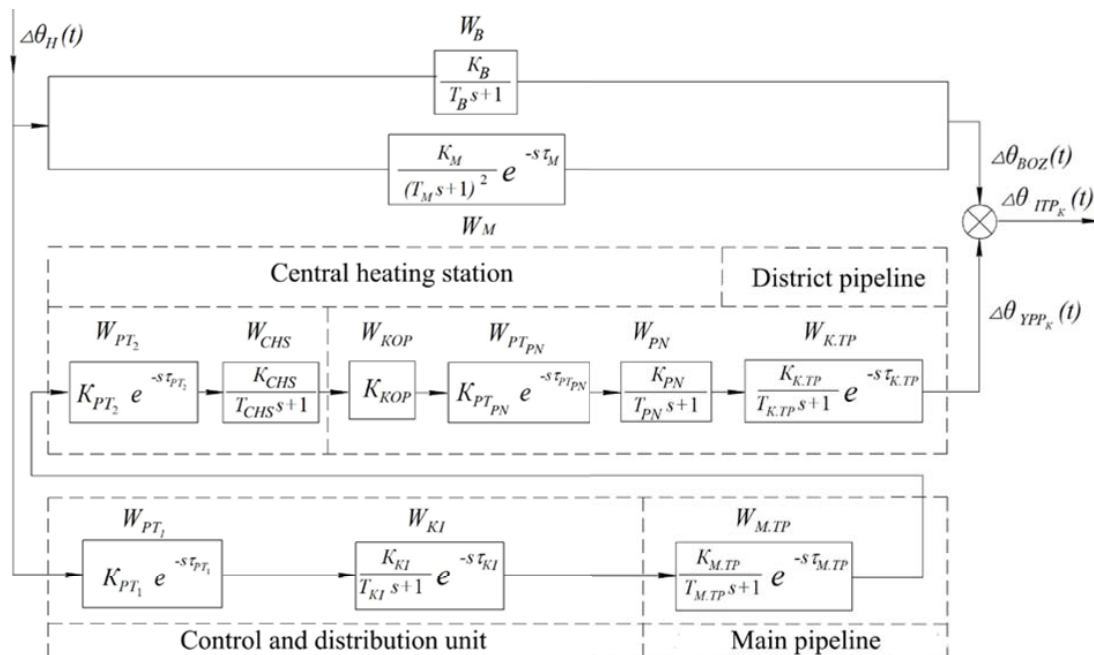


Figure 2. Operator model of the Main and local control circuits (subsystem of ACS CCHSS with dynamic peak load and correction device): W_{KOP} , W_{PTPN} , W_{PN} - transfer functions of a correction device, a peak load temperature controller, and a peak load.

The generalized transfer functions of existing and proposed operator models of the automated control system of a CCHSS, which ensure invariance of the control action to external disturbances, presented in Figures 1, 2, are expressed by the corresponding dependencies (1,3) and (2,4) [4].

At the input of a heat-consuming object:

$$W_{11} = \frac{K_{PT_1} K_{KI} K_{M.TP}}{(T_{KI}s + 1)(T_{M.TP}s + 1)} e^{-s(\tau_{PT_1} + \tau_{KI} + \tau_{M.TP})} \times \frac{K_{PT_2} K_{CHS} K_{K.TP}}{(T_{CHS}s + 1)(T_{K.TP}s + 1)} e^{-s(\tau_{PT_2} + \tau_{K.TP})} - \left(\frac{K_B}{T_B s + 1} + \frac{K_M}{(T_M s + 1)} e^{-s\tau_M} \right); \quad (1)$$

$$W_{12} = \frac{K_{PT_1} K_{KI} K_{M.TP}}{(T_{KI}s + 1)(T_{M.TP}s + 1)} e^{-s(\tau_{PT_1} + \tau_{KI})} \times \frac{K_{PT_2} K_{CHS}}{(T_{CHS}s + 1)} e^{-s\tau_{PT_2}} \times \frac{K_{KOP} K_{PT_PN} K_{PN} K_{K.TP}}{(T_{PN}s + 1)(T_{K.TP}s + 1)} e^{-s(\tau_{PT_PN} + \tau_{K.TP})} - \left(\frac{K_B}{T_B s + 1} + \frac{K_M}{(T_M s + 1)} e^{-s\tau_M} \right). \quad (2)$$

At the output of a heat-consuming object:

$$W_{21} = \frac{K_{PT_1} K_{KI} K_{M.TP}}{(T_{KI}s + 1)(T_{M.TP}s + 1)} e^{-s(\tau_{PT_1} + \tau_{KI} + \tau_{M.TP})} \times \frac{K_{PT_2} K_{CHS} K_{K.TP}}{(T_{CHS}s + 1)(T_{K.TP}s + 1)} e^{-s(\tau_{PT_2} + \tau_{K.TP})} \times \left(\frac{K_{PT_3} K_{CO}}{(T_{CO}s + 1)} e^{-s\tau_{PT_3}} + \frac{K_{PT_4} K_{GB}}{(T_{GB}s + 1)} e^{-s\tau_{PT_4}} \right) - \left(\frac{K_B}{T_B s + 1} + \frac{K_M}{(T_M s + 1)} e^{-s\tau_M} \right); \quad (3)$$

$$W_{2.2} = \frac{K_{PT_1} K_{KI} K_{M.TP}}{(T_{KI}s + 1)(T_{M.TP}s + 1)} e^{-s(\tau_{PT_1} + \tau_{KI})} \times \frac{K_{PT_2} K_{CHS}}{(T_{CHS}s + 1)} e^{-s\tau_{PT_2}} \times \frac{K_{KOP} K_{PT_PN} K_{PN} K_{K.TP}}{(T_{PN}s + 1)(T_{K.TP}s + 1)} e^{-s(\tau_{PT_PN} + \tau_{K.TP})} \times$$

$$\times \left(\frac{K_{PT_3} K_{CO}}{(T_{CO}s + 1)} e^{-s\tau_{PT_3}} + \frac{K_{PT_4} K_{GB}}{(T_{GB}s + 1)} e^{-s\tau_{PT_4}} \right) - \left(\frac{K_B}{T_B s + 1} + \frac{K_M}{(T_M s + 1)} e^{-s\tau_M} \right). \quad (4)$$

The numerical values of transfer coefficients, time constants and time lag, included in formulas (1-4), are presented in table 1.

Table 1. Values of the parameters of the model of the automated control system of a combined centralized heat supply system [5, 6, 7].

Transfer coefficient	K_{PT_1}	K_{PT_2}	$K_{PT_{PN}}$	K_{PT_3}	K_{PT_4}	K_{KI}	K_{CHS}
Value	1.6	1.6	1.4	0.9	0.8	0.9	0.9
Time constant. s	-	-	-	-	-	T_{KI}	T_{CHS}
Value	-	-	-	-	-	0.01	0.01
Lag time. s	τ_{PT_1}	τ_{PT_2}	$\tau_{PT_{PN}}$	τ_{PT_3}	τ_{PT_4}	τ_{KI}	-
Value	0.002	0.004	0.001	0.001	0.001	0.001	-
Transfer coefficient	K_{PN}	$K_{M.TP}$	$K_{K.TP}$	K_{CO}	K_{GB}	K_B	K_M
Value	0.7	0.7	0.7	0.7	0.46	0.8	0.2
Time constant. s	T_{PN}	$T_{M.TP}$	$T_{K.TP}$	T_{CO}	T_{GB}	T_B	T_M
Value	0.01	0.15	0.1	0.15	0.05	0.4	1
Lag time. s	-	$\tau_{M.TP}$	$\tau_{K.TP}$	-	-	-	τ_M
Value	-	0.15	0.005	-	-	-	0.17

Note: K_{PT1} , K_{PT2} , K_{PTPN} , K_{PT3} , K_{PT4} - transfer coefficients of the regulators of: combined source, central heat supply station, peak load, heating systems and hot water supply; K_{KI} , K_{CHS} , K_{PN} , $K_{M.TP}$, $T_{K.TP}$, K_{CO} , K_{GB} - transfer coefficients of the combined source, central heat supply station, peak load, main pipelines, district pipelines, heating systems and hot water supply; K_M , K_B - coefficients of transfer through the channels of slow (external heat-retaining walls) and fast (external non-heat retaining walls, windows) heat losses; T_{KI} , T_{CHS} , T_{PN} , $T_{M.TP}$, T_{CO} , T_{GB} , T_B , T_M - time constants, combined source, central heating station, peak load, main pipelines, district pipelines, heating and hot water supply systems, through the channels of slow and fast heat loss; τ_{PT1} , τ_{PT2} , τ_{PTPN} , τ_{PT3} , τ_{PT4} , τ_M - lag time of regulators of: combined source, central heat supply station, peak load, heating systems and hot water supply systems; τ_{KI} , $\tau_{M.TP}$, $\tau_{K.TP}$, τ_M - lag time of the combined source, main pipelines, district pipelines and through the channel of slow heat losses.

For calculations with the help of the MathCAD computer system, we decided to use a conditional time of 20 h = 1 s. For example, the time constant for the channel of slow heat losses $T_M = 1$ corresponds to the actual time of 20 hours.

As can be seen from Figures 1, 2, the operator model of the proposed structure of the automated control system of a CCHSS and its corresponding generalized transfer function differ from the operator model of the existing structure of the automated control system of a CCHSS by the presence of a peak load with a correction device.

Peak load is designed to maintain temperature of a heat-transfer fluid in accordance with the temperature schedule during periods of a sharp decrease in the outside air temperature. It is located next to a group of heat-consuming objects and is controlled by its own temperature regulator. It eliminates the effect of transport lag in the period of time when the heat-transfer fluid having the temperature that corresponds to the temperature schedule and flowing from a combined source located several kilometers away reaches its peak load.

The second purpose of the peak load is to provide reserve heat supply to heat-consuming facilities, for example, to provide consumers with hot water during preventive maintenance of a CHPP in the summer period or in case of emergency situations at a CHPP.

The correction device ensures stability of functioning of the automated control system of a CCHSS, set characteristics of quality of the heat-transfer fluid temperature control and minimal energy costs while maintaining the heat-transfer fluid temperature in accordance with the temperature schedule.

Simulation of the automated control system of a CCHSS was carried out by the example of a CCHSS of the Oryol territorial generating company (TGC-4), operating on a temperature schedule of 110 ... 70 °C with a cut-off of 100 °C.

The choice of the optimal settings of a correction device has been made by the graph-parametric method [6, 9]. As an optimization criterion, we selected the integral quality criterion, which characterizes the conditional (heat-transfer fluid flow rate $G = 1$) energy costs required to maintain the temperature schedule with a given accuracy (control error) $\varepsilon_{ZAD} = \pm 3^\circ\text{C}$ [3, 7].

Equations (1-4) and the data given in Table 1 were inserted into the MathCAD computer system. Using the direct and inverse Laplace transformations, we have obtained solutions of equations in the form of graphs representing the temporal characteristics of the transition process, shown in Figures 3, 4.

Out of various graphs obtained, Figure 3 shows the temporal characteristics of the transient processes at the input of a heat-consuming object for models with the existing and proposed control structures, at this the latter - with optimal settings of the correction device which ensures the stable functioning of the control system and maintainance of heat-transfer fluid temperature in accordance with the temperature schedule to a precision of $\varepsilon = \pm 1,5^\circ\text{C}$.

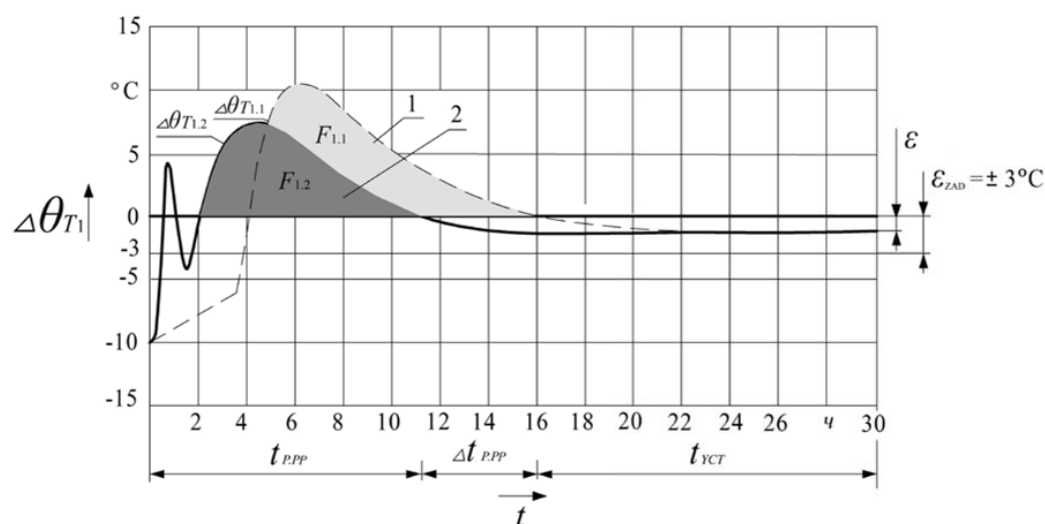


Figure 3. Temporal characteristics of transient processes at the input of a heat-consuming object for models: 1 - with the existing control structure; 2 - with the proposed control structure.

Figure 4 presents similar temporal characteristics of transient processes for models with the existing and proposed control structures at the output of a heat-consuming object.

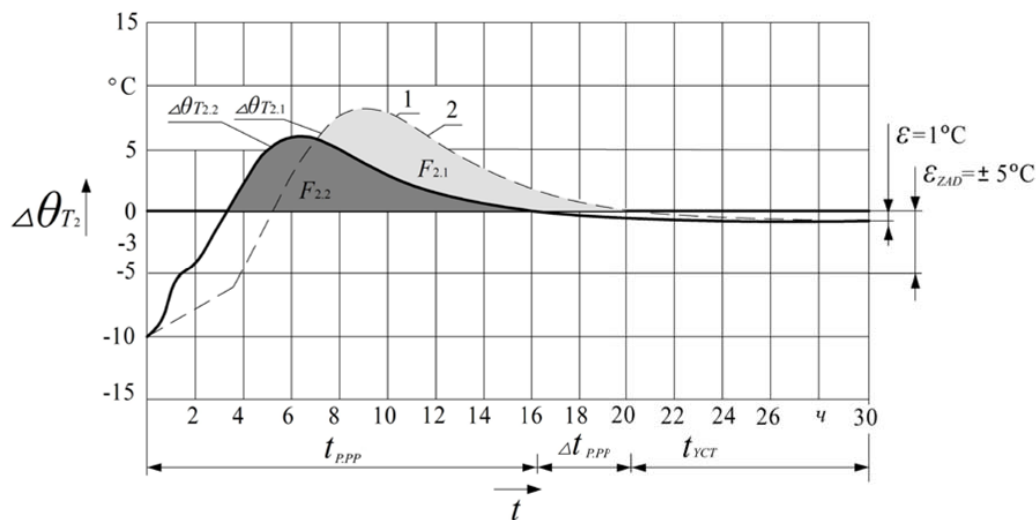


Figure 4. Temporal characteristics of transient processes at the output of a heat-consuming object for models: 1- with the existing control structure; 2 - with the proposed control structure.

A comparative analysis of conditioned energy costs was carried out to adjust a correction device that ensures similar control error (Figures 1, 2). The parameters of a correction device which were used to implement the comparative analysis are shown in Table 2.

Table 2. Parameters of a correction device.

Transfer coefficient, K_1	10
Transfer coefficient, K_2	65
Time constant, T_{KOP}	0.005

Note: The value of the time constant of a correction device $T_{KOP} = 0.025$ corresponds to the actual time of 1800 s.

As a result of a comparative analysis, it was found that conditioned energy costs for controlling the temperature of heat-transfer fluid at the input of a heat-consuming object for the model with the existing control structure (Figures 1, 3) were:

$$F_{1,1} = \int_{4.7}^{20.1} \Delta\theta_{T_{1,1}} d(t) = 5.43 \text{ GJ}, \quad (5)$$

At the same time, conditioned energy costs for controlling the temperature of heat-transfer fluid at the input of a heat-consuming object for the model with the proposed control structure (Figures 2, 4) were:

$$F_{1,2} = \int_{4.1}^{17.9} \Delta\theta_{T_{1,2}} d(t) = 3.12 \text{ GJ}, \quad (6)$$

where $F_{1,1}$, $F_{1,2}$ are areas characterizing energy costs for maintenance of the heat-transfer fluid temperature in accordance with the temperature schedule with a given control error in the existing and proposed control models; $\Delta\theta_{T_{1,1}}$, $\Delta\theta_{T_{1,2}}$ the value of deviation of the heat-transfer fluid temperature from the temperature schedule. A similar picture was observed at the output of a heat consuming object. For the model with the existing control structure (Figures 1, 4), conditioned energy costs were:

$$F_{1,1} = \int_{5.3}^{21} \Delta\theta_{T_{1,1}} d(t) = 5.57 \text{ GJ}. \quad (7)$$

While, for the model with the proposed control structure (Figures 2, 4), conditioned energy costs were:

$$F_{1,2} = \int_{4.7}^{17.8} \theta_{\tau_{1,2}} d(t) = 3.61 \text{ GJ} \cdot \quad (8)$$

The total conditioned energy costs for controlling the heat-transfer fluid temperature at the input and output of a heat-consuming object for models with the existing and proposed control were 11 gigajoule and 6.73 gigajoule, respectively. Thus, the total conditioned energy costs for the model with the proposed control structure are less than in the existing control structure by 4.27 gigajoule or 39%, which proves the prospected viability of the proposed control structure.

3. Conclusion

By means of a structural-parametric synthesis we proposed the structure of ACS of a CCHSS with a peak load and determined the parameters of a correction device for the peak load controller. An integral criterion for assessment of the quality of the control system, which represents an area of the positive half-wave of the optimal characteristic curve reduced to energy costs was proposed. The values of parameters of the peak load controller were determined, which ensure the minimum energy costs and the set error of maintainance of the temperature schedule in buildings with different thermal characteristics, expressed through the ratio of fast and slow heat losses.

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