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Investigation of Transient Process of Heat Carrier Temperature of Water to Air Heat Exchanger

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Introduction

Fuel and energy consumption in Lithuanian households in 2010 comprised 33,3% of total fuel and energy final consumption [1]. About 44% of this energy is consumed for building heating [2]. Automation is one of the ways for saving heating energy and making comfortable indoor environment of buildings.

Intermittent heating of buildings is mostly implemented by programmable heating controllers. These controllers regulate temperature of heat carrier, supply to heating system, according to set program and depending of outdoor temperature and sometimes depending of both outdoor and indoor temperatures [3,4]. Temperature of supply heat carrier is regulated by controlled mixing of supply and return heat carrier. This mixing is implemented by two-way, three-way or four-way valves [3,4]. Temperature of supply heat carrier depends not only on position of mixing valve, but also on return heat carrier temperature and its dynamics.

Radiators and water to air heat exchangers are mostly used for heat transfer from heat carrier to premises [4,5]. Quite many papers are published which analyze static and dynamic characteristics of radiators [6,7]. When investigating water to air heat exchangers, control channel "temperature of inlet heat carrier – outlet air temperature" is emphasized [8], whereas when designing and adjusting heating controllers one has to know the dynamic parameters of heat carrier temperature, returning of heat exchanger.

The purpose of this research is to estimate the form of transient process of water to air heat exchanger outlet heat carrier temperature and to develop the transfer function for heat carrier temperature control needs. The response of outlet heat carrier temperature to the instantaneous change of inlet heat carrier temperature was analyzed.

Methods

Relative thermal indicators recalculated for heat exchanger tube of 1 m length, through which heat carrier flows, are used in modeling and calculating. Assumptions that facilitate thermal calculations are applied:

1) the rate and the velocity of heat carrier flow in heat exchanger tubes are constant;

2) there is no heat transfer in the axial (heat carrier flow) direction;

3) the temperature of heat exchanger tube wall is the same throughout tube thickness (including the fins, if they are);

4) the surrounding temperature (the temperature of heat exchanger inlet air) is constant;

5) the temperatures of heat exchanger and heat carrier are considered as over-temperatures over surrounding temperature;

6) thermal parameters of heat exchanger and heat carrier (specific heat capacity, heat transfer coefficient) are stable during analyzed transient process.

Instantaneous change of inlet heat carrier temperature causes a spread of heat carrier temperature front through the heat exchanger. After certain time interval the temperature front reaches the outlet of heat exchanger. This time interval is time delay of transient process of heat carrier temperature and can be calculated on basis of heat exchanger tube length and heat carrier flow velocity.

Change of temperature front spreading through the heat exchanger is similar to one spreading through the conduit [9]. This assumption is based on findings that change of initial temperature front is independent of conduit heat losses [9]. In case of heat exchanger initial temperature front is considered independent of heat exchanger heat transfer to surrounding and can be calculated using methods [9] on basis of parameters of heat exchanger structure and parameters of its operating regime.

The mathematical model of heat exchanger for investigation of outlet heat carrier temperature change from initial jump to steady state was developed. When modeling, heat exchanger in the direction of heat carrier flow was divided in the elementary segments of chosen length. Thermal processes of the elementary segment were described by differential equations. Heat carrier current was modeled as portion flow from one segment to the next. Transient process of heat carrier temperature was modeled by calculation of temperature state and its time change for each elementary segment. The software QBasic was used for simulation. Heat exchanger Volcano VR1 (firm Euroheat) with forced air circulation was chosen as simulation example. The empirical mathematical expressions for estimation in engineering calculations of transient process of outlet heat carrier temperature were formulated, referenced to analysis of simulation results.

Mathematical model

The delay of heat carrier in heat exchanger is

$$\tau_w = l_c / (v_w N) = 3600 l_c S_c / q_w , \quad (1)$$

here τ_w – time delay of heat carrier (water) in heat exchanger, s; l_c – overall length of tubes through which heat carrier flows, m; v_w – velocity of heat carrier, ms^{-1}; N – number of tube bundles of heat exchanger connected in parallel; S_c – internal area of tube cross-section, m^2; q_w – rate of heat carrier flow through heat exchanger, m^{3}h^{-1}.

The initial jump of outlet heat carrier temperature Θ_{2wp}, that is provoked by instantaneous change of inlet heat carrier temperature Θ_{1wp} is [9]

$$\Theta_{2wp} = \Theta_{1wp} e^{-(\alpha_{wc}\tau_w)/c_w} = K_p \Theta_{1wp} , \quad (2)$$

here α_{wc} – relative heat transfer coefficient from heat carrier to tube wall of 1 m tube length, Wm^{-1}K^{-1}; c_w – relative heat capacity of heat carrier situated in tube of 1 m length, Jm^{-1}K^{-1}; K_p – coefficient of initial temperature jump of outlet heat carrier.

Coefficient α_{wc} was calculated for particular heat exchanger referenced to heat transfer laws from fluid flow to conduit wall [9,10]. The parameters of heat exchanger Volcano VR1 wherein heat carrier (water of 70 ˚C) flow through tubes which overall length of 14 m, internal diameter of 10 mm and connected to three parallel bundles are: $\alpha_{wc} = 235 q_w^{0,8}$ Wm^{-1}K^{-1} and $c_w = 320$ Jm^{-1}K^{-1}.

If a form of heat carrier and tube wall temperature distribution in the direction of heat carrier flow is considered to be linear (this form is not exactly linear but close to such [10]), heat balance of heat exchanger in steady state can be formulated

$$k_h \left(\frac{\Theta_{1cs} + \Theta_{2cs}}{2} \right) = \frac{1}{3600} c_w \rho_w q_w \left(\Theta_{1ws} - \Theta_{2ws} \right), \quad (3)$$

here k_h – heat transfer coefficient from entire heat exchanger to air, WK^{-1}; Θ_{1cs}, Θ_{2cs} – temperatures of heat exchanger tube wall respectively in heat exchanger inlet and outlet, ˚C; Θ_{1ws}, Θ_{2ws} – temperatures of heat carrier respectively in heat exchanger inlet and outlet, ˚C.

Coefficient k_h of particular heat exchanger for given operation regime can be found from tables of heat exchanger thermal parameters [5]. Usage of parameter tables is inconvenient when modeling, therefore rated thermal parameters are approximated by appropriate for water to air heat exchangers power function [11]

$$k_h = B v_w^n v_a^m , \quad (4)$$

here v_a – average velocity of air through heat exchanger; B, n, m – coefficients which depend on structure of heat exchanger.

Having estimated that velocity of heat carrier is proportional to flow rate and air velocity is proportional to relative frequency f^* of current supply to heat exchanger fan expression (4) can be rewritten

$$k_h = B_1 q_w^{n1} (f^*)^{m1} . \quad (5)$$

Coefficients B_1, n_1, m_1 can be defined by rated thermal parameters of particular heat exchanger. With reference to rated thermal parameters of heat exchanger Volcano VR1 [5] the following expression of heat transfer coefficient is formulated

$$k_h = 390 q_w^{0.187} (f^*)^{0.367} . \quad (6)$$

Temperature of heat exchanger tube wall Θ_{cs} and temperature of heat carrier Θ_{ws} in steady state are related with coefficient k_s

$$k_s = \frac{\Theta_{cs}}{\Theta_{ws}} = \frac{\alpha_{wc}}{\alpha_{wc} + \alpha_{ca}} , \quad (7)$$

here α_{ca} – relative heat transfer coefficient from tube wall to air of 1 m tube, Wm^{-1}K^{-1}; $\alpha_{ca} = k_h/l_c$.

Heat exchanger outlet heat carrier steady state temperature Θ_{2ws} calculated from (3) and (7) is

$$\Theta_{2ws} = \frac{c_w \rho_w q_w - 1800 k_h k_s}{c_w \rho_w q_w + 1800 k_h k_s} \Theta_{1ws} = K_h \Theta_{1ws} , \quad (8)$$

here K_h – steady state heat transfer coefficient of heat exchanger.

Change of outlet heat carrier temperature from initial jump to steady state value is analyzed by mathematical modeling of heat exchanger. Heat exchanger in the direction of heat carrier flow is divided for modeling in the elementary segments of chosen length. Model of thermal process in elementary segment of heat exchanger tube is presented in Fig. 1.

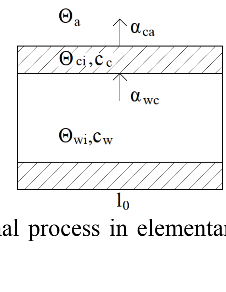

Fig. 1. Model of thermal process in elementary segment of heat exchanger tube

Within the modeling cycle time τ_0 heat carrier passes along the elementary segment of length l_0: $\tau_0 = l_0/v_w$. The following equations describe heat balance of the elementary segment within time τ_0:

$$\begin{cases} c_w \dfrac{d\Theta_{wi}}{d\tau} = -\alpha_{wc}\left(\Theta_{wi} - \Theta_{ci}\right), \\ c_c \dfrac{d\Theta_{ci}}{d\tau} = \alpha_{wc}\left(\Theta_{wi} - \Theta_{ci}\right) - \alpha_{ca}\left(\Theta_{ci} - \Theta_a\right), \end{cases} \quad (9)$$

here Θ_a – surrounding (air) temperature, ˚C (assumption that temperatures of heat carrier and heat exchanger are considered as over-temperatures suggests the assumption that $\Theta_a = 0$); c_c – relative heat capacity of the 1 m heat exchanger tube wall (including fins, if they are), $Jm^{-1}K^{-1}$.

If heat exchanger consist of the structure of different metals (for example, finned tubes including copper tubes and aluminum fins), coefficient c_c is calculated as weighted mean heat capacity of 1 m tube length. This coefficient of heat exchanger Volcano VR1, which consist of 10 mm internal diameter and 1 mm wall thickness copper tubes and of 28 mm width and 0,1 mm thickness aluminum fins stated in each 2,5 mm tube range, is: $c_c = 190\ Jm^{-1}K^{-1}$.

When modeling the change of temperatures Θ_{wi} and Θ_{ci} within time τ_0 is calculated according to equations (9). As time τ_0 elapses it is considered that heat carrier instantly flows from one segment to the next. Transient process of outlet heat carrier temperature Θ_{2w} is composed as the sum of temperature changes Θ_{wi} at terminal heat exchanger segment.

Simulation results

Simulation of transient process of heat exchanger Volcano VR1 outlet heat carrier temperature, provoked by unitary instantaneous change of inlet heat carrier temperature, was performed by mathematical model developed by software QBasic. Model according to presented above equations can be successfully designed on the basis of other software. Examples of simulation results at heat carrier flow rate $q_w = 0,5\ m^3h^{-1}$ and at different relative frequency f^* of current supply to heat exchanger fan are presented in Fig. 2.

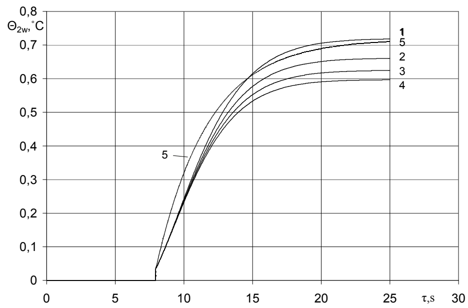

Fig. 2. Response curves of heat exchanger outlet heat carrier temperature at $q_w = 0,5\ m^3h^{-1}$ and $f^* = 0,25$ (curve 1), $f^* = 0,5$ (curve 2), $f^* = 0,75$ (curve 3), $f^* = 1,0$ (curve 4); 5 – the exponent replacing curve 1

Presented examples show that change of outlet heat carrier temperature from initial jump to steady state value is not exactly first order lag (exponential) process, but is close to such. Therefore for many tasks of automatic control of heating devices and systems this change can be considered as generally known first order lag process. The 5 curve in Fig. 2 represents exponential process replacing first simulated curve. Time constant of this exponential process is 3,8 s.

Summarizing many simulation results it was defined that the time constant $T_{w\Theta}$ of the exponential process approximating heat exchanger outlet heat carrier temperature change from initial jump to steady state value can be evaluated by following empirical equation

$$T_{w\Theta} = \frac{l_c c_c K_h}{N v_w c_w (1 - K_p)}. \quad (10)$$

Results of calculation by disclosed above equations of heat exchanger outlet heat carrier steady state temperature Θ_{2ws} and of time constant $T_{w\Theta}$ of exponential process approximating temperature change are close to results of simulation. Examples of calculated (index *cal*) and simulated (index *sim*) results for heat exchanger Volcano VR1 are: $\Theta_{2ws\ cal} = 0,719$ ˚C, $T_{w\Theta\ cal} = 3,5$ s, $\Theta_{2ws\ sim} = 0,718$ ˚C, $T_{w\Theta\ sim} = 3,8$ s, when $q_w = 0,5\ m^3h^{-1}$ and $f^* = 0,25$, and $\Theta_{2ws\ cal} = 0,774$ ˚C, $T_{w\Theta\ cal} = 1,9$ s, $\Theta_{2ws\ sim} = 0,759$ ˚C, $T_{w\Theta\ sim} = 2,0$ s, when $q_w = 1,0\ m^3h^{-1}$ and $f^* = 0,5$.

When change of heat exchanger outlet heat carrier temperature from the initial jump to the steady state value is considered as first order lag process, heat exchanger in the automatic control system (ACS) of heat carrier temperature can be represented by block scheme shown in Fig. 3.

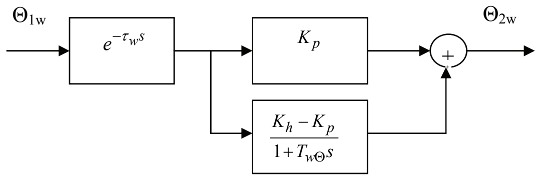

Fig. 3. Block scheme of heat exchanger in the heat carrier temperature ACS

Overall transfer function $W_\Theta(s)$ of heat exchanger heat carrier temperature control is

$$W_\Theta(s) = \frac{K_p T_{w\Theta} s + K_h}{T_{w\Theta} s + 1} e^{-\tau_w s}, \quad (11)$$

here s – Laplace operator.

Conclusions

Transient process of outlet heat carrier temperature of water to air heat exchanger is tripartite: the time delay, the initial jump of temperature and the temperature change from initial jump to steady state value. The delay, the initial jump of temperature and steady state temperature can be determined by analytical calculations, based on parameters of heat exchanger structure and parameters of its operation regime (corresponding equations are presented in the article).

Change of outlet heat carrier temperature from the initial jump to the steady state value is not exactly first order lag (exponential) process, but for many tasks of automatic control of heating devices and systems this change can be considered as such.

Water to air heat exchanger in the ACS of heat carrier temperature can be represented as common delay block connected with paralleled proportional and first order lag blocks. Time constant of this first order lag process can be calculated using empirical equation formulated on basis of simulation results and presented in this article.

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L. Brazdeikis. Investigation of Transient Process of Heat Carrier Temperature of Water to Air Heat Exchanger // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 2(118). – P. 99–102.

Transient process of the outlet heat carrier temperature of water to air heat exchanger is investigated. This transient process, provoked by instantaneous change of inlet heat carrier temperature, is tripartite: the time delay, the initial jump of temperature and the temperature change from the initial jump to the steady state value. The mathematical expressions for calculation of the delay, the initial jump and the steady state temperature are presented. Mathematical model for investigation of the temperature change from the initial jump to the steady state is described. It was defined that this temperature change, at precise evaluation, is not the first order lag (exponential) process, but for many tasks of automatic control of heating devices can be considered as such. The block scheme of heat exchanger representation in ACS of heat carrier temperature is delivered. The empirical equation for calculation of exponential process time constant is proposed. Ill. 3, bibl. 11 (in English; abstracts in English and Lithuanian).

L. Brazdeikis. Vandens–oro šilumokaičio šilumnešio temperatūros pereinamojo proceso tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 2(118). – P. 99–102.

Tiriamas iš vandens–oro šilumokaičio ištekančio šilumnešio temperatūros pereinamasis procesas, kurį sukelia į šilumokaitį tiekiamo šilumnešio temperatūros šuolinis pokytis. Šis pereinamasis procesas susideda iš trijų dalių: vėlinimo, pradinio šuolio ir temperatūros kitimo nuo pradinio šuolio iki nusistovėjusios vertės. Pateikiamos lygtys vėlinimo trukmės, pradinio šuolio ir nusistovėjusiai temperatūroms apskaičiuoti. Ištekančio šilumnešio temperatūros kitimui nuo pradinio šuolio iki nusistovėjusios vertės tirti sudarytas šilumnešio temperatūros šilumokaityje matematinis modelis. Nustatyta, kad šis kitimas nėra tiksliai eksponentinis, tačiau, sprendžiant daugelį šildymo įrenginių automatinio reguliavimo uždavinių gali būti tokiu pakeičiamas. Sudaryta šilumokaičio vaizdavimo šilumnešio temperatūros ARS struktūrinė schema bei pateikiama empirinė lygis pakeičiančiojo eksponentinio proceso laiko pastoviajai apskaičiuoti. Il. 3, bibl. 11 (anglų kalba; santraukos anglų ir lietuvių k.).