CONTROL SYSTEM OF GAS COOLER OF HEAT PUMP ON CARBON DIOXIDE FOR DISTRICT HEATING SYSTEM

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Abstract: The control system of the district heating system with the use of the heat pump for heating of the heating–system water arriving from combined heat power (CHP) plant is considered. Possibility of PID-controller with gain scheduling utilization with the coefficients changing depending on gas cooler mode of operation for temperature disturbances compensation of direct heating–system water is shown.

Keywords: Heat Pump on Carbon Dioxide, Control System, District Heating Systems.

1. INTRODUCTION

Present work is the continuation of a cycle of the author's works devoted to the utilization of heat pumps in systems of the centralized heat supply for the purpose of gas economy used for heating. In the previous works block diagrams of heat pumps on carbon dioxide (THCO2) for the considered task solution have been offered, and economic efficiency for conditions of the prices for gas and electric energy in Republic of Moldova is shown [1-7]. According to a method [8] gas cooler has been calculated, on the base of the shell-and-coil counterflow heat exchanger. At the same time the problem of the calculation of heat pump dynamic characteristics is not solved in the literature devoted to the heat pumps on carbon dioxide.

The problem consists that the heat pump for a considered problem works in a supercritical cycle, and gas characteristics vary on length of a gas cooler considerably. Methods of gas cooler time constants and amplification factors calculation in the literature are absent. It is connected with the difficulty of the gas cooler dynamics equations solutions which are formulated in the form of the equations in partial derivatives. The works related to the description of heat exchangers as a control objects with the distributed parameters were conducted by academician B.N. Deviatov and his school. In these works the general form of the equations is offered and is specified that for the simplification of researches it is necessary to reduce these equations to two-dimensional transfer functions. In the further A.A. Sheviakov works [12, 13] it has been shown how to pass from systems of the equations in partial derivatives to the separate equations which have not been connected among them.

However the problem has been solved for objects where properties of heat-carrying agents did not change. In the following works L. Malinovsky [14], N.H. Abu–Hamdeh [15], D. Averous and others [16] various schemes of the numerical decision of the equations of dynamics of the counterflow heat exchanger were proposed. We solved a problem of CO_2 gas cooler transitive characteristics definition basing on the numerical decision of the equations of dynamics. The block diagram of system is considered and transients for one of system contours are constructed.

List of symbols: T_1 – Gas temperature after the gas cooler; T_2 – Water temperature after the gas cooler; dt - sampling time; dx – sampling of the gas cooler length.

2. CONTROLLED OBJECT

The idea of the system is: heat power station takes the part of the return water from the district heating system, warms it up to necessary level and further the pump feeds the water to the mixing node of the heat supply system where it is mixed with the water from CHP with the lowered temperature level, comparative to the existing temperature chart of CHP. The flux of water from the heat pump station to CHP freezes at that time. The considerable economy of natural gas on the CHP is assured due to this solution, are lowering the losses of heat in the heat supply system and the tax for the population for the heat energy consumed may be decreased [1-7]. The simplified scheme of the object of investigation is shown on the Fig.1.

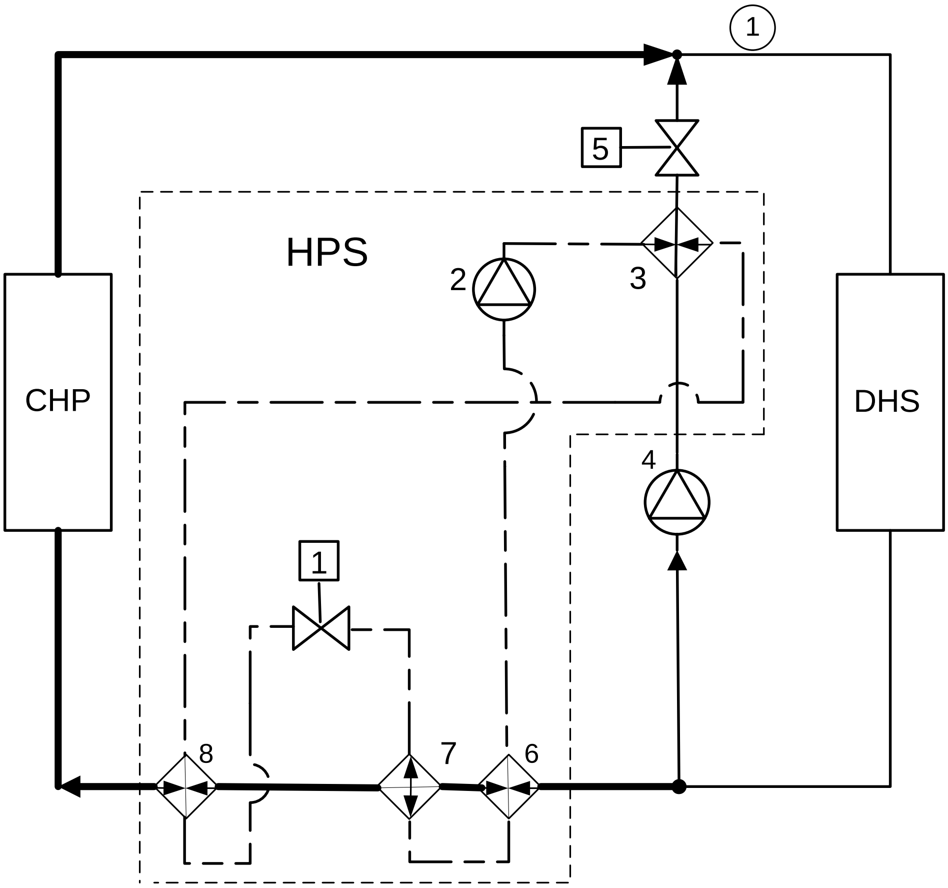

Fig.1 Block diagram of the use of heat pump in district heating system.

Abbreviations on the Figure 1: DHS – district heating system; HPS – heat power station, CHP – combined heat power plant. The essence of the temperature control of water in the p.1 of the scheme consists in the change of the gas temperature by means of the coordinated control of the control valve 1, gas superheater 3 regime (i.e. gas temperature before the compressor 2 and the pressure of the compressor by the means of the control system of pressure valve 3, and the compressor capacity. We consider the heat supply system uses the quantitative method of control, when the flow rates of water after the CHP and in the point 1 are constant. The pump 4 feeds the water via the water control valve 5 to the mixing node. Gas superheater, evaporator, and gas supercooler are identified by numbers 6, 7, 8 respectively. The control of the temperature after the gas superheater realizes by means of the control valve, which is installed parallel to the gas superheater, the compressor productivity may be controlled by the variable speed drive; the pressure after the control valve is controlled by means of the valve 1. The slowest element of control scheme of the temperature after the gas cooler is control system of the gas superheater. As results of preliminary executed calculations, transfer function of the control system of gas superheater on the channel «the set point – the gas temperature on an exit» can be approximated with an element with transfer function of such a structure:

$$W_1(p) = \frac{k_1}{(T_{11}p+1)(T_{22}p+1)}. \quad (1)$$

Such type of control action introduces additional requirements for the gas temperature on the outlet of the gas cooler control system.

3. MATHEMATICAL MODEL OF GAS COOLER

Models of heat exchangers "gas-liquid" as controlled objects with the distributed parameters were investigated in B/N/ Deviatov's [8-10], A.A. Sheviakov's [11, 12] works, however, in their works were considered heat exchangers with constant heat-carrier parameters.

As HPS gas cooler working in a supercritical cycle represents a dynamic element with variable parameters and can be described with the system of the first order partial differential equations of a following type:

$$\begin{aligned} \frac{\partial T_1}{\partial t} + v_1 \frac{dT_1}{dx} &= K_{12}(v_1, v_2, c_1, \rho_1, c_2, \rho_2) \cdot \left(T_2 - T_1\right) \\ \frac{\partial T_2}{\partial t} - v_2 \frac{dT_2}{dx} &= K_{13}(v_1, v_2, c_1, \rho_1, c_2, \rho_2) \cdot \left(T_1 - T_2\right) \end{aligned} \quad (2)$$

Output value of the controlled object is the water temperature after gas cooler $-T_2$. Operating influences are the temperature of a working body, and speed of its velocity v_1. Similar problems were considered in a set of works, say, for example [8–14]. However, in the case under consideration in the equations (1) and (2) coefficients K_{12}, K_{13} depend from v_1, v_2 and thermophysical heat-carriers properties. The solution of this system can be found by methods of the approached integration of the differential equations in partial derivatives. In work [8] it is shown that for the construction of the static model of the shell-and-coil heat exchanger working carbon dioxide in a supercritical cycle of the thermal pump it is necessary to use calculation method [8], instead of the discrete method (splitting into segments or $\varepsilon - NTU$ method).

There were made the following assumptions in the solution of equations (2):

1. The heat transfer to the surroundings is negligible.
2. The flows are sufficiently turbulent to cause effective heat transfer (assumed fully developed boundary layers).
3. There is no conductive heat transfer in the direction of fluid flow for both wall and fluids.
4. Specific heats and densities of the gas and of the water are variable on the range of there working temperatures and flow rates.
5. The tube shell is sufficiently thin and its thermal capacity is negligible, such that all the heat loss is absorbed by the secondary fluid.

Just the paragraph 4 of the assumptions stresses the difference between the assumptions of the presented work and the other works [14-16].

The set of partial differential equations given by (2) is solved numerically by means of explicit Euler center difference method [17]. It is used central difference method to convert the spatial derivative to a difference and is used the forward difference method to convert time partial derivative to a difference. The result of the computer simulation of transients of the gas and water temperatures on the outlet of the heat exchanger is presented on the fig.2. It is imposed a step signal on the input of the gas cooler, equal to $5^\circ C$.

$$
\begin{aligned}
T_{1,i}^{j+1} &= T_{1,i}^{j} - \frac{dt}{2\cdot dx}\cdot v_1(j-1,i)\left[T_{1,i+1}^{j} - T_{1,i-1}^{j}\right] + dt\cdot K_{12}(j-1,i)\left(T_{2,i}^{j} - T_{1,i}^{j}\right) \\
T_{2,i}^{j+1} &= T_{2,i}^{j} + \frac{dt}{2\cdot dx}\cdot v_2(j-1,i)\left[T_{2,i+1}^{j} - T_{2,i-1}^{j}\right] + dt\cdot K_{13}(j-1,i)\left(T_{1,i}^{j} - T_{2,i}^{j}\right)
\end{aligned} \tag{3}
$$

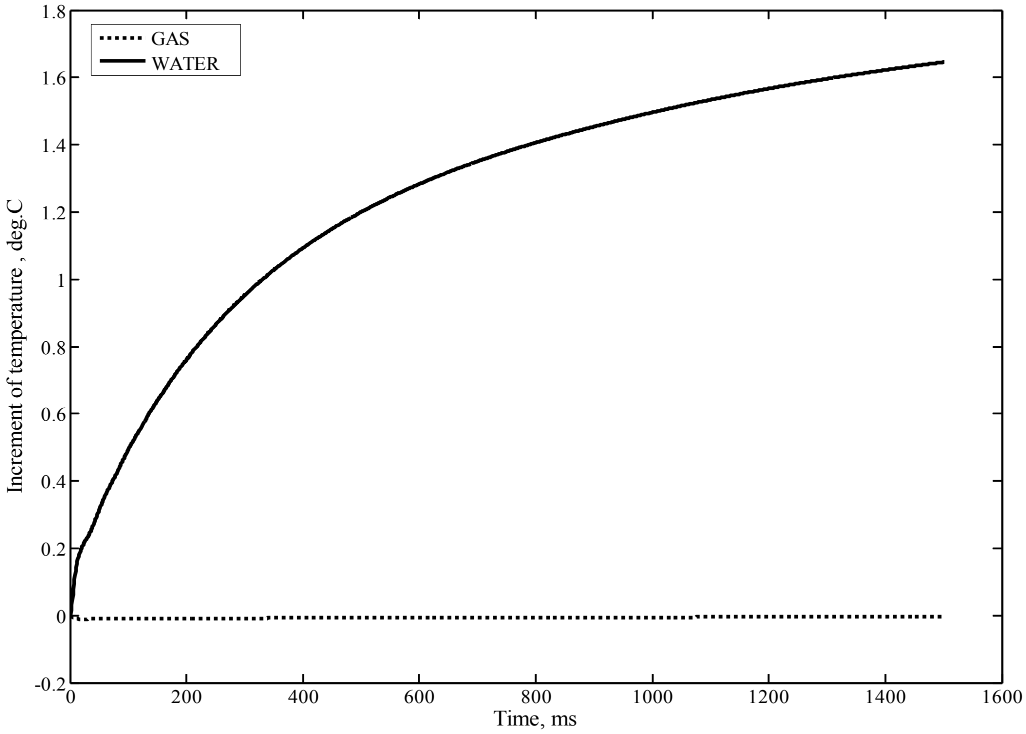

Fig.2. Temperature variances of gas (dotted line) and water (solid line) on gas cooler outlets.

In table 1 the data about temperature on gas cooler exits in the end of transient at two gas temperatures values on its input are shown.

Gas and water temperatures on the inlet and on the outlet of gas cooler. Table 1

Gas temperature on the inlet of gas cooler	Gas temperature on the outlet of gas cooler	Water temperature on the inlet of gas cooler	Water temperature on the outlet of gas cooler
70	28.1468	27,01	47.5391
75	28.2023	27,01	49.3320

As table 1 analysis shows, target gas temperature after gas cooler at its jump on an input has changed only on 0,05°C. It gives the opportunity to affirm that gas temperature influence during the transient on a gas supercooler and, hence, and on the evaporator and gas superheater will be minimal.

The analysis of the system of the equations (2) solution shows that dynamic properties of gas cooler on the channel «gas temperature – water temperature» can be approximated by the dynamic properties of the second order and the first order links included in parallel.

$$W(p) = \frac{k_1}{(T_{11}p+1)(T_{21}p+1)} + \frac{k_2}{T_{31}p+1}. \tag{4}$$

This approximation made on the basis of the solution of the system of differential equations in partial derivatives (taking into account that object parameters are variable along the gas cooler length) gives the opportunity to raise the validity of the synthesis of a control system problem solution. The problem facing the HPS (heat pump station) controller is not reacting periodically on the disturbances and with the minimum time of transient.

4. CONTROLLER DESIGN.

Let us consider the work of the system during the step disturbance of the temperature of the water from CHP plant. Thus, the distributed-parameter nature of the system is fully taken into account in a systematic way. Within the so-called late lumping approach, the controller is directly designed on the basis of the distributed – parameter model and the control law is then (numerically) approximated for the purpose of implementation on the real system.
A regulator for a control system we will search in a class of PID-controllers with gain scheduling.

$$u(t) = K_P(\vec{a}) \cdot e(t) + K_I(\vec{a}) \cdot \int_0^T e(\tau)d\tau + K_D(\vec{a}) \cdot \frac{de(t)}{dt}, \tag{5}$$

Where $\vec{a}$ – vector of parameters of the controlled object.

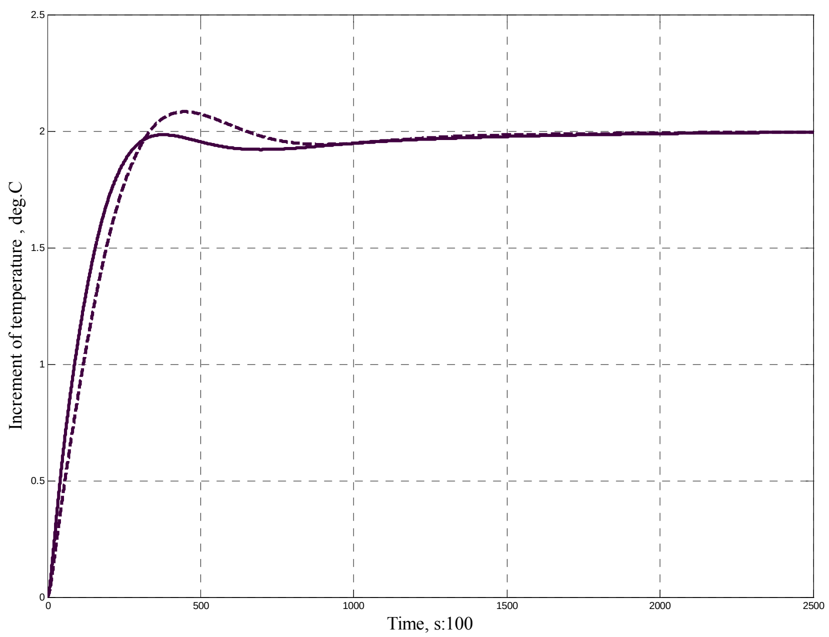

Fig.3. Transients of the system at the different parameters of the controlled object at the uniform parameters of the PID–control law.

From fig.3 it is obvious that at constant settings of the PID–controller and at variable control object characteristics in transient overshoot appears (the schedule with dashed lines) which is undesirable. For the elimination of it is necessary to use the PID–controller with gain scheduling, with the change of parameters depending on control object parameters (the schedule with continuous lines).

5. CONCLUSION.

Within the so-called late lumping approach, the PID controller with gain scheduling for gas cooler of the heat pump on carbon dioxide is directly designed on the basis of the distributed-parameter model and the control law is then (numerically) approximated for the purpose of implementation on the real system. In general, it turns out that an appropriate formulation of the mathematical model of distributed-parameter systems drastically simplifies the subsequent control design task.

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