Analysis of the thermal power hydraulic system in undisturbed state

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Abstract. The development of a model for the analysis of the undisturbed state of a heat-power hydraulic system - a heat supply system, which is an important stage in the design and optimization of the system, is considered. The main parameters of the system, such as thermal loads, heat flows, heat transfer through pipes and heat exchangers, the location and characteristics of equipment (boilers, pumps, etc.) are analyzed. The development of a mathematical model of the system, which should take into account all the main factors affecting heat exchange and the efficiency of the system is completed. The model as a system of equations and includes such parameters as temperature, pressure, coolant flow, etc. is presented. Based on this model, it is possible to analyze various operating modes of the system, optimize parameters and make decisions to improve it. When developing the model, the possibility of various perturbations is taken into account. To analyze the undisturbed state of the system, the influence of such disturbances is excluded and its basic operation is considered. When developing a flow distribution analysis model for a thermal power system, energy equivalence was applied. The developed model of analysis of the undisturbed state of the thermal energy system will allow more accurately design and control such a hydraulic system, improve its efficiency and reliability.

1 Introduction

Mathematical models for analyzing the undisturbed state of a thermal power hydraulic system (TPHS) on the example of heat supply systems should take into account the influence of regulators on the operation of such systems [1] and allow optimizing its parameters to achieve optimal operation.

The hardware design of TPHS also includes the presence of various sensors and measuring devices for monitoring and controlling the system parameters. These can be temperature sensors, pressure sensors, flow meters and other devices that allow you to get information about the current state of the system and respond to changes.

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Pumps and valves that ensure proper circulation and distribution of the heat carrier in the system are also an important element of the hardware design. They should be selected taking into account the features of the object and the required system parameters.

Special attention should be paid to the automatic control system, which allows you to automatically maintain the set parameters in the system and react to changes. Such a system may include controllers and programmable logic controllers, as well as various actuators that execute controller commands.

2 The development of a mathematical model for the analysis of the TPHS in undisturbed state

The accuracy and quality of the obtained solutions depend on the correct choice of the parameters of the components - vector functions, and the correct modeling of their interaction with other elements of the system.

The method of calculating hydraulic systems with adjustable parameters includes the following stages: description of the initial system with adjustable parameters; recalculation of the system as an object with concentrated parameters; application of the linking method to solve the system as a quasi-stationary one; obtaining phase variables from the internal cycle; recalculation of adjustable parameters based on phase variables; repetition of the steps 2-5 until convergence is achieved.

The use of this technique makes it possible to efficiently calculate hydraulic systems with several adjustable parameters, taking into account their influence on other system parameters. At the same time, the internal iterative process can be complex and requires careful selection of the linking method and convergence criteria.

When developing TPHS analysis models, we assume that subscriber subsystems (SSS) have a unified structure. This allows us to simplify the process of model development when forming flow distribution models in TPHS based on the application of the variation principle of least action in the Helmholtz form [2, 3]. The variation problem has seven groups of terms [2, 4].

It is possible to use a typical methodology for the formation of variational problems based on the successful application of the extended variational principle to systems with concentrated parameters [2]. This allows us to avoid unnecessary mathematical calculations and focus on the qualitative aspects of the models.

In TPHS power nodes (PN) are the nodes [4] through which energy is exchanged between the studied fragment of the system (SFS) and the environment. In this case, the energy is transported through the supply pipelines, the PSs act as points of supply and selection of energy.

Even if the system is theoretically closed, there are losses of the desired product (DP) to the environment. These losses can be compensated either by directly extracting the energy consumed, or by tracking leaks and DP costs, which can be regarded as normalized leaks.

In the studied TPHS there are two classes of active elements: kinetic energy sources (pumps that circulate the medium) and potential energy sources (pumps that maintain pressure in the network) [5].

According to the SFS structural model, the system contains not only energy sources and drains, but also various elements that affect the hydraulic characteristics of the flow. These elements include pipes, kinematic connections that ensure the movement of the medium in the system [6, 7, 8].

Pipes usually have a constant diameter and are designed to provide a certain hydraulic resistance to flow. In addition, there are local resistances in the system, such as valves and regulators [9, 10]. These elements are placed on the sections of the system, as well as at sources and drains, and can change the hydraulic characteristics of the flow [11, 12, 13].

In general, the coefficients of hydraulic resistances of local resistances depend on the phase variables of the system, such as the flow velocity and pressure [14, 15, 16, 17].

All these elements together form a structural model of the SFS, which allows analyzing and designing the system in accordance with its hydraulic characteristics and flow requirements [18, 19, 20, 21].

SFS is limited by a set of PNs $J^z_{\pi(f)} \cup J^z_{\eta\,(P)} \cup J^z_{\eta(q)} \cup J^z_{\eta(f)}$, which containe subsets of power supplies $J^z_{\pi(f)}$ and consumers $J^z_{\eta(P)} \cup J^z_{\eta(q)} \cup J^z_{\eta(f)}$.

If the temperature changes along the system, then it is necessary to consider this when modeling the hydraulic parameters of the system, since this can lead to changes in the pressures and flows of the medium.

In the unsteady mode of DP flow in the system, the specified parameters are also the function S(τ), which describes the change in cross-sectional area, and the function $\dot{Q} = dQ/d\tau$, which describes the change in the orientation of the section in space. These parameters determine the development of unsteady processes, such as pressure drops and turbulence in the system.

Let's describe the surface forces: H_j is the source pressure, in which $j \in J^z_{\pi(f)}$; H_j is the back pressure of drains, in which $j \in J^z_{\eta(P)} \cup J^z_{\eta(q)} \cup J^z_{\eta(f)}$; friction forces in the SFS, at n sites ($i \in I^z$), as well as volumetric forces. These forces together determine the dynamics of the environment and affect the flow of the DP in the system.

Provided that the density and diameter in the area are constant, as well as the flow energy W is constant, we can conclude that the kinetic energy of the system is constant.

The required parameters make it possible to determine the elements of the SFS, as well as their interaction with the flow of the medium. Information about the SFS structure and its characteristics allows one to calculate the dynamics of the medium flow using hydrodynamic equations, including the equations of conservation of mass, momentum and energy.

Solving these equations makes it possible to determine the flow speed and pressure in various elements of the SFS and evaluate the influence of various factors on its characteristics.

The I. Bernoulli's equation is one of the basic equations of hydrodynamics and describes the laws of conservation of energy in the flow of an ideal incompressible fluid. This equation relates the pressure, velocity and height of the flow. I. Bernoulli's equation in solving hydraulic problems makes it possible to find a connection between various variables of the system and determine the modes of fluid motion.

The I. Bernoulli's equation can be considered as a separate relation in variational problems and used to find the extremals of the functional. In general, it is only part of the system of equations describing the hydraulic system, and in order to fully solve the problem, it is necessary to take into account other equations of hydrodynamics, as well as the conditions and limitations of the problem.

The system of equations in the HS model describes the interaction of various components of the system, and includes equations describing physical laws, equations of state and other relationships. The design scheme, on the other hand, is a graphical representation of the system, where each component is represented by its node, and the connections between the components are edges or connections. When choosing pseudo-variables for system modeling, both the subsystem of equations and the type of structural formation in the calculation scheme are usually taken into account.

The HS model includes both a system of equations that describe the interaction of system components, and a calculation diagram that displays the structural formation of the system.

Pseudovariables are chosen to take into account both the equations and the structural formation.

Independent circuits are formed by introducing additional pseudo-variables, which represent flows of the medium on the circuits of the design circuit. This allows us to take into account the conditions of unambiguity for all elements of the SFS and initial variables.

One can consider each independent chain separately, form the necessary conditions for uniqueness at its boundaries, and carry out calculations. This approach simplifies the process of isolating IFS and provides more accurate results.

To model unsteady flow distribution, the vector-matrix form of recording can be represented as the follows:

$$C_{p\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u(k)}_{n(d)}\right)\times Q^{u(k]}_{n\times 1}+E_{n(d)}\times\dot{Q}^{u(k]}_{n\times 1}\right\}=M^{t}_{p\times e}\times\hat{H}^{(k)}_{e\times 1}\pm\sum_{i}H(Q)^{u(k)}_{i}; \tag{1}$$

$$K_{r\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u(k)}_{n(d)}\right)\times Q^{u(k)}_{n\times 1}+E_{n(d)}\times\dot{Q}^{u(k)}_{n\times 1}\right\}=0_{r\times 1}\pm\sum_{i}H(Q)^{u(k)}_{i}; \tag{2}$$

$$A_{m\times n}\times Q^{u(k)]}_{n\times 1}=\hat{g}^{(k)}_{m\times 1}; \tag{3}$$

p is the number of independent circuits in the design scheme (p=e-1); n=$\left\{I^{z}\right\}$ and m= $\left\{J^{z}_{\eta(q)}\cup J^{z}_{\chi}\right\}$; e=$\left\{J^{z}_{\pi(f)}\cup J^{z}_{\eta(P)}\cup J^{z}_{\eta(f)}\right\}$is the number of PNs with a given potential; L_i, F_i are accordingly the length and cross-sectional area of the plot i; ; $\sum_{i}H(Q)^{u(k)}_{i}$ is the sum of pump pressures; u(k) is the iteration number of the double loop; S_i is the coefficient of hydraulic resistance of the site i; $R(Q)_i$ - variable resistance of the flow, pressure, temperature regulator installed on section i in the form of a diagonal matrix element; $R_i= S_i\left|Q_i\right|^{\alpha-1}$- hydraulic resistance of a passive element in the form of a diagonal matrix element; $\hat{H}$, $\hat{g}$- matrices-columns of values of nodal potential and selection (inflow) fixed as boundary conditions (in time) for PN j; ρ - density of the transported medium; $E_i=\left(\rho L_i/gF_i\right)$ - hydraulic inductance of section i, determined by the results of the two previous iterations (k-1) and (k-2); M- route matrix; C, K, A. - adjacency matrices of independent circuits, contours and incident matrix, respectively.

Model (1)-(3) can be used to describe the dynamics of hydraulic systems in an approximate form, providing a fairly accurate description of the basic properties of the system.

A steady-state flow distribution model can be obtained from the equations (1)-(3) by excluding variables that depend on time. At the same time, there is no need to use an external iterative loop.

$$C_{p\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u}_{n(d)}\right)\times Q^{u}_{n\times 1}\right\}=M^{t}_{p\times e}\times\hat{H}_{e\times 1}\pm\sum_{i}H(Q)^{u}_{i}; \tag{4}$$

$$K_{r\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u}_{n(d)}\right)\times Q^{u}_{n\times 1}\right\}=0_{r\times 1}\pm\sum_{i}H(Q)^{u}_{i}; \tag{5}$$

$$A_{m\times n}\times Q^{u}_{n\times 1}=\hat{g}_{m\times 1}; \tag{6}$$

The nonisothermicity of the flow can be taken into account by introducing appropriate thermodynamic equations into the model, taking into account the change in the medium temperature. To do this, the laws of conservation of energy can be used, including convective and conductive heat flows, as well as the continuity equation and the equation of motion of the medium.

It is also possible to use numerical modeling methods, such as the finite element method or the finite difference method, to numerically solve a system of equations that takes into account the nonisothermicity of the flow.

Temperature changes due to heat losses in the system caused by thermal radiation, convection and conductivity should be taken into account. These factors can make significant changes in the temperature of the pipeline and should be taken into account when analyzing the heat exchange process.

There may be other causes of temperature changes, such as changes in the composition of gases or liquids inside the pipeline, chemical reactions, etc. All these factors can have a significant impact on temperature and should be taken into account in real calculations.

To simplify the modeling of the heat exchange process in a pipeline system, it is often sufficient to take into account only the main factors, such as heat exchange with the environment and mixing of flows. This allows you to get fairly accurate results with minimal modeling costs.

The Darcy-Weisbach formula makes it possible to determine the hydraulic resistance of section I of the pipeline at a variable temperature [4]

$$\Delta P_i = S_i \frac{Q_i^{\alpha}}{D_i^{\beta}} \frac{1}{T_{-}} \int_0^{L_i} T(x)dx = S_i \frac{Q_i^{\alpha}}{D_i^{\beta}} \frac{\overline{T}_i}{T_{-}} L_i ; \tag{7}$$

$T(x)$, $\overline{T}$ - denote the variable and averaged water temperature along the pipe, that is, the temperature dependence on the x coordinate along the pipe; T_{-} is the standard temperature, which is used to bring the flow rate to standard conditions.

In the general formulation, when we exclude inertia forces, the flow regime is considered to be steady. This means that the velocities and distribution of the flow parameters remain constant over time. When we take into account the friction force, it depends on the viscosity of the liquid and the pressure gradient or flow rate.

According to the equation (7), the friction force also depends on temperature. This means that when calculating the flow regime within the framework of the general formulation, it is necessary to take into account the dependence of the friction force on temperature. The equation (7) takes this dependence into account, and it can be used to calculate the friction force depending on the water temperature.

The definition of an additional variable $\overline{T}$ in thermal processes means the introduction of an additional unknown quantity.

Additional boundary conditions should be associated with constraints that are valid at the boundaries of the section i.

For example, if a constant heat flow condition is set at the boundary of section i, then an additional condition can be introduced for the equality of heat flows at the boundaries of section i and its neighboring sections [j, j+1].

Such an additional boundary condition makes it possible to determine indefinite Lagrange multipliers that can be used to solve the heat transfer problem.

The introduction of these additional conditions makes it possible to associate the values of temperature and heat flow at the boundaries of section i with the corresponding values at the boundaries of its neighboring sections [j, j+1].

$$T = \begin{cases} T' & \text{when } x=0 \quad \text{- temperature in the initial node after mixing;} \\ T'' & \text{when } x=L \quad \text{- temperature at the final node before mixing;} \\ T & \text{when } 0<x<L \quad \text{- current temperature.} \end{cases}$$

We introduce the assumption that the process of mixing flows with different temperatures proceeds within the node without energy loss. Then we will write the mathematical model of steady-state flow distribution with a non-isothermal flow of a viscous medium in TPHS in the following form:

$$C_{p\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u}_{n(d)}\right)\times Q^{u}_{n\times 1}\right\}=M^{t}_{p\times e}\times\hat{H}_{e\times 1}\pm\sum_{i}H(Q)^{u}_{i}; \tag{8}$$

$$K_{r\times n}\times\left\{\left(R_{n(d)}+R(Q)^{u}_{n(d)}\right)\times Q^{u}_{n\times 1}\right\}=0_{r\times 1}\pm\sum_{i}H(Q)^{u}_{i}; \tag{9}$$

$$A_{m\times n}\times Q^{u}_{n\times 1}=\hat{g}_{m\times 1}; \tag{10}$$

$$E_{n(d)}\times\left(B_{n(d)}\times\Theta_{n\times 1}+T''_{n\times 1}\right)=-\vec{A}^{t}_{n\times m}\times T'_{m\times 1}; \tag{11}$$

$$\overleftarrow{A}_{m\times n}\times Q^{u}_{n(d)}\times T''_{n\times 1}-\vec{A}_{m\times n}\times Q^{u}_{n(d)}\times T'_{n\times 1}=\vec{g}_{m(d)}\times T'_{m\times 1}-\overleftarrow{g}_{m(d)}\times\hat{T}_{m\times 1}; \tag{12}$$

The V.G. Shukhov's formula allows us to estimate the temperature change along the pipeline under the condition of const T0. It is based on the thermal analogue of the Darcy-Weisbach formula, which makes it applicable for hydraulic calculations of magnetic gas pipelines

$$T(x)=T_0+\left(T'-T_0\right)\exp\left[-k\pi Dx\,/\,(M\,C_p)\right] \tag{13}$$

the temperature at the final node j+1 of the section i [j, j+1] can be determined as the follows

$$T''_{i,j+1}=T_0+\left(T'_j-T_0\right)\exp\left[-k\pi D_iL_i/\,(M_iC_p)\right]; \tag{14}$$

M_i is the mass flow rate of the transported medium in section i.

From (13) and (14) we obtain an equation for determining the average temperature of the medium at the site

$$\overline{T}_i=T_0+\left(T'_j-T_0\right)\frac{1-\exp\left[-k\pi D_iL_i/\,(M_iC_p)\right]}{k\pi D_iL_i/\,(M_iC_p)}; \tag{15}$$

The convergence of hydraulic equations solutions is checked at each iteration. If the solution satisfies certain convergence conditions, then the iterative process is considered completed.

By solving the system of equations (8)-(12) and controlling the completeness of the iterative process according to hydraulic equations, it is possible to obtain more accurate values of average temperatures and achieve convergence in the system.

The triple cyclic interaction makes it possible to take into account the non-isothermicity of the flow and non-stationarity in the model of a system with adjustable parameters.

If the quality of the results is of great importance, it is necessary to take into account the differences in heat exchange in the sections of the distribution network and in the SSS.

Heat exchange in the distribution network usually occurs at large distances, where convective mechanisms of heat and mass transfer prevail.

In SSS, on the contrary, heat exchange occurs over short distances and can be more complex, including processes such as condensation, evaporation and phase transition. Therefore, when demanding high quality results, it is necessary to detail the SSS model and structure.

The inclusion of various heat exchange and phase transition processes in the model will help to obtain a more accurate assessment of the system operation and more accurate data on the distribution of heat in the system.

In closed systems, make-up pumps provide compensation for water losses due to possible leaks. They maintain constant pressure and regulate the flow in the system to ensure normal operation.

In open systems, make-up pumps are used to replenish water withdrawals. They supply water from a reservoir or other source to the system to compensate for water consumption by subscribers.

The location of the make-up pumps must be correctly chosen to ensure the efficient operation of the system. They are usually installed on the lower floors of the building to ensure proper pressure and flow.

An important aspect of consideration when designing a cold and hot water supply system is the choice of the correct number and type of backup pumps. They should be able to provide the necessary pressure and volume of water for all subscribers and take into account possible losses due to leaks or other factors.

Make-up pumps play an important role in ensuring the normal functioning of the cold and hot water supply system. They provide compensation for losses, maintain constant pressure and flow in the system and replenish water withdrawals.

3 Conclusion

The mathematical model of steady-state flow distribution obtained on the basis of the application of the variational principle and energy equivalence for non-isothermal water flow in the TPHS takes into account the following basic parameters:

- the hydraulic resistance of the pipe, which depends on the pipe diameter, flow mode and water characteristics. This affects the pressure distribution in the system;
- heat exchange with the environment, which depends on the temperature difference between water and the environment, as well as on the surface area of the pipe and the heat transfer coefficient. This affects the temperature distribution in the system;
- the thermal capacity of water, which depends on the mass and heat capacity of the water. This affects the rate of temperature change in the system;
- steady-state flow, which describes the equilibrium between pressure and heat losses in the system. This allows you to determine the steady-state distribution of parameters.

This model can be used to determine the optimal distribution of thermal loads in the fuel and energy complex, as well as to analyze the flow distribution in other systems where non-isothermal water flow is present.

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