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DYNAMIC CONTROL OF HEAT EXCHANGE PROCESSES
FOR TRIGENERATION POWER SYSTEMS WITH FUEL CELLS

Abstract. The article considers the issues related to the development of energy technologies based on trigeneration with the use of fuel cells, which is expedient to use for additional generation of electrical energy. The possibilities of fuel cells to integrate them into traditional energy systems are shown; technological schemes using PEMFC, PAFC, and MCFC fuel cells are given. Maintaining a stable operating mode depends on temperature stability, so models of heat exchange processes are given and calculations of dynamic parameters for process stabilization under various external influences and dynamic control correction schemes are presented. The tools MatlabSimulink are used as a research tool.

Keywords: energy, trigeneration, fuel cell, heat exchange, model, calculations, MatlabSimulink tools.

Energy technologies belonging to the new generation should be able, in addition to providing their own high energy efficiency, should also successfully "embed", integrate into the existing energy system to improve the efficiency of energy conversion and ensure a more complete controllability and operational
One of such new generation energy technologies are energy technologies based on fuel cells, topless cells, creating technological opportunities for successful and full productive use of energy, which previously could not be used by the technological capabilities and equipment of the "old" generation. The development of fuel cell technology creates great opportunities for research in the field of power generation. The following are various subsystems that integrate a fuel cell (FC) system into a conventional power, metallurgical or other technological system. In such a system, the residual heat not used in the technological process makes it possible to additionally obtain hot water with a temperature in the range of 80°C as a useful product. This temperature is usually sufficient to start absorption cooling cycles. Figures 1, 2 and 3 show the system structures proposed for fuel cell (FC) trigeneration to obtain a higher level of overall energy efficiency.

Fig. 1 Schematic of PEMFC fuel cell technology in trigeneration mode
For example, PEMFC fuel cell technology of about one kilowatt at full load is characterized by electrical efficiency (EE) of about 40% and thermal efficiency (ET) of about 30%. This creates real possibilities for the use of this technology in polygeneration processes by showing that the generator system operates in a very suitable mode with a generator temperature in the range (60...65)°C. This temperature is compatible with the temperature of the heat released by the PEMFC, which is usually in the 80°C range.

Trigeneration with PAFC type fuel cells. Consideration is given to using PAFC technology to operate an air conditioning system at a site with a hot summer climate. Under these conditions, air conditioning equipment can consume more than 75% of the electricity generated, typically during peak hours.

Figure 2 shows the configuration adopted in an absorption refrigeration system using PAFC technology, located in Kuwait in particular. This system is rated at 200 kW and produces 105 kW of thermal energy at 120°C and 100 kW at 60°C. The system uses lithium bromide water as the working vapor; the electrical efficiency (EE) at full load is 45% and the thermal efficiency (TE) is 35%.

![Functional diagram of the process air cooling system using the PAFC fuel cell](image_url)
Trigeneration with MCFC technology. Figure 3 shows the MCFC technology integrated into the process cooling system by absorption. This MCFC fuel cell cooling system showed electrical efficiency (EE) results of 42.27% and thermal efficiency (TE) of 44.21%. Thus, the total, total energy conversion efficiency, expressed in terms of fuel efficiency, is 86.48%. Considered SOFC technology, used to obtain air conditioning or hot water for use in residential and non-residential buildings. The system uses water/lithium bromide in an absorption cooling cycle as the operating couple. The results show that this combination of technologies presents major technical and environmental advantages. The SOFC proposed in this example is a pre-commercial 110 kW tube model developed by Siemens-Westinghouse. According to the developer, the system has the following efficiency figures: electrical efficiency is 43.3%; thermal efficiency in heating is 43.7%; thermal efficiency in cooling is 52.6%; thermal efficiency in hot water production is 46.7%. This figure yields global efficiency results in three operating modes of up to 87.95%, 95.9% and 90%, respectively.

Of particular interest are systems capable of using heat sources with low temperature (below 100°C), i.e. capable of using residual heat of industrial origin or produced in cogeneration plants. In relation to industrial processes that use heat energy, they are classified according to the temperature level of the heat required: processes with low temperature, below 100°C; processes with high temperature, from 300°C to 700°C: some chemical industries.

Thus, given the thermal characteristics of fuel cells, this process is based on one of the different fuel cell technologies: PEMFC, PAFC, MCFC or SOFC. Fuel cells can operate in two ways: with constant power or variable power determined by the following load.

In this regard, it should be noted that high-temperature fuel cells are more suitable for the first mode of operation, while low-temperature fuel cells are more suitable for the second mode because of the shorter startup time.

Modeling and calculations of the parameters of thermal exchange processes of industrial heat generation elements with the involvement of H2S components are discussed below.
Basic technological scheme of the energy heat exchange unit. Technological processes of heat energy devices with elements of industrial heat generation, including cogeneration or trigeneration plants, as well as H2S, are characterized in almost all applications by exchange of thermal energy with the transfer of heat energy from more heated bodies or heat carriers to less heated bodies or through them to liquid (e.g., water) or gas (e.g., steam-gas) streams. These processes of heat energy transfer occur in technical objects through the use of special devices or equipment - heat exchangers. They can be implemented in the form of various in size and volume devices and can have a very diverse design, applicable in technological schemes in Fig. 1, 2 and 3. In this case, the principle of operation remains the same and is shown in Figure 4.

To study the operation of the heat exchanger, as one of the main types of heat power and heat engineering equipment, let's consider a generalized, in a sense, model of the heat exchanger. Technological scheme of the model is given in figure 4 and it fully reflects all processes, which with sufficient degree of reliability describe similar equipment of different sizes and thermal capacities.
Structurally, Figure 4 shows: the steam flow in the steam line, the control valve with the ability to control at a given temperature, the working tank of the heat exchanger, a device for mixing the working fluid to equalize the degree of heating of all layers of the working fluid, including the near-wall and the bottom layers of fluid, the tank heat exchanger working tank with pipelines: input - cold working fluid and output - the liquid heated as a result of heat exchange. The main task is to stabilize the heat exchange process with constancy of the specified temperature mode of the heated working liquid at the outlet of the heat exchanger's working vessel. Let's also note that similarly the cooling process can be provided, i.e. temperature reduction with its stabilization.

Technological process is as follows. Hot steam flow passing through the heating pipeline inside the working tank of the exchanger gives its energy and heats the cold liquid inside the working tank to a certain temperature. The heating process is monitored by a temperature sensor. By regulating the flow of steam with a valve, as well as the volume of flowing liquid, we provide the specified parameters in terms of temperature, as shown in Figure 5. As already mentioned, the main task under consideration is to stabilize the temperature parameters.
Figure 5 shows a continuous line with breaks in the process of heating the working fluid from the cold state and its exit to a stable value of the output temperature. The broken lines are associated with the operation of the heating steam valve through the steam pipeline. For certainty, the time duration of the process in question is taken as 200 seconds, with the first value of the calculated steady-state temperature reaching 80 seconds at the calculated value of the net lag of 10 seconds. The temperature measurement and the effect on the control valve are carried out after 10 seconds. These time durations are realistic for the thermal equipment in use.

Figure 5 (left) shows comparative curves of acceleration of the illustrative model of the heat exchanger: a) idealized and b) taking into account some discreteness of the steam supply control valve.

Fig. 5 Comparative curves of acceleration of the illustration model of the heat exchanger idealized (left, blue) and taking into account the work of the steam supply control valve (left, broken) and (right) without taking into account the work of the control device (right, blue) and optimized by the speed of the technical optimum (right, red)

It should be noted that without participation of regulating devices, for example, the specified steam valve, the processes will have uncontrolled character and may have quite arbitrary dependences of the output coordinate - temperature. There can be an oscillatory character with a very significant value of overregulation. Figure 5 shows curves of heat-exchange processes of the heat exchanger without regard to
the regulator and optimized in terms of speed to "technical optimum" (TO) with speed not more than 5.0 values of the control time constants and the value of overshoot not more than 5%. The process of setting the automatic control system to "symmetrical optimum" (SO) is also possible. In this case, a better response time of about 3.0 values of time constants will be achieved, but the overshoot will reach a value comparable to 50% of the steady-state value. Figure 5 below shows curves roughly comparable to the optimal process criteria listed above.

**Mathematical description of the controlled process of exchange of thermal energy.** Figure 6 shows a schematic diagram of the unchangeable part (left) of the illustration model of the heat exchanger, in which the thermal processes are described as characteristic processes inherent to an open-loop dynamic system. This diagram has two control (setting) inputs and one output. At the output of the presented structure there is an output parameter - the temperature at the heat exchanger outlet. The inputs of this system have the following functions: the first input determines the value of the control signals of the steam supply valve; the second input - determines the degree of influence of external disturbing influences on this object.

![Schematic diagram](image)

**Fig. 6** Schematic diagram of the unchangeable part of the illustration model of the heat exchanger as an open dynamic system (left) and a closed negative-image coupling by output parameter (right)

The signal transmission through both the first and the second inputs is characterized by an aperiodic process and a "pure lag" value. For each input, these
values are different and have well-defined values, determined by the design parameters of the heat exchanger.

The general view of the structure, closed by the negative feedback and the controller with proportional-integral regulator in series is shown in Figure 6 (right). This structural scheme additionally includes a control element for sequential correction of the control signal, which together with the introduced single negative feedback stabilizes the output parameter and improves the dynamic control properties of the heat exchange system. The controller, for example, is taken as a typical proportional-integral (PI) dynamic link with gain and time constant

$$K_c = 0.859(\theta/\tau)^{-0.977}, \quad \tau_c = (\theta/\tau)^{0.680}/0.674.$$  

It should be noted that the parameters of the invariable part describing the dynamic properties of the heat exchange process depend on a variety of design parameters of a particular heat exchange apparatus, as well as the parameters of liquids or gases involved in the thermal energy exchange.

In this regard, the calculated parameters accepted as an example for research can be changed without loss of adequacy of models and proposed solutions in accordance with the parameters of the specific heat exchange processes and apparatuses under study.

Figure 7 (left) shows a variant of the heat exchange process modeling scheme described by an open-loop control structure with a consistently included regulator for the input control signal, which ensures compensation for the influence of external disturbing influences. This structure implements, in essence, the perturbation control principle. For this purpose, an additional control controller is introduced into the unchangeable part of the system. The input of this controller is taken as the control signal stabilizing the output temperature of the heat exchanger. The output is connected to the input of the dynamic link describing the heating process. The structure and transfer function of this controller is also defined by the parameters of the desired dynamic processes.

The control structure shown in Figure 7 (right), which implements the principle of combined control with a direct correction channel and compensation of disturbing influences, offers more complete capabilities.
Fig. 7 Block diagram of the illustration model of a heat exchanger as a dynamic system with a control in series with a controller compensating disturbing influences (left) and with combined control and series-parallel correction and compensation of the influence of disturbing influences (right)

Digital calculation models of heat exchange process and results of computer simulation. For the analysis of dynamic processes, which would provide the desired characteristics of heat exchange processes to the best extent, we will use a digital model, which is fully adequate to the ongoing physical processes in the heat exchange apparatus and implement the structural diagram in Figure 8, left.

Schematic diagram of the digital model is given in the MatlabSimulink modeling system and is presented in Figure 8, right.

Fig. 8 Schematic diagram of the heat exchanger model as a dynamic system in the MatlabSimulink modeling system (left) and the graphical user interface for studying the heat exchanger processes as an open-loop dynamic system in the MatlabSimulink modeling system (right)
Figure 8 shows a mnemonic diagram (left) and a block diagram (right) to calculate the parameters of the heat exchanger. In this scheme, simulating the processes of heat exchange, the control actions are carried out by two control channels: a) the channel of direct regulation and b) the channel of disturbing influences.

Fig. 9 Calculated parameters of heat exchanger processes as an open-loop dynamic system with different calculated parameters of the direct channel.
In Figure 9, from top to bottom curves (A) ... (E) the results of calculations for the following cases of variation of parameters of the direct channel correction links (gain/lag): curves (A) - 0.1/1.0; curves (B) - 1.0/1.0; curves (C) - 2.0/1.0; curves (D) - 2.0/10.0).

The above studies and calculations show that in the open state the dynamic system describing heat exchange processes according to the model shown in Fig. 9 does not satisfy the above requirements with respect to the desired stability of heat exchange processes. Therefore, in order to investigate the possibilities of improving the regulating properties of the heat exchange system, we perform further additional research.

Fig. 10 Graphic user interface for the study of heat exchanger processes as a closed dynamic system with sequential correction of the direct control signal in the MatlabSimulink simulation system

Figure 10 shows a mnemonic diagram (left) and a block diagram (right) to calculate the parameters of the heat exchanger with the introduction of a stabilizing output temperature feedback. In this scheme, which simulates heat exchange processes and adequately describes them for heat-exchange equipment of any capacity and size, control actions are carried out by two regulating channels: the channel of direct regulation and the channel of perturbing influences. In this case, in addition to the direct control channel, a serial correcting element is introduced, which has a structural diagram of a standard proportional-integral (PI) regulator. The mathematical description is given above. The parameters of the regulator in the
process of research have the possibility of changing in a fairly wide range. In addition to the serial correcting link to ensure the stability of the output coordinates a single negative feedback is connected.

Fig. 11 Computational curves of heat exchanger processes as a closed dynamic system with sequential correction of the direct control signal
In Figure 11, from top to bottom curves (A), ... (E) there are results of calculations for the following cases of variation of parameters of the forward control signal correction links (gain/lag): curves (A) - 0,1/1,0; curves (B) - 1,0/1,0; curves (C) - 2,0/1,0; curves (D) - 2,0/10,0; curves (E) - 2,0/40,0.

Figure 12 shows the mnemonic diagram of the graphical user interface for the study of heat exchange processes, implementing the model as an open-loop dynamic system with correction of disturbing influences in the MatlabSimulink modeling system. To study the dynamic processes of the heat exchange apparatus, this scheme also provides for changing two parameters. Calculation results are shown in Figure 13.

Fig. 12 Graphic user interface for the study of heat exchanger processes as an open-loop dynamic system with correction of disturbing influences in the MatlabSimulink simulation system

Figure 13 from top to bottom curves (A), ... (E) shows calculation results for the following cases of variation of parameters of direct channel correction links (gain/lag) curves (A) - 0,1/1,0; curves (B) - 1,0/1,0; curves (C) - 2,0/1,0; curves (D) - 2,0/10,0; curves (E) - 2,0/40,0.

Figure 14 shows the mnemonic diagram (left) and the structural diagram (right) for calculation of the parameters of the heat-exchange equipment model. In this
scheme, additional control actions are carried out by two control channels: a) the direct control channel with sequential correction and single feedback on the input parameter and b) the parallel correcting direct channel, which carries out direct parallel correction of perturbing influences of the external environment.

Fig. 13 Calculation curves of heat exchanger processes, as an open dynamic system with correction of disturbing influences
Fig. 14 Graphic user interface for the study of heat exchanger processes as a closed dynamic system with sequential correction of the direct control signal and correction of disturbing influences in the MatlabSimulink simulation system

Figure 15 from top to bottom curves (A), ... (E) shows calculation results for the following cases of variation of parameters of direct channel correction circuits (gain/lag): curves (A) - 0,1/1,0; curves (B) - 1,0/1,0; curves (C) - 2,0/1,0; curves (D) - 2,0/10,0; curves (E) - 2,0/40,0.

It is obvious, that changing of correction circuit parameters leads to changing of dynamic characteristics. At that, the following changes take place: a) time of regulating the output coordinate; b) value of overshooting; c) level of oscillation of running dynamic processes; d) values of statism or static regulation error of output characteristics of the object under study, which carries out the heat energy exchange process in the equipment considered above.

When performing the calculations, it is assumed that the achieved accuracy of the solution of the differential equations describing the above thermal processes in the heat exchange equipment with the application of trigeneration technologies with fuel cell components (cells) is determined by the established relative error of the mathematical method of solution and the step of integration. For the above results, this calculation error is not more than 1,0х10⁻⁶. For all of the above calculated curves, the time of the calculated dynamic process is 200.0 seconds.
Fig. 15 Calculated curves of heat exchanger processes as a closed dynamic system with sequential correction of direct control signal and correction of disturbing influences

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