Automatic control system for operation modes and calibration of technological parameters of evaporation cooling apparatuses

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Abstract. The paper provides the scheme and algorithm of the automatic system controlling the operation modes of evaporation cooling apparatuses for industrial recirculating water of local recirculating water supply systems. The authors have described the principle of parameter registration and the automatic calibration of the main parameters at the commissioning stage and during the operation of heat and mass transfer technological equipment. The authors have developed a new approach to the use of elastically deformable heat and mass transfer packing blocks and wastes from metalworking machines as packing contact devices for evaporation cooling apparatuses. Compressed blocks of metal shavings can be volumetrically elastically deformed which allows adjusting operation modes automatically and solving partly a very serious problem of disposing industrial wastes from machine-building enterprises. The article also covers developing of evaporation cooling apparatuses.

1. Introduction

Export of low-grade heat from recirculating water by cooling it with air is widely used in various technical devices and technological systems. This method of cooling circulating water is widely used in many industries: chemical, petrochemical, oil and gas, nuclear, metallurgical, construction, food and many other related industries. In local recirculating water supply systems small-sized evaporation cooling apparatuses (cooling towers) are widely used. Therefore, developing and designing evaporation cooling devices which being of small size and costing little have relatively high thermal performance is a vital engineering task [1-8]. The main structural element of evaporation cooling apparatuses which is responsible for high-quality performance is the heat and mass transfer packing (sprinkler). The main purpose of the heat and mass transfer packing contact devices is the development of the contact surface between the contacting phases, however there are even more important characteristics such as the ability to develop intensive hydrodynamic operation modes, holding capacity, etc. Working on the development of these characteristics and the intensification of heat and mass transfer processes has always bordered on the incredibly tempting prospect of controlling the hydrodynamic operation modes of packing heat and mass transfer devices and creating packing contact devices capable of automatically adjusting to
standard operation modes regardless of fluctuations in the flow rates of the contacting phases and seasonal operation conditions of the equipment.

There exists a huge number of heat and mass transfer packings oriented to a wide range of technological problems and types of technological equipment [1, 2, 9-43]. However, despite many of the mare of high efficiency they have a number of significant drawbacks such as high cost, labor-output ratio and adaptability to streamlined manufacture, the inability to control the basic geometric and technological parameters, and a narrow focus on the requirements of a particular technological process. Working on eliminating the above drawbacks the authors have found a promising direction in the study and development of new heat and mass transfer contact packings which can be automatically controlled to meet the requirements of a particular process and device, have natural structural and surface intensification effects provided by manufacturing features and very low cost since the use of these packing materials is connected with the disposal of industrial wastes formed in large quantities at metalworking enterprises (machine-building, defense and other industries) [44-48].

And most importantly, the use of such packing materials in combination with the developed automatic control systems will allow controlling the hydrodynamic operation modes of evaporation cooling heat and mass transfer devices and carrying out ongoing auto-adjustment of technological parameters of heat and mass transfer devices. The authors mean metal shavings which are formed during the machining of stainless high-alloy steel grades at metalworking machines. They are of particular interest to the authors because they have resistance to weathering, chemical resistance, corrosion resistance, acid resistance, sufficiently high mechanical strength and high elasticity. All of the above characteristics depend on the composition. In addition to accessibility and resistance to aggressive environments, this packing material (metal shavings) has two main advantages.

These are natural intensification effects connected with the spiral structure of the packing elements and the formation of a micro-ribbed surface, and elastic mechanical control of the packing material volume which makes it possible to control hydrodynamic regimes, and accordingly intensify heat and mass transfer processes in evaporation cooling apparatuses meant for industrial recirculating water, and if necessary reduce water droplet entrainment from the device, thereby reducing losses and the required replenishment of recirculating industrial cycles.

It should be mentioned that any packing material having bulk-elastic properties that can satisfy the requirements of a specific process and device can be considered as elastically deformable evaporation cooling packing units to be automatically controlled. That is, the key to a successful automated system for controlling the parameters and modes of heat and mass transfer packing devices is elastic deformation of the packing contact blocks, even in a narrow range this will significantly affect performance and operation parameters.

To recognize and classify samples of packing materials that meet the requirements of certain heat and mass transfer processes a classification technique for processing experimental data \( \lambda = f(Re_{nd}) \) has been developed [49-51]. After hydrodynamic express studies it allows showing how to industrially apply packing materials, in particular for the evaporation cooling process of the recirculating water, and it also allows predicting the performance of the packing material in terms of energy efficiency in operation.

2. Methods and materials
The automated control system of the evaporation cooling apparatus shown in figure 1 is meant for the automated search and maintenance of the device operation mode providing the set temperature of the cooled heat-carrying agent (water) at the lowest energy cost.

Figure 2 shows the heat and mass transfer device for evaporation cooling of recirculating water with automatic regulation of the packing block operation modes. Figure 2 shows the variant of the apparatus with the lower control of the hydraulic cylinders. The article provides schemes and algorithms for an upper location of the hydraulic cylinders.
Figure 1. Automated control system for the operation modes of the evaporation cooling apparatus.

The control system consists of hydraulic cylinders HC1 and HC2, vertically moving the grid UG which causes elastic deformation (compression) of the packing when the grid is lowered and compression release when the grid rises. The casing of one of the hydraulic cylinders has an ultrasonic distance sensor to measure the distance to the target T which is a metal plate fixed to the grid. In the output pipe there is a temperature sensor to measure the temperature of the heat transfer agent passing through the device. Information from the sensors is transmitted to the programmable logic controller PLC in which the control program is cyclically executed. According to the program, the controller gives control signals to the hydraulic valves V1 ... V4 which are used to inject oil into the upper and lower chambers of the hydraulic cylinders, and V3 and V4 are used to discharge oil from the chambers into the
oil reservoir OR. The oil pump P serves to create oil pressure in the hydraulic system. Its drive motor M2 starts and stops by PLC commands.

The electric motor M1 of the axial fan F is powered through the frequency converter FC while the PLC sends control commands to the FC to start, stop the electric motor, as well as increase (f+) or decrease (f−) the frequency of the supply voltage of the electric motor M1. At the same time a signal is received from the FC to the PLC inputs that the fan motor is running (Fan= 0 or 1).

Figure 3 shows the algorithm of the control program. Firstly the operator enters the value of the required heat transfer agent temperature at the output of the device \( t_{req} \). Then the program receives from the controller memory the constant values depending on the particular device. The reaction time of the cooling tower TR is the time which is needed to change the temperature of the heat transfer agent since the moment of changing the device operation parameter. The temperature control error determines the deviation limits of the actual temperature of the leaving heat transfer agent from \( t_{req} \), which is considered acceptable. The lower \( H_{max} \) and upper \( H_0 \) limiting grid coordinates are the distance according to the sensor S1 corresponding to the extreme lower and upper grid positions. These values are entered into

Figure 2. Heat and mass transfer apparatus for evaporation cooling of recirculating water with automatic regulation of the packing block operation modes: 1 – device body; 2 – sprinklers; 3 – elastically deformable packing block; 4 - hydraulic cylinders of the control system; 5 – lower moving grid of the packing block; 6 – droplet trap; 7 – fan; 8 – air intake windows; 9 – drainage tank.
the PLC memory during commissioning and determined experimentally. The “flag” Fan variable is also initialized indicating the device fan to be running.

Further, the program determines the minimum \( t_{\text{min}} \) and maximum \( t_{\text{max}} \) of the temperature interval in which it is necessary to keep the temperature of the leaving heat transfer agent.

From the sensor \( S1 \) the program receives the actual distance to the target on the grid that is the actual coordinate of the grid \( H_{\text{fact}} \). Further program execution takes place in two flows.

In the first flow, the temperature of the heat transfer agent \( t_q \) is received from the sensor \( S2 \), and then the status of the fan motor Fan is obtained. Next the program compares the actual temperature of the heat transfer agent leaving the device with the limit values of the range of permissible temperatures \( t_{\text{min}} \) and \( t_{\text{max}} \). If the cooled heat transfer agent is colder than the minimum temperature of the range, the program reduces the required grid coordinate by one step which is equal to \( 1/100 \) of the value of the grid move. This causes the grid to rise and the packing to get compression release. Next the program checks the simultaneous implementation of the conditions: the calculated required coordinate of the grid is equal to the coordinate of the extreme upper position or above it and the fan of the device is working. If the conditions are met, the PLC sends a command to the frequency converter to reduce the fan speed by one step, and if the fan rotates at the minimum frequency, stop it. Then the program forcibly assigns the value of the extreme upper coordinate to the variable of the required grid coordinate. If one of the conditions is not met, the program does not change the fan operation mode.

If the cooled heat transfer agent is hotter than the maximum temperature of the range, the program increases the required grid coordinate by one step. This causes the lowering of the grid and compression of the packing. Next the program checks the implementation of the condition: the calculated required grid coordinate is equal to the coordinate of the lowermost position or above it. If this condition is met, the PLC instructs the frequency converter to increase the speed by one step, and if the fan did not work, start it at the minimum frequency. After that, the program forcibly assigns the grid coordinates the value corresponding to its lower limit position.

If none of the conditions for comparison with the limit values of the temperature range is met, then the heat transfer agent temperature is within acceptable limits and it is not necessary to change the operation mode of the device.

Further, the program waits for a time corresponding to the response time, and then repeats the described actions starting from the moment the actual grid coordinate is received.

In the second flow the program controls the hydraulic system to make the grid achieve the calculated required coordinates. After receiving from the sensor \( S1 \) the actual grid coordinate \( H_{\text{fact}} \), the program waits for 3 seconds for the algorithm of the first flow to be completely executed at least once. The program checks if the grid is currently above the required coordinate. If this condition is met, the controller issues a command to start the hydraulic pump drive motor \( M2 \). After that, the PLC issues a command to close valves \( V2 \) and \( V3 \) and open valves \( V1 \) and \( V4 \). Oil begins to be pumped into the upper chambers of the cylinders and discharged from the lower ones, which leads to lowering of the grate.

If the condition is not met, the program checks whether the grid is currently below the required coordinate. If this condition is met, the PLC issues a command to start the hydraulic pump drive motor \( M2 \). After that, the PLC issues a command to close valves \( V1 \) and \( V4 \) and open valves \( V2 \) and \( V3 \). The oil begins to be pumped into the lower chambers of the cylinders and discharged from the upper ones, which leads to the rise of the grid.

If none of the conditions is met, the grid is in the desired position. In this case, the controller issues a command to close all valves \( V1-V4 \), which leads to the fixation of the grid, and then stops the motor \( M2 \).

The execution of this algorithm is also cyclically repeated. This ensures constant monitoring of the temperature of the leaving heat transfer agent and the adaptation of the operation mode of the device to ensure sufficient cooling of the heat transfer agent with minimal energy costs.

We shall consider the calibration algorithm of the main technological parameters of the evaporation cooling apparatus. Calibration allows you to automatically obtain the values of the variables necessary for the operation of the program for continuous automatic control of the operation mode of the
evaporation cooling apparatus. The calibration process is carried out once at the final stage of commissioning and can be carried out periodically during operation of the device if the accuracy of regulation has become unsatisfactory due to permanent deformation of the packing block or clogging of the packing, as well as after its replacement.

Figure 3. The algorithm for automatic control of the operation modes of evaporation cooling devices.
A necessary requirement when performing the calibration is the supply of a heat transfer agent having the most stable temperature above ambient temperature. This may be the average temperature at which the device will have to function during operation.

The algorithm of the automated calibration program is shown in figure 4. The program starts with the input of the permissible error in the temperature control of the cooled heat transfer agent $dt$. This parameter is determined by the requirements of technological processes of the closed recirculating cycle of the local water supply system.

Next, the program prepares the device for calibration, it issues a command to stop the electric drive of the fan $M1$, and then to start the electric drive of the oil pump $M2$. The pump will run continuously throughout the calibration process.

The program receives the actual grid coordinate from the sensor $S1$ and writes it to the variable $H_{\text{fact}}$ after which it writes the same value to the variable $MV$ (movement). The program then issues a command to open valves $V1$ and $V4$. Oil pressure enters the upper chambers of the cylinders and the grid begins to lower compressing the packing. After a delay of 0.5 seconds, the program once again receives the actual grid coordinate from sensor $S1$ and writes it to the variable $H_{\text{fact}}$ and compares the values of $H_{\text{fact}}$ and $MV$. Their equality means that the grid has stopped moving, then the program issues a command to close valves $V1$ and $V4$, which leads to a stop and fixation of the grid. Otherwise, the program section is cyclically repeated until it is detected that the grid has stopped. After that, the grid coordinate is written into the variable $H_{\text{max}}$ as the lower limit of the grid stroke.

At the next stage the program issues a command to open valves $V2$ and $V3$ and likewise determines that the grid has risen up to the stop. Then the program issues a command to close valves $V2$ and $V3$, and the grid coordinate is written to the variable $H_0$ as the upper limit of the stroke of the grid.

To prevent a rapid increase in the residual deformation of the packing the lower limit of the grid working stroke is shifted upward by $1/10$ of a certain limiting stroke. For this, the value of $H_{\text{max}}$ is recalculated. Further, the program determines the response time $TR$ of the device, that is, the time needed to establish constant temperature of the leaving heat transfer agent since the moment of the stop of the grid. First, the program receives the actual grid coordinate and, if it is not in the extreme upper position $H_0$, issues a command to open valves $V2$ and $V3$ until the grid comes to this position.

After that, the program reads from the sensor $S2$ the actual temperature of the leaving heat transfer agent and writes it into the variable $t_{\text{fact}}$ and $t_{\text{prev}}$ (previous). And after 30 seconds of waiting, it once again reads the actual temperature of the leaving heat transfer agent $t_{\text{fact}}$ from the sensor $S2$. If $t_{\text{fact}}$ and $t_{\text{prev}}$ are not equal, the temperature continues to change.

When the temperature has settled, the program proceeds to a step-by-step measurement of the time to establish the temperature. The program calculates the coordinate by which the grid should be moved for the next measurement $H_{\text{refl}}$ (target). After that, the program checks if the grid goes over the lower stroke limit. In this case, the program stops the execution of the cycle. Otherwise, the program receives the actual grid coordinate from sensor $S1$ and, if it is less than $H_{\text{reg}}$, issues a command to open valves $V1$, $V4$. The grid begins to move down, while the cycle of checking its coordinates is repeated until the grid is in the coordinate $H_{\text{reg}}$.

Then the program issues a command to close the valves $V1$, $V4$ and the grid is fixed. Immediately after this, the system timer starts counting into the variable $TR_{\text{prev}}$ (reaction previous), and then the program receives the actual temperature of the leaving heat transfer agent from sensor $S2$ after which the cycle of checking the temperature change with a frequency of 30 seconds starts. When the temperature has stopped changing, the $TR_{\text{prev}}$ countdown stops, and the program determines whether the specific time is longer than that which was written to the $TR$ variable earlier. At the first iteration of the cycle $TR$ is equal to 0. If it is, the program sets the $TR$ variable to $TR_{\text{prev}}$. If it is not, the $TR$ value remains the same, and the program proceeds to the next iteration of the measurement cycle of the device reaction time by temperature at the next grid coordinate.
Figure 4. The calibration algorithm for the main technological parameters of the evaporation cooling apparatus allowing automatic control of operation modes of technological equipment.
After the reaction time of the device is determined at each point, the program stores the found values of the variables $H_0, H_{\text{max}}, TR, dt$, in the PLC permanent memory, and then prepares the device for normal operation. The program receives the actual coordinate of the grid and issues a command to open valves V2, V3 and holds them open until the grid rises to its highest position, and when it is reached, issues a command to close the valves. Then the program issues a command to stop the electric drive of the oil pump $M_2$. This completes the calibration.

That is, in the most unfavorable seasonal operation conditions, the heat and mass transfer device of evaporation cooling will automatically adjust and switch to an intensive hydrodynamic operation mode with a dense compressed packing and high speeds of washing with the air flow, these conditions contribute to the intensification of heat and mass transfer processes. The automatic calibration of parameters will allow the device to tune to optimal (reference) operating modes. In the process of changing seasonal weather conditions, thermal performance will decrease and the device will automatically switch to smooth energy saving modes with an increase in the porosity of the packing blocks and a decrease in the intensity of the air flow until the fan is completely turned off.

3. Conclusions
The developed system of automatic adjustment of the operation modes of packing heat and mass transfer devices for evaporation cooling of recirculating water of local recirculating water supply systems allows automatic adjusting of hydrodynamic modes, thereby automatically adjusting to the best thermal performance with the lowest ablation and energy costs, and all this is combined with an integrated parameter registration system neutralizing the seasonal operation conditions of the cooling evaporator.

The automatic calibration mode of the technological parameters of evaporation cooling apparatuses has been presented, which allows recognizing and maintaining reference thermophysical performance indicators during operation, taking into account the hydrodynamic features of a particular packing material (evaporative cooling packing unit) and other important factors that are critical for the device performance. The factors are large-scale transfer, seasonal features of exploitation, etc.

The use of compressed metal shavings as automatically adjustable packing blocks for evaporative cooling, due to the implementation of optimal (reference) hydrodynamic modes and the possibility of fine automatic control, taking into account the complex parameter registration system, as well as the cost and production technology, obliges the authors to develop this promising direction. Experimental data showed that for all the main hydraulic characteristics, sectional regulation of the packing material allows working in a very wide operation range, that is, it will allow replacing a large number of industrial packing devices [52, 53].

As a packing material for automatically controlled evaporation cooling units, not only elastically deformable metal shavings in the form of wastes can be considered which would obviously put researchers and designers of technological equipment within a certain framework, but also packing materials for evaporative cooling units can be obtained purposefully by machining with the required chemical and physico-mechanical characteristics, and with certain conditions by cutting to make packing materials have the desired geometry and surface characteristics that meet the requirements of evaporative cooling devices for recirculating water in addition to the best thermophysical parameters of their work.

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