Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 176 (2017) 689 – 698

Procedia Engineering

www.elsevier.com/locate/procedia

Dynamics and Vibroacoustics of Machines

Study of coil heat exchanger of mechatronic sample conditioning system

A.G. Gimadiev, A.V. Utkin*

Samara National Research University, Moskovskoe shosse, 34, Samara, 443086, Russian Federation

Abstract

The heat exchanger is the main part of mechatronic sample conditioning system. Static and dynamic characteristics of heat exchanger influence on the accuracy of sample temperature maintaining. Adjustable parameter of the heat exchanger is the final sample temperature; the control factor is cooling water flow rate. The inlet sample temperature, the inlet cooling water temperature and the sample flow rate can be attributed to disturbing factors. To ensure the efficient operation of sampling system is necessary to know of heat exchanger characteristics when the control and disturbing factor are present. In present work, secondary countercurrent coil heat exchanger with core tube is studied. On the basis of 30 experiments semi-empirical correlation for prediction of overall heat transfer coefficient is proposed. Temperature transient response is investigated theoretically and experimentally when inlet sample temperature is subjected to sudden change. The dynamic behavior is approximated by aperiodic link with time delay link. The obtained for heat exchanger dynamic dependences can be used in the design of mehatronic sample conditioning system, operating at steady and transient state, in the choice of the law of the controlling sample temperature and the algorithm of diagnosing deposits on the surface of the coil.

Peer-review under responsibility of the organizing committee of the international conference on Dynamics and Vibroacoustics of Machines

Keywords: Heat exchanger; sampling system; subject of regulation; heat transfer coefficient; semi-empirical correlation; dynamic behavior; calculation; experiment.

* Utkin A.V... Tel.: +7-927-014-00-75.
E-mail address: utkin-alexey1@yandex.ru

Peer-review under responsibility of the organizing committee of the international conference on Dynamics and Vibroacoustics of Machines
doi:10.1016/j.proeng.2017.02.314

1. Introduction

In thermal and nuclear energy industry heat exchangers are used for cooling of samples of steam, condensate or water selected for chemical analysis. The sample is extracted from the boiler and turbine equipment, has a temperature of 540 °C and pressure of 32 MPa [1]. Maximum allowable temperature for on-line chemistry analyzers is not more than 50 °C. Therefore, the samples are pre-cooled in the sample conditioning system, in which there are three heat exchangers (coolers) sometimes. The last heat exchanger is supplied with automatic control system of sample temperature. Disturbing factors such as inlet cooling water temperature, inlet sample temperature and sample flow rate affect on the heat exchanger of sample conditioning system in the process. In most systems, the control factor is the cooling water flow rate [2]. To determine the optimal control action in the mechatronic sample conditioning system, the selection and quality settings of equipment, the heat exchanger dynamic characteristics are necessary to know. Therefore, the study of the sample heat exchanger as the mechatronic sample conditioning system regulation object, has important practical significance.

Transient response in the heat exchanger is the subject of several studies. In [3] presents the results of theoretical and experimental studies of the tube-in-tube heat exchanger dynamic when flow rate of hot fluid is subjected to sudden change. This work shows that the outlet temperature is approximated by a first order response with a transport delay. In the model of heat exchanger the thermophysical properties of the fluids are assumed constant, that is valid only for small temperature changes occurring in the heat exchanger.

In [4] it is shown tubular heat exchanger dynamic model, which was developed from partial differential equations neglecting wall capacitance and heat transfer coefficients variation. This model gives good agreement with experimental data. Additionally amplitude-frequency and phase-frequency characteristics of the heat exchanger are given when a sinusoidal perturbation of hot fluid flow. It is established that there is a resonance at the specific frequencies, the value of which depends from the heat exchanger design and flow rate.

Most transient response studies dedicated to tube-in-tube heat exchangers; however, little attention is paid to coil heat exchangers having a sufficient efficiency and reliability. For application toward to coil heat exchanger of tube-in-tube heat exchangers modeling principle it is sufficient to determine of heat transfer coefficient.

Articles [5; 6] are devoted to the study of heat exchangers with finned tubes and double coil. To determine the heat transfer coefficients was carried out a direct measurement of the wall temperature and fluid temperature. This approach has a significant drawback – thermocouple and their mounting make certain a disturbance in the flow that affects the heat transfer rate. Therefore, it is reasonable to use the indirect method aimed at determination of heat transfer coefficients by graphical or by compiling dependencies obtained with experimental data.

Paper [7] shown the application Wilson method, based on the determination of heat transfer coefficients from the average temperature difference and heat flux. The assumption is that the temperature of one of the fluid varies within a small range and impact of this change on the heat transfer can be neglected. This greatly simplifies the calculation, but for some systems, such assumptions are not applicable. In most cases to determine of heat transfer coefficients applied processing of experimental results using least squares method [8, 9].

For the determination of heat transfer coefficients of coil heat exchangers, there are several empirical dependencies, which are used at the design stage of the heat exchanger and give a reasonable result. In [10] compares the empirical formulas derived by different authors for several coil variants. From this work it follows that with increasing Reynolds number increases the discrepancy between the results. However, the formula, which most adequately describes the process, not offered by authors.

Using the above mentioned dependencies to describe the shell space introduces additional error. This is because the geometry of the shell space may be different. In addition to the coil in shell space may be present the guide, turbulence and other details.

The purpose of this work is the creation of static and dynamic model of coil heat exchanger with application of semi-empirical correlations for heat transfer coefficients calculation.

Nomenclature

A_f	Minimum flow cross-section area of shell, m^2
A_p	Wetted surface area on the shell side, m^2
b	Coil pitch, m
C	Specific heat capacity, J/kg K
d	Tube diameter, m
D	Shell diameter, m
D_{avg}	Average coil diameter, m
h	Heat transfer coefficient, W/m^2 K
H	Shell length, m
k	Thermal conductivity, W/m K
L	Length of coil tube, m
Nu	Nusselt number
Pr	Prandtl number
Q	Flow rate, LPM
Re	Reynolds number
T	Temperature, °C
U	Overall heat transfer coefficient, W/m K
V	Volume, m^3
Z	Loop number
Greek letter	
ρ	Density, kg/m^3
υ	Kinematic viscosity, m^2/s
Subscripts	
in	Inner
out	Outer
s	Sample
c	Cooling water
w	Wall

2. Description of heat exchanger and experimental set-up

As the object of study, countercurrent coil heat exchanger is selected. Heat exchanger consist of a coil (Fig.1), placed in the annular space (shell space) between the case and core tube. A water sample with a temperature not exceeding 120 °C comes to the coil, which is cooled by process water (cooling water) flowing in the shell space. The presence of the core tube increases the velocity of the cooling water, as a consequence of heat transfer intensification. The coil has $Z = 16$ loop with an average diameter of coiling D_{avg} and coil pitch b (table 1).

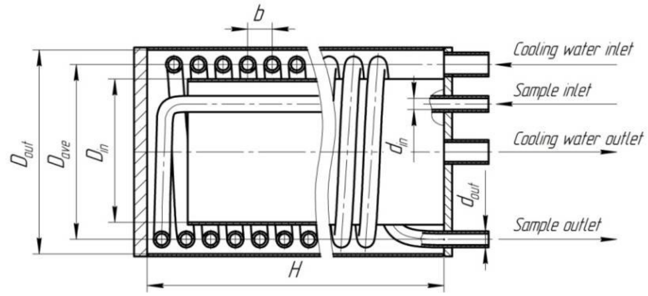
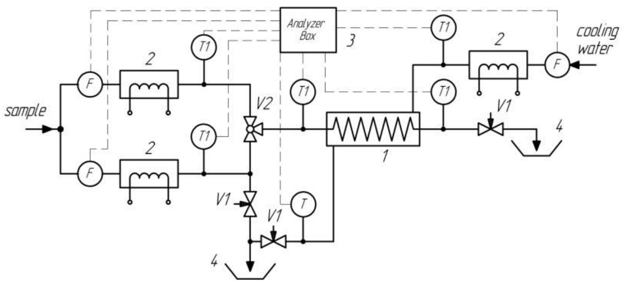


Fig. 1. Schematic construction of coil heat exchanger.

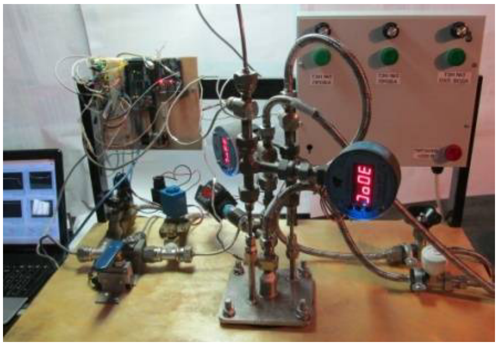
Table 1. Geometrical parameters of coil heat exchanger.

D_{out}, мм	D_{in}, мм	D_{avg}, мм	d_{out}, мм	d_{in}, мм	b, мм	H, мм	Z
127	89	108	10	7	15	300	16

For experimental investigations of heat exchanger performance, the authors created a set-up, whose flow diagram and appearance are shown in fig. 2.



a)



b)

1 – heat exchanger
2 – tubular heating element
3 – analyzer box
4 – draw-off

F – flowmeter
T1 – thermocouple
V1 – needle valve
V2 – three-way valve

Fig. 2. Flow diagram (a) and appearance (b) of experimental set-up.

The experimental set-up can implement two modes of heat exchanger study. The first one is the static mode, when outlet temperature of the sample and the cooling water is determinated in the steady state. The second mode is dynamic test, when temperature of both fluids is measured at transient response when inlet sample temperature is subjected to sudden change.

Range of operating parameters in determining the static characteristics of the heat exchanger is given in table 2. These values are primarily determined by characteristics of mechatronic sample conditioning system.

Table 2. Range of operating parameters in determining the static characteristics.

Parameter	Range
Sample flow rate, LPM	0.3…1.0
Cooling water flow rate, LPM	0.5…9.0
Inlet sample temperature, °C	30…120
Inlet cooling water temperature, °C	20…35

Range of operating parameters in determining the dynamic characteristics of the heat exchanger is given in table 3.

Table 3. Range of operating parameters in determining the dynamic characteristics.

Test	Sample flow rate, LPM	Cooling water flow rate, LPM	Inlet cooling water temperature, °C	Start inlet sample temperature, °C	Finish inlet sample temperature, °C
1	0.8	2	23	35	67
2	0.6	2.2	23	80	45

Water from water supply system is uses in the capacity of the sample and cooling water. The required fluid temperature at the inlet of the heat exchanger 1 is provided tubular heating elements 2. Five thermocouples T1 are located directly in the flow at the inlet and outlet of the heat exchanger. They produce a temperature measurement every 200 ms with uncertainty ±1 °C. Flow rate regulation of sample and cooling water are produced by needle valves V1. Turbine flowmeters F produce a flow rate measurement with uncertainty of less than 4 %. Information acquisition is performed by special unit 4 and information is displayed on the operator panel.

3. Static characteristics of the heat exchanger

When designing and choosing heat exchanger needs to know what the temperature will be at the heat exchanger outlet under the given boundary conditions. These characteristics are representing as dependence of approach temperature from the sample flow. Build these charts can be quite accurately subject to finding the overall heat transfer coefficients. The overall heat transfer coefficient is depended on the heat transfer coefficients of sample and cooling water, thermal resistance of the wall and deposits on the coil surface.

To determine of heat transfer coefficients need to know the temperature of fluid and wall. Installing thermocouples directly on the coil wall entails a complication of experimental setup and the additional error due to disturbances in the flow. Therefore an indirect method is preferably used, based on an approximate calculation of the heat transfer coefficient using the initial and outlet temperatures of fluid and their flow rates.

The heat transfer rate of a heat exchanger Q_s^t can be calculated from the sample side as

$$Q_s^t = Q_s \rho_s C_s (T_{s.\,in} - T_{s.\,out})$$

where Q_s ρ_s, C_s – respectively, sample flow rate, sample density and sample specific heat capacity; $T_{s.\,in}$, $T_{s.\,out}$ - respectively, inlet and outlet sample temperature.

The heat transfer rate of a heat exchanger Q_c^t can be calculated from the cooling water side as

$$Q_c^t = Q_c \rho_c C_c (T_{c.\,out} - T_{c.\,in})$$

where Q_c ρ_c, C_c – respectively, cooling water flow rate, cooling water density and cooling water specific heat capacity; $T_{c.\,in}$, $T_{c.\,out}$ – respectively, inlet and outlet cooling water temperature.

The average heat transfer rate of a heat exchanger Q_{avg}^t is calculated by the expression

$$Q_{avg}^t = \frac{Q_s^t + Q_c^t}{2}$$

Experimental overall heat transfer coefficient $U_{\exp}$ is defined as

$$U_{\exp} = \frac{Q_{avg}^t}{\pi l \overline{\Delta t}} \tag{1}$$

where l – coil tube length; $\overline{\Delta t} = (\Delta t_g - \Delta t_l) / \ln(\Delta t_g / \Delta t_l)$ – log mean temperature difference [11]; $\Delta t_g = T_{s.in} - T_{c.out}$, $\Delta t_l = T_{s.out} - T_{c.in}$.

The theoretical overall heat transfer coefficient is defined by three components

$$\frac{1}{U} = \frac{1}{h_s d} + \frac{1}{2k_w} \ln(\frac{d_{out}}{d_{in}}) + \frac{1}{h_c D} \tag{2}$$

where h_s, h_c - heat transfer coefficients respectively of sample and cooling water; $d = d_{in}$ - hydraulic diameter of coil tube; k_w - thermal conductivity of coil tube; D - hydraulic diameter of shell space.

Value D is calculated by the expression $D = 4A_f H / A_p$, where A_f - the minimum flow cross-section area of shell; A_p - wetted surface area on the shell side; H - length of heat exchanger.

When calculating of theoretical overall heat transfer coefficient (2) value h_s и h_c are unknown. They are determined from the equations

$$h_s = \frac{Nu_s k_s}{d}, \; h_c = \frac{Nu_c k_c}{D} \tag{3}$$

where Nu_s , k_s - respectively, Nusselt number of sample and sample thermal conductivity, Nu_c , k_c - respectively, Nusselt number of cooling water and cooling water thermal conductivity.

Since the current in the coil is not affected by turbulence, Nusselt number of sample can be calculated as [12]

$$Nu_s = 0.021 \mathrm{Re}_s^{0.8} \mathrm{Pr}_s^{0.2} \tag{4}$$

where $\mathrm{Re}_s = 4Q_s / (\pi d v_s)$ - Reynolds number of sample; v_s - sample kinematic viscosity; Pr_s - Prandtl number of sample.

The expression to determine the Nusselt number of the cooling water is

$$Nu_c = X \mathrm{Re}_c^m \mathrm{Pr}_c^n \tag{5}$$

where $\mathrm{Re}_c = 4Q_c / (\pi D v_c)$ - Reynolds number of cooling water, v_c - cooling water kinematic viscosity, Pr_c - Prandtl number of cooling water; X , m , n, - unknown coefficients .

By substituting equations (3) into equation (2) and expressing them Nu_s и Nu_c expressions (4) и (5), is obtained

$$\frac{1}{U} = \frac{1}{0.21 \mathrm{Re}_s^{0.8} \mathrm{Pr}_s^{0.2} k_s} + \frac{1}{2k_w} \ln(\frac{d_{out}}{d_{in}}) + \frac{1}{X \mathrm{Re}_c^m \mathrm{Pr}_c^n k_c} \tag{6}$$

On the basis of relationship (6) can be receive semi-empirical overall heat transfer coefficient U_{pred} , which can be calculated using the heat exchanger performance over a wide range of design and operational parameters. To do this, the unknown coefficients in the expression (6) must be determined using least square method for a series of data points:

$$\sum_{j=1}^{N} (\frac{1}{U_{\exp_j}} - \frac{1}{0.21 \mathrm{Re}_{s_j}^{0.8} \mathrm{Pr}_{s_j}^{0.2} k_{s_j}} - \frac{1}{2k_w} \ln(\frac{d_{out}}{d_{in}}) - \frac{1}{X \mathrm{Re}_{c_j}^m \mathrm{Pr}_{c_j}^n k_{c_j}})^2 \to 0$$

where $U_{\exp_j}$ - overall heat transfer coefficient, calculated by the expression (1) for a number of experiments $j=1...N$.

Note that the data used in the calculation only for those experiments for which the conditions are met [13]

$$\frac{|Q_{avg}^t| - |Q_s^t|}{|Q_{avg}^t|} \cdot 100\% \le 10\%, \quad \frac{|Q_{avg}^t| - |Q_c^t|}{|Q_{avg}^t|} \cdot 100\% \le 10\%$$

As a result of processing by the method of least squares data 30 experiments the semi-empirical expression for heat transfer coefficient U_{pred} is obtained

$$U_{pred} = \left[\frac{1}{0.021 \mathrm{Re}_s^{0.8} \mathrm{Pr}_s^{0.2} k_s} + \frac{1}{2k_w} \ln(\frac{d_{out}}{d_{in}}) + \frac{1}{0.569 \mathrm{Re}_c^{0.471} \mathrm{Pr}_c^{0.2} k_c} \right]^{-1} \tag{7}$$

The overall heat transfer coefficient calculated by formula (7) corresponds to the experimental values in a wide range of the heat exchanger operating parameters (1) within the error 8 % (fig. 3)

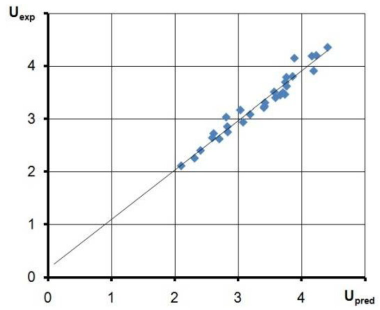


Fig. 3. The comparison of experimental and prediction overall heat transfer coefficient
◆ – Experiment; — – Approximation using least square analysis.

Often in engineering practice it is necessary to determine the outlet temperature of fluids for the already existing design of the heat exchanger and the input parameters of fluids. For such calculations it is convenient to use a semi-empirical overall heat transfer coefficient and the equation [14]

$$T_{s.out} = T_{s.in} - \delta T_s \tag{8}$$

where

$$\delta T_s = (T_{s.in} - T_{c.in}) \cdot \frac{1 - \exp\left[\frac{\pi L U_{pred}}{Q_s \rho_s C_s}\left(\frac{Q_s \rho_s C_s}{Q_c \rho_c C_c} - 1\right)\right]}{1 - \frac{Q_s \rho_s C_s}{Q_c \rho_c C_c} \exp\left[\frac{\pi L U_{pred}}{Q_s \rho_s C_s}\left(\frac{Q_s \rho_s C_s}{Q_c \rho_c C_c} - 1\right)\right]}$$

Using the expression (8) can define the characteristics of the heat exchanger in all operating modes in the form of the dependencies shown in fig. 4.

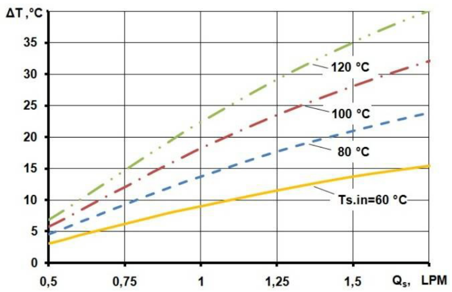


Fig. 4. The dependence of approach temperature ($\Delta T = T_{s.out} - T_{c.in}$) from sample flow rate Q_s with various inlet sample temperature $T_{s.in}$ (cooling water flow rate 9 LPM, inlet cooling water temperature 25 °C).

4. Dynamic model of heat exchanger

Heat transfer process is generally described by a system of nonlinear differential equations in partial derivatives [15, 16]. This approach represents of heat exchanger as an object with distributed parameters, but the algorithms for solving such systems are quite complex and in engineering practice are used rarely. It is appropriate to calculate the dynamics of the heat exchanger using lumped parameters [17, 18].

In this work, a cellular model of the heat exchanger is used. In this model the heat exchanger is divided into a finite number of elements. In each cell model of ideal mixing is implemented, i.e., the temperature of the liquid at the outlet of the cell is equal to the average temperature in the cell. This approach allows to simplify of calculation, and to obtain the results with acceptable accuracy.

When building a mathematical model of heat exchanger dynamics, the following assumptions are accepted: thermal resistance of the coil tube is negligible; heat exchange with the environment is missing; heat transfer in the coil tube inside core tube is low; the mode of fluid flow is established immediately.

The structure of the estimated model is presented in fig. 5.

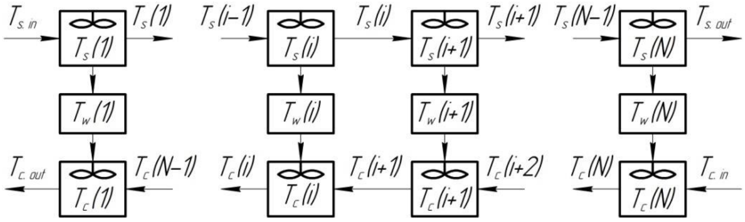


Fig. 5. The structure of the estimated model.

The system of equations describing the heat transfer process in each cell taking into account the accepted assumptions is

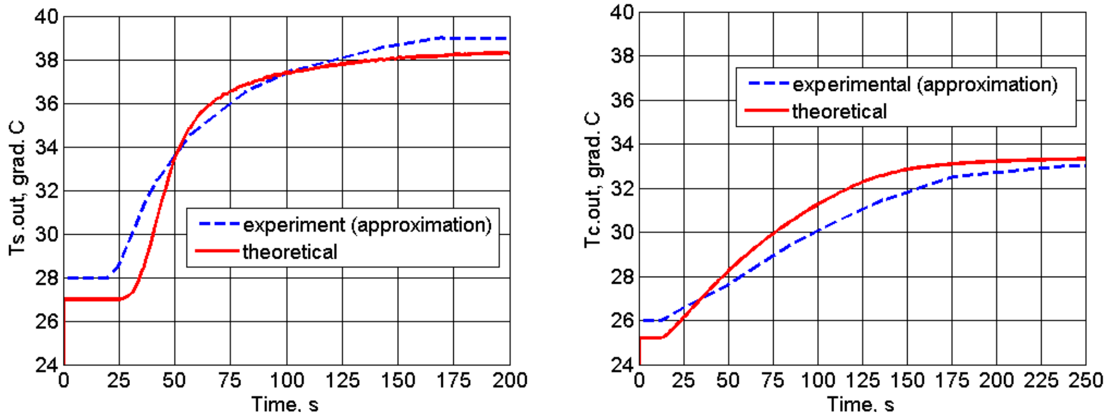
$$\left.\begin{aligned}
&\frac{V_s\rho_s(i)\,C_s(i)}{N}\frac{dT_s(i)}{dt}=Q_s\rho_s(i)C_s(i)\left[T_s(i)-T_s(i-1)\right]-\frac{h_s(i)F_{in}}{N}\left[T_s(i)-T_w(i)\right]\\
&\frac{V_c\rho_c(i)C_c(i)}{N}\frac{dT_c(i)}{dt}=Q_c\rho_c(i)C_c(i)\left[T_c(i)-T_c(i+1)\right]+\frac{h_c(i)F_{out}}{N}\left[T_w(i)-T_c(i)\right]\\
&\frac{M_wC_w}{N}\frac{dT_w(i)}{dt}=\frac{h_s(i)F_{in}}{N}\left[T_s(i)-T_w(i)\right]-\frac{h_c(i)F_{out}}{N}\left[T_w(i)-T_c(i)\right]
\end{aligned}\right\} \tag{9}$$

where V_s, V_c - respectively, sample volume and cooling water volume in heat exchanger; M_w - coil mass, C_w - coil tube specific heat capacity; i - cell number; N - number of splits.

The first and second equations of system (9) represent energy conservation law which applied to the sample and the cooling water. The third equation describes the process of energy accumulation by coil.

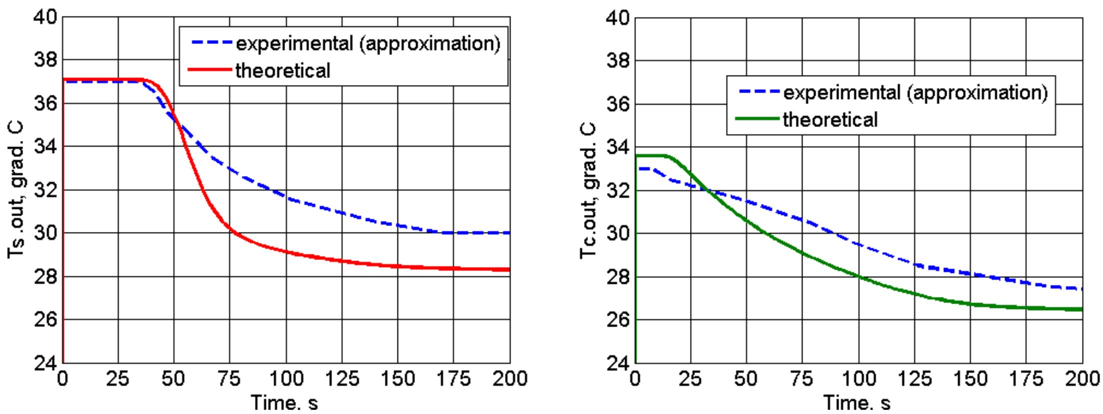
Considering that the flow regime is established immediately, the coefficients h_s и h_c are calculated using semi-empirical relationships derived in sec. 3. The dependence of thermophysical properties of liquids on temperature is interpolated from table values. To solve this problem in MATLAB/Simulink is necessary to provide a serial chain of cells, each of which implements of the algorithm for solving the system of equations (9). The temperature of the fluid when passing from one cell to another must undergo a transport delay due to the motion of the fluid channel of the heat exchanger. The use of MATLAB/Simulink allows for the later automatically convert of the heat exchanger dynamic model in C code and load it into the programmable logic controller.

In the first, the number of splits affect on accuracy of the calculations. Preliminary calculations determined that by splitting the system from $N=12$ to $N=16$ the results do not differ more than 2 %. The results heat exchanger transfer characteristics calculation with parameters at the input shown in Table 3, are shown in Fig. 6, 7.



a) b)

Fig. 6. Theoretical and experimental transient response of outlet sample temperature (a) and outlet cooling water temperature (b) for test №1.



a) b)

Fig. 7. Theoretical and experimental transient response of outlet sample temperature (a) and outlet cooling water temperature (b) for test №2.

The difference between the experimental and theoretical values can be explained by the fact that the heat exchanger shell has a heat capacity influencing on liquids temperature. For example in Fig. 7 shows that the housing of the heat exchanger continues to heat up the two liquids with a sharp decrease in the temperature of the sample at the entrance that were not considered in the calculation. As a consequence, the experimental transient response is shifted to the right.

From the analysis of the above diagrams it follows that the heat exchanger as regulation subject of mechatronic sample conditioning system is described by serial connection of an aperiodic link and link transport delay. In the future, the authors plan to conduct a series of experiments to establish the dependence of the time constant and transfer ratio of the aperiodic link and time transport lag of the heat exchanger as the object of regulation of mechatronic sample conditioning system from the input parameters at relatively small deviations of the disturbing and control actions.

5. Conclusion

An experimental set-up which includes the heaters of the sample and cooling water, measuring of the temperature and flow of sample and cooling water, electronic components processing and visualization of signals is designed.

The set-up allows to study of stationary and transient processes of heat transfer in various types of heat exchangers and their combinations, to check the efficiency of measures for improvement of heat exchangers.

Countercurrent coil heat exchanger of mechatronic sample conditioning system is studied in experimental set-up. As a result of processing of data 30 experiments by least squares method expression to determine the semi-empirical overall heat transfer coefficient is obtained. Using the semi-empirical overall heat transfer coefficient outlet temperature of the sample is calculated for a wide range of input parameters of the heat exchanger to within ±2 °C.

Based on the conditions of quasi-stationary mode of heat transfer process, the cellular model of the dynamics of the heat exchanger is compiled. It is established that when calculating the optimal number of splits must be equal to the number of coil loops. The results of the research allow asserting that the heat exchanger as regulation subject of mechatronic sample conditioning system is described by serial connection of an aperiodic link and link transport delay.

The obtained dependences can be used in the development of mechatronic sample conditioning system, operating under stationary and transient conditions, in the development of control system and algorithm of diagnosing the amount of deposits on the surface of the coil.

References

[1] PTC 19.11-2008, Steam and water sampling, conditioning, and analysis in the power cycle, ASME, 2008.
[2] D.E. Seborg, T.F. Edgar, E.A. Mellichamp, F. J. Doyle, Process Dynamics and Control, 3rd edition, John Wiley & Sons, New York, 2011.
[3] M.A. Abdelghani-Idrissi, F. Bagui, L. Estel, Analytical and experimental response time to flow rate step along a counter flow double pipe heat exchanger, International Journal of Heat and Mass Transfer. 44 (2001) 3721–3730.
[4] Franklin Joe Stermole, The dynamic response of flow forced heat exchangers, Retrospective Theses and Dissertations, 1963.
[5] Paisarn Naphon, Thermal performance and pressure drop of the helical-coil heat exchangers with and without helically crimped fins, International Communications in Heat and Mass Transfer. 31 (2007) 321-330.
[6] Patil Amar, H.M. Dange, Experimental studies of double pipe helical coil heat exchanger with micro fins, International Journal for Innovative Research in Science & Technology. 1 (5) (2014) 33-37.
[7] John W. Rose, Heat-transfer coefficients. Wilson plots and accuracy of thermal measurements, Experimental Thermal and Fluid Science. 28 (2004) 77-86.
[8] M.R. Salimpour, Heat transfer coefficients of shell and coiled tube heat exchangers, Experimental Thermal and Fluid Science. 33 (2009) 203-207.
[9] W. Witchayanuwat, S. Kheawhom, Heat transfer coefficients for particulate airflow in shell and coiled tube heat exchangers, International Scholarly and Scientific Research & Innovation, 3(5) (2009), 271-275.
[10] Pramod S. Purandarea, Parametric analysis of helical coil heat exchanger, International Journal of Engineering Research & Technology. 1 (8) (2012) 1-5.
[11] N. Jamshidi, M. Farhadi, D.D. Ganji, K. Sedighi, Experimental analysis of heat transfer enhancement in shell and helical tube heat exchangers, Applied Thermal Engineering. 51 (2013) 644-652
[12] Y.L. Arzumanov, E.M. Khalatov, V. I., A. I. Chekmazov, Design fundamentals of gas parameter control systems in automation complexes, Spektr, Moscow, 2013. (in Russian)
[13] Dr. Sattar Jaber Habeeb Al-Jabair, Ammar.A.Hussain.A.AL-taee, Experimental study of heat transfer coefficients of shell and helically coiled tube heat exchangers, Eng. &Tech. Journal. 31 (1) (2013) 172-196.
[14] Isachenko V.P., Osipova V.A. Heat transfer, Energy, Moscow, 1975.
[15] P. C. Simoes, J. Fernandes, Jose Paulo Mota, Dynamic model of a supercritical carbon dioxide heat exchanger, J. of Supercritical Fluids 35 (2005) 167–173.
[16] B. Beauchamp1 , L. Lamarche1, S. Kajl1, A dynamic model of a vertical direct expansion ground heat exchanger, RE&PQJ, 1 (6) (2008) 545-551.
[17] Shu-Xia Li, Jie-Sheng Wang, Dynamic Modeling of Steam Condenser and Design of PI Controller Based on Grey Wolf Optimizer, Mathematical Problems in Engineering, 2015.
[18] Abdulrahman A.A. Enhemed, Rosbi Bin Mamat, Dirman Hanafi, Mathematical modeling of industrial heat exchanger system, Applied Mechanics and Materials, 229-231 (2012) 2122-2124.