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# The heat exchange character methods of analysis

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**Abstract:** *The heat exchange character methods of analysis.* The equation of heat exchange obtained with the Vernotte correction gives solutions indicating the oscillatory character of the heat exchange. The nature of this has been confirmed in studies presented in this paper. The measuring position of the heat exchanger model was designed and manufactured. The temperatures courses in the resistance heating element and the corresponding passive element were studied. The results were analyzed using the methods of signal analysis. The step function (STEP) and the frequency response (Bode plots) were studied. The results indicate a great diversity of the oscillation parameters. They have a different frequencies of free vibrations and different maximum amplitudes.

*Key words*: heat exchange, oscillation, Vernotte, heat exchanger

## INTRODUCTION

Many researchers are now studied the nature of the heat exchange taking into account velocity of heat disturbance propagation. The subject of their research is described in the literature as non-Fourier heat transfer. Theoretical considerations concern the situation in which the Fourier–Kirchhoff equation, describing the heat exchange in the body, is extended for Vernotte [1961] correction and has the form:

$$\mathbf{q} = -\lambda \nabla T - \frac{a}{w^2} \frac{\partial \mathbf{q}}{\partial t} \tag{1}$$

where:
$a$ – thermal diffusivity [$m^2 \cdot s^{-1}$];
$\mathbf{q}$ – heat flux [W];
$t$ – time [s];
$T$ – temperature [°C];
$w$ – heat velocity [$m \cdot s^{-1}$];
$\lambda$ – thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$].

Occurring in the formula (1) the velocity of heat propagation is of great value. However, in many cases, the assumption that its value as equal to infinity (as in the classic Fourier equation) leads to a too large simplification. These problems are analyzed in a lot of work. There are two main directions of research. The first attempts to solve equation (1) at different boundary conditions and various parameters of the heat exchange. The nature of the heat exchange is then described as based on the obtained solutions. It can then be analyzed on the basis of numerical simulations, e.g. [Barletta and Zanchini 1996, Abdel-Hamid 1999, Mossaie 2009]. The second trend of research is related to experiments in which the nature of the heat exchange is determined for different physical situations. Solution of equation (1) is the function describing the damped oscillation, and their presence was confirmed by various researchers. The processes using the impact of very short laser pulses, described in Ai and Li [2005] and [Wang et al.

[2011], are typical situations in which this kind of character can occur. The research describing the operation of the core of a nuclear reactor (BWR – Boiling Water Reactor) in which also observed occurring oscillations is described in [Espinosa-Paredes and Espinosa-Martinez [2009] and Espinosa-Paredes et al. [2011]. The equivalent electrical model of the investigated system is proposing in Valle-Hernandez et al. [2011]. Oscillations in the course of resistance heating are described in [Wesołowski et al. [2011]. The observations for shell-and-tube, plate and model of heat exchanger are described in Piotrowska and Chochowski [2012] and Piotrowska [2013]. The model of heat exchanger as a cylindrical inductor and oscillations occurring during transient states are presented in Berezyuk et al. [2013].

Measurements of the operating heat exchangers are expensive and do not allow full control over the heat exchange parameter values. Using the heat exchanger model the measurements of temperature courses of the inlet and outlet are carried out, with the given values of the parameters of the process and the environment. Measuring position was designed to allow control of variability of these parameters and register of the results. The high frequency of measurement is required for the precise analyse of the heat exchange process. The short period of recording time is required for further applications of the results to a signal analysis. The results must be obtained from the frequency (called Shannon frequency) exceeding twice the approximation frequency.

## MATERIAL AND METHODS

The flat, spiral-shaped element, resistance heated and arranged in the air was taken as a primary side of the heat exchanger model. The shape of the element modelling the secondary side of the heat exchanger is identical, both elements are placed one above the other, which allows heat transfer through an air, taking the role of medium. It is planned to further modification and extension of the existing measuring position, allowing the use of the other media (for example, so-called transformer oil). The shapes of the elements used and their positioning are shown in Figure 1. The basic shape is made from a copper rod about 1 m long, in diameter $\varphi = 5$ mm. and the additional shapes of a rod having the same diameter, but with a half of the length.

The measurements were carried out in the laboratory room, with stabilization of the environment conditions. The studies carried out on a different measuring station, described in Piotrowska [2008], revealed the strong disturbance of the heat transfer by an air, if no cover is used. The shield used in the present measuring position has a shape of a cube (Fig. 2). The walls of the shield is made of two layers of aluminium sheet, the thermal insulation was placed between them.

The thermocouples of type K with an insulated end and with a tip diameter of 0.5 mm were used for the experiments. These thermocouples have a time constant of 0.8 s, but their small thickness is associated with certain difficulties, as described in Chochowski, Piotrowska [2005]. In order to obtain correct results of measurement of temperature, difficult even more because of the small diam-

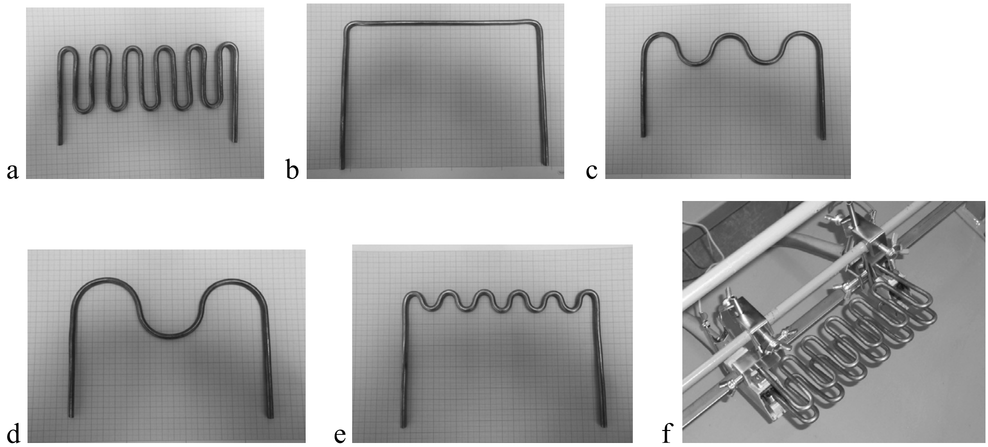

FIGURE 1. Shapes of elements used to the heat exchanger model: (a) basic shape, (b, c, d, e) – complementary shapes; (f) the positional relationship between the elements

FIGURE 2. Shield used in the measuring position

eter and smooth surface of the elements, where the temperature is measured, the final section of the thermocouple should be wrapped several times around the rod, and only the tip is fixed perpendicular to the rod. The thermocouples are connected to the Multipoint Videographic Recorder Screen Master 3000 (ABB) with 24 channels and ability to simultaneously record and archive the readings of all the channels. Reading is performed every 1 s and the courses of the measured values are visualizing in real time on the monitor. Due to the use of the described position of the resistance heating AC voltage to 230 V, it was necessary to use other measuring devices for measuring and recording the voltage and current supply. Resistance heating elements of copper is carried out with a high current intensity values (greater than 400 A), but with a low voltage (about 500 mV). This current is obtained on the secondary side of the transformer, whose primary side is energized mains voltage reduced to about 100 V (autotransformer). All current and voltage (the primary and secondary side of the transformer) are measured using gauges clamp or by direct connecting wires. All cable ends (free and clamp meters) are connected to the measurement scanner card, which is an extension of a multimeter M3500A produced by PICOTEST. Setting the parameters of measurement and registration process takes place in a computer connected to a multimeter. Diagram of the measuring position is shown in Figure 3.

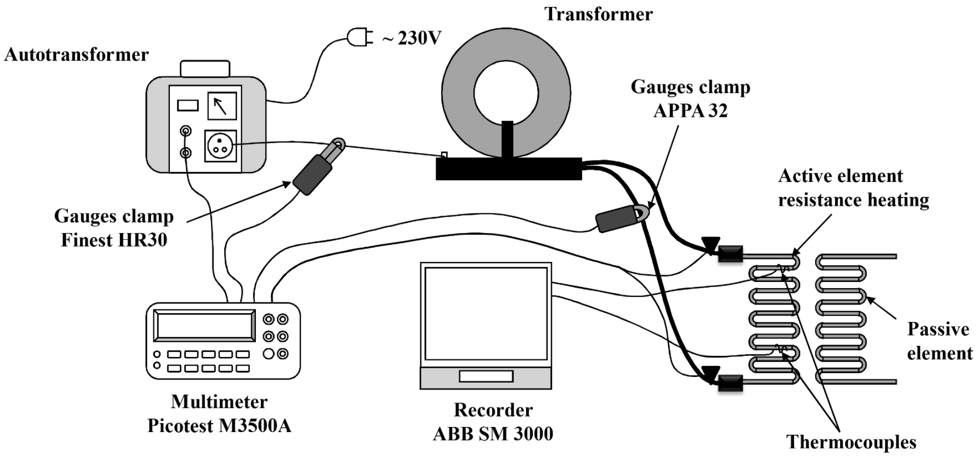


FIGURE 3. Schematic of the measuring position

Analysis of the heat exchanger model dynamics was carried out using analysis of signals. The heat exchanger is treated as an element with a single input and single output (SISO). The input is the temperature of the active side of the heat exchanger (hot side) and the output is the temperature of the passive side (cold side). The air is medium between active and passive elements (Fig. 4). Using signal analysis methods (e.g. investigation of the time and/or frequency characteristics) the character of the investigated element is determined by the analysis of the way in which an input signal is converted into an output signal. In the present case, both signals are the signals of the temperature, the temperature of the active element and passive element of the heat exchanger, respectively. The values of temperature measurement errors for thermocouples and recorder SM 3000 are as follows:

- Multipoint Videographic Recorder SM 3000: ± 0.1% of reading;
- Thermocouples Type K: –40÷375°C ±1.5°C, 375÷1000°C ±0.4%.

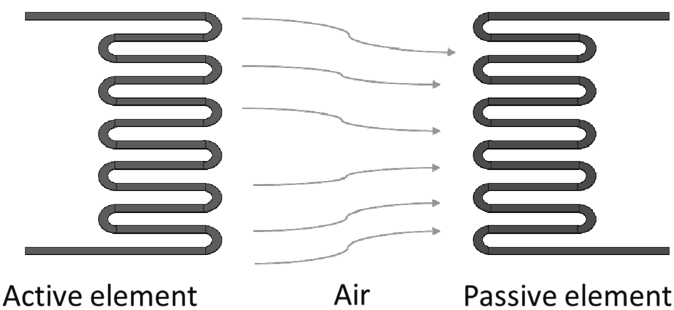


FIGURE 4. Schematic model of the heat exchanger

## RESULTS AND DISCUSSION

Analysis of the test results was carried out using two software packages: Excel and MATLAB with additional toolboxes. Using the Excel package made a preliminary analysis of the results: the course of the active and passive elements temperature, the achieved maximum values of temperature, stability time etc. Sample graphic realization of such an analysis is presented in Figure 5.

Only the use of MATLAB and the addition Signal Identification Toolbox has provided the possibility of precise analysis. After selecting the relevant parts of heating: on the primary side active element (e.g. data from Fig. 5a), on the secondary side passive (e.g. Fig. 5b) and assign them the appropriate role of the signal at the input and the output, a model was selected. The choice of models is done by selecting a particular structure and then designate the parameters (controlled by the minimized FPE – Final Prediction Error, and FIT maximized to 100). The next step is the analysis method in the domain of time and frequency, which are graphically presented as a reaction element to the step function (STEP) and Bode plots.

Figure 6 presents the courses of STEP and Bode plot for the amplitude of the measurement data, presented in Figure 5, corresponding to the heat flux equal to 104 W. Analysis of the time and frequency dependencies enables the observation of the nature of the process (e.g. inertial or oscillating). In the example above, it was confirmed oscillatory character of the investigated phenomenon, as it was observed by other investigators in vari-

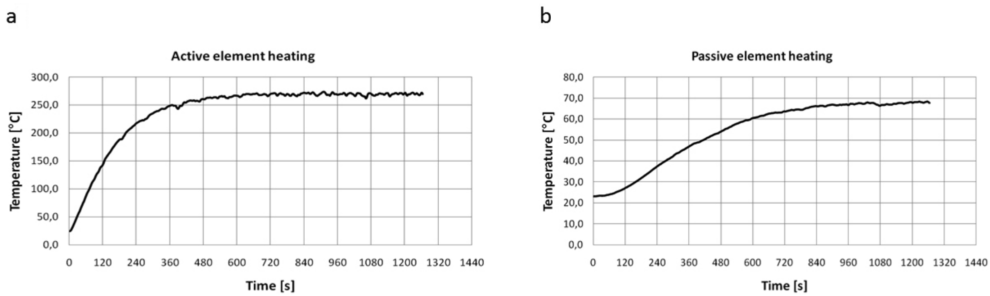


FIGURE 5. The values of the temperature of the heat exchanger elements: (a) active, (b) passive

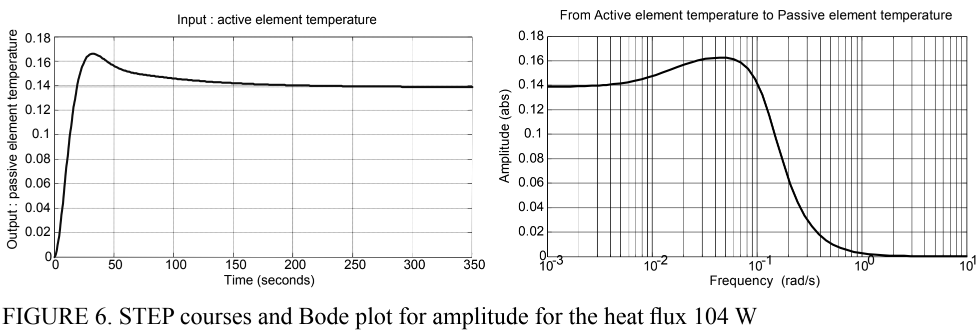


FIGURE 6. STEP courses and Bode plot for amplitude for the heat flux 104 W

ous heat exchange processes. The following figures show similar characteristics for heating a heat flux greater value. These values are respectively equal to 148 W for Figure 7 and 206 W for Figure 8. The oscillating nature of the course, possible to observe already on the STEP course, shows great diversity, it is possible to evaluate only after analyzing the Bode plots. rses and Bode plot for amplitude for the heat flux 206 W

tude indicates increasing the intensity of the emerging vibrations. Decreasing the frequency may indicate a slower vibration damping.

## CONCLUSIONS

The detailed analysis of the heat exchange in the heat exchanger model confirmed their oscillatory character in

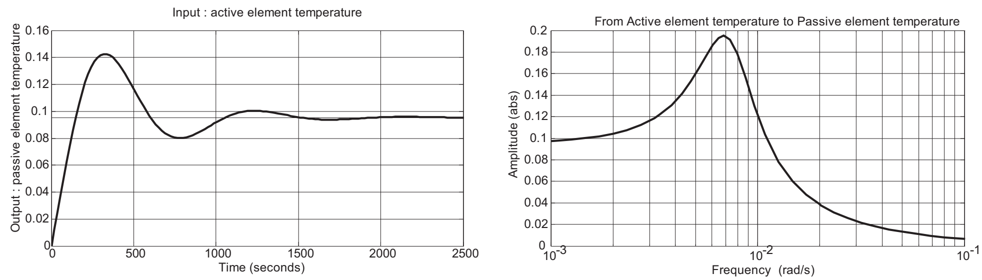


FIGURE 7. STEP courses and Bode plot for amplitude for the heat flux 148 W

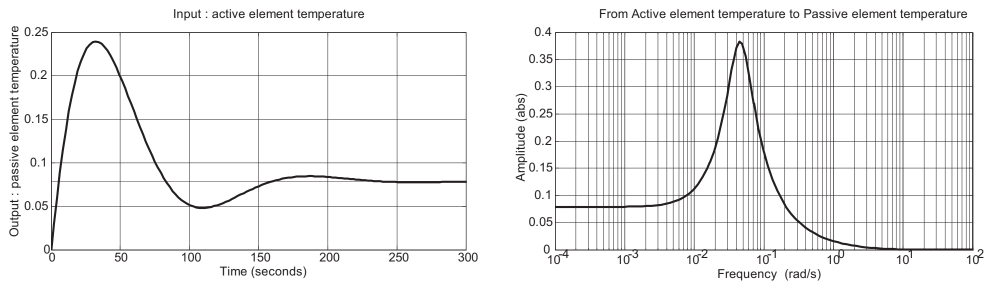


FIGURE 8. STEP courses and Bode plot for amplitude for the heat flux 206 W

Comparison of data From Figures 6, 7 and 8 points to the growing value of the amplitude of the oscillation with increasing values of heat flux 0.163, 0.196 and 0.383, respectively). The frequency changes from 0.05 rad $\cdot$ s $^{-1}$ at the heat flow equal to 104 W by a value of 0.007 for $q$ = 148 W, up to the value of 0.044 for the largest of the analyzed heat flows equal to 206 W. The increasing ampli-

the transient states. The measurement position planned for this purpose and the heat exchanger model were described in the presented paper. The transient response (STEP) and the frequency response (Bode diagram) are tools using for the detailed investigation of the heat exchange phenomenon. The increasing amplitude may indicate increasing the intensity of the emerging vibrations. However, the study did not allow to find a relationship between the heat flux and the frequency of occurring oscillations. This requires further analysis, because these are vibrations damped. The frequency of damped oscillations is a function of vibration (free) and damping factor. The next analyzes will attempt to determine the frequency of free vibration and find their relationship with the value of the heat flux.

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**Streszczenie:** *Metody analizy charakteru wymiany ciepła.* Celem pracy jest analiza charakteru przebiegu wymiany ciepłą w modelowym wymienniku ciepła, uwzględniająca zwłaszcza pojawiające się oscylacje temperatury. Opisano szczegółowo zaprojektowane i wykonane stanowisko pomiarowe. Przedstawiono metodykę pomiarów oraz metodykę analizy uwzględniającej charakterystyki skokowe i częstotliwościowe układu. Opisano modelowy wymiennik ciepła oraz jego odniesienie do warunków rzeczywistych. Przestawiono przykładowe wyniki analiz, wskazujące na duże zróżnicowanie charakteru wymiany ciepła w badanym wymienniku modelowym. Zaobserwowano zależność tego charakteru od wartości wymienianego strumienia ciepła.

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