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Analysis of temperature oscillations parameters of heat exchanging systems

Ewa Piotrowska *, Piotr Skowroński

Fundamental Engineering Department, Warsaw University of Life Sciences, Warsaw, Poland

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ABSTRACT

The oscillations of temperature in the transient states of heat exchanging systems were investigated. The experiments were carried out using a heat exchanger model. The resistance heating cooper rod was an active side and an element (identical in shape) situated above them, but without contact, was the passive side of the model heat exchanger. During the experiments, the oscillatory character of the changing temperature of the passive element versus the active element was observed. The following parameters of these oscillations were investigated: frequency of free oscillations, damping coefficient and relative damping coefficient. The values of heat flux, distances between elements and their shapes (in pair) were changed and their influence on the parameters of the oscillations were investigated. The value of heat flux has the greatest impact on the values of all the examined oscillation parameters; there is an increase in the value of all the parameters along with the increase in the value of the heat flux. There was no influence of the shape of the element on the values of the investigated parameters. The values of the frequency of free oscillations and the damping coefficient decrease at an increasing distance between them, but the relative damping coefficient increases. These dependencies indicate the complex nature of the studied oscillations.

1. Introduction

The oscillations of temperature in the transient states of heat exchanging systems have been observed by various researchers. The dynamics of a plate heat exchanger as a part of a hybrid system is described in [1]. The author observed temperature oscillations in transient states. Analogous oscillations for various types of heat exchangers (plate, shell-and-tube) have been described in [2]. In paper [3], the course of temperature changes in a heat exchanger was analyzed, in which heat exchange occurs between mediums with dynamically variable properties (commonly found e.g. in the food industry, such as milk). The simulations showed the appearance of temperature oscillations. A team of authors (Rao, Maiti, Das) published a series of three articles: [4–6], in which they studied heat exchangers. In article [4] they investigated the reactions of the exchanger on various excitations, in article [5] they defined the properties of various types of heat exchangers. In both articles, temperature oscillations are observed in numerical simulations. In article [6], the dynamics of pressure field, flow velocity and temperature in steady states and in the transient state were examined. Temperature oscillations in transient states have been also observed. An explanation of the nature of the observed phenomena is proposed by many authors. The theoretical basis was introduced in [7] and [8]. Formulation in the currently known form as the non-Fourier heat conduction was carried out in Vernotte [9] and Cattaneo [10] and described as the Cattaneo-Vernotte correction. The equation, after appropriate transformations, takes the form:

$$\frac{\partial T}{\partial t} + \tau \frac{\partial^2 T}{\partial t^2} = a_t \nabla^2 T \quad (1)$$

This equation includes some delay, relaxation time τ, with which the temperature change at a certain point propagates to other points of the body. In the classic Fourier equation, the change is made at every point in the body at the same moment. Due to the similarity of the phenomenon to the propagation of any wave, e.g. acoustic, in the literature the term "second sound wave" is also used, which was introduced in work [11]. Due to the important role of the concept of relaxation time in the analyzed processes, a large part of researchers focus on determining the value of τ. For homogeneous metals, liquids and gases it has a value of 10^{-8} to 10^{-12} s [12], while its value is significant for mixtures or materials with a non-homogeneous structure, reaching values from 10 to 54 s [13].

* Corresponding author at: Warsaw University of Life Sciences, ul. Nowoursynowska 164, 02-787 Warsaw, Poland.

E-mail address: ewa_piotrowska@sggw.pl (E. Piotrowska).

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Nomenclature

Symbol	Quantity
A	maximal amplitude in function (7) and (8)
A, B, D, E	shapes of elements, presented in Fig. 4
a_t	thermal diffusivity
BJ	Box-Jenkins type model
BJ22221	Box-Jenkins model defined by 2-degree polynomials
$B(q)$, $C(q)$, $D(q)$, $F(q)$	polynomials in BJ equation
$e(t)$	disturbance function
FIT, FPE	valuations of models, described by (5) and (6)
I	current
j	imaginary unit
k	the number of the model coefficients
n	the number of the experimental points
P	thermal power
q	discrete variable in BJ equation
t	time
T	temperature
U	voltage
u_B	standard uncertainty of type B
x	point in Fig. 3
$x(t)$	temperature inlet
y	point in Fig. 3
$X(j\omega)$	Fourier transformation of the function $x(t)$
$y_1, \ldots, y_n$	the values of the measurements
$y_{m1}, \ldots, y_{mn}$	the values calculated from the model
$y(t)$	temperature outlet
z	point in Fig. 3

Greek symbols

α	damping coefficient
τ	delay time
ω	the frequency of damped oscillations
ω_0	the frequency of free oscillations
ζ	relative damping coefficient

Indexes

const	constant value
mean	mean value
max	maximum value
r	recorder
th	thermocouples

Analytical considerations are based on various methods of solving these problems. In [14] the theory of thermoelasticity is analyzed analytically and numerically. This is based on the analogy between heat conduction and the linear mechanical model of elasticity.

In work [15], what is called extended thermodynamics and its consequences for the behavior of entropy are analyzed. In [16], simulated heat exchange courses were compared using models based on two theories: the Cattaneo-Vernotte theory and the thermo-mass theory. In works [17] and [18], the authors present considerations regarding the influence of the numerical method used to solve the problem of the form of results obtained as a result of simulation. In work [19], the analytical and numerical solution of the problem of non-Fourier heat conduction in a finite medium with a constant source of heat was compared, obtaining a satisfactory agreement of results.

Solution of the non-Fourier heat conduction problem often led to temperature oscillations. These oscillations are tested on the basis of analytical solutions of hyperbolic equations in work [20]. A generalized thermoelasticity theory was used to solve the 2-dimensional thermal problem in work [21]. In [22], analytical solutions of hyperbolic equations were analyzed, regarding a pulsating laser as a heat source or periodic heating. The temperature oscillations appeared as a result. The influence of the relaxation time on the course of heat exchange is described in [23], showing that only for the zero value of relaxation time is the course inertial, in other cases it is oscillatory.

Analysis of thermal cracking in finite layers [24] and in layered composite materials [25] was carried out taking into account the hyperbolic heat exchange conditions. The obtained results were compared with the results obtained assuming the classic Fourier heat exchange. The conditions of hyperbolic heat exchange caused temperature oscillations.

Analysis of material properties was carried out in [26] and [27]. The authors of work [26] studied the behavior of the Shape Memory Alloys (SMA), developing a model based on the non-Fourier heat transfer, then using simulations. The authors of paper [27] described the course of heat exchange in the granular material, considering the cases of Fourier and non-Fourier heat transfer. A similar study of heat exchange considering these two cases was carried out by the authors in [28] for a flat collector absorber. Temperature oscillations have been also obtained by the authors of the work [29], studying and comparing with each other several models describing the heat exchange in multilayered media. The authors of work [30] built the model and analyze its properties numerically. The subject of their research was a piezoelectric rod considered under hyperbolic heat transfer conditions. As a result of numerical simulations, the authors also observed oscillations.

In [31], the authors examined heat exchangers and compared two models – parabolic (classic) and hyperbolic (non-Fourier) in the description of axial temperature profiles in a shell-and-tube heat exchanger. Calculation results indicate a better fit of the hyperbolic model. In [32], numerical simulations of the temperature course in a counter-current heat exchanger were carried out, observing temperature oscillations.

In order to be able to analyze the phenomenon of the appearance of temperature oscillations, a measurement stand was made on which the model of the heat exchanger was tested. This made it possible to change and fully control the process parameters in order to analyze their impact on the parameters of the oscillations that arise.

2. Material and methods

The measurement stand is presented in Fig. 1. The heat exchanger is modelled by two elements: active (transferring heat) and passive (collecting heat). The element modelling the primary (active) side of the heat exchanger was made of copper rod with a diameter of 5 mm. The element modelling the secondary (passive) side of the heat exchanger was identical in shape and dimensions to the active element and was placed directly above the active element, without contact between them (Fig. 1). The medium was air. Details of the construction of the elements appear in the Appendix A. The active element was resistance-heated. Heat transfer between the active and passive elements was analyzed for different values of heat flux, determined by voltage and current values in the power supply of the primary side. Temperatures were measured at six points of each element, situated one above the other, using coated K-type thermocouples (insulated, 0.5 mm