Determination of thermal diffusivity for rigid body at non-stationary thermal conditions

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Abstract. In this paper we present a new method for calculation of the thermal diffusivity of a rigid body. This method is based on contactless thermal treatment of the examined construction material by an infrared radiation source. Further we analytically find one-dimensional non-stationary temperature field of a rigid body during its heating using data from thermal elements. The calculation of the thermal diffusivity of a rigid body is made using differential heat equation.

Introduction

Thermal diffusivity \( a_t \) is a heat diffusion parameter, which is used for analytical description of non-stationary processes of heat transfer in various nature objects: rigid bodies, liquid and gaseous mediums [1].

Heat exchange theory [2,3] says that differential heat equation (in the absence of internal heat sources) is the following:

\[ \frac{\partial t}{\partial \tau} = a_t \nabla^2 t \]  

(1)

where \( a_t \) is proportionality factor in linear, homogeneous, second order partial differential equation, m\(^2\)/s.
Thus, it is essential to know thermal diffusivity $a_t$ to solve equation (1) and to investigate evolution of non-stationary temperature field of a rigid body in space and time. For example, the genuine solution of the heat equation (1) using heat source technique includes thermal-physical coefficient $a_t$ [4].

In construction thermal physics finding the solution of equation (1) and determination of coefficient are of current interest, as heat transfer through enclosures is always non-stationary. Ambient temperature, solar radiation intensity, wind force and direction are continuously changing, as well as indoor temperature, which is regulated by heating system and additional internal heat inputs. Fluctuations of temperature, energy and mass flows, which occur at ambient air separated by enclosures, result in variation of thermal behavior of the building itself [5].

Besides this, in construction heat engineering consideration of heat transfer at non-stationary conditions is essential when solving the following problems: determination of inner temperature fluctuation amplitudes related to irregularity of heat emission by heating system; calculation of temperature oscillation decay in enclosures caused by ambient air temperature alteration or solar radiation impact on wall surface; warming up and cooling down of massive enclosures; improving the safety of cast-in-place construction at adverse climatic conditions, reduce of energy consumption, etc [6–16]. There are a lot of literature sources concerning various methods and devices for thermal diffusivity determination of construction materials [17–25].

Classical method of a-calorimeter is based on regularities of warming up (cooling down) of material sample under study at intensive heat exchange medium with $Bi \rightarrow \infty$. For regular thermal conditions the unknown value of thermal diffusivity $a_t$ is linearly dependent on material cool down rate [26]. Cool down rate is denoted according to differential thermocouple. One of its joints is located at central area of the sample, another one is located at intensive heat exchange medium. Proportionality factor, which mathematically connects thermal diffusivity coefficient of a rigid body with cool down rate depends on geometrical parameters of the sample under study [27].

The disadvantage of this method is technical complexity of organization and carrying out theses thermal measurements. For implementation of this method one must have an a-calorimeter preheated to high temperatures in a dry cupboard and a liquid thermostat with intensive medium mixing, which provides the following condition: $Bi \rightarrow \infty$.

Contact methods based on thermal non-destructive testing are the modern techniques for determination of material thermal diffusivity. The main feature of these methods, in comparison with classical ones, is the contact of temperature gauges with particular surface areas of the sample under study. Material thermal diffusivity determination is based on sample surface temperature measurements at radiative-convective warm up. These measurements are performed for two key points: edge and mid-facet. The temperature complex is calculated from a plot of sample heating. Material thermal diffusivity is calculated from the known distance between temperature measurement points taking into account temperature complex rate of change [18].

This method is nearly free of disadvantages. However, there is a need for heating chambers which fit the sample size, and this adds complexity for its practical implementation.

This work presents a special combined experimental and computational method for determination of a rigid body thermal diffusivity. This method excludes the main disadvantage of the mentioned-above techniques, namely: formation of non-stationary thermal conditions using complex and overall heat sources.

**Materials and Methods**

Fig.1 presents a schematic diagram for combined experimental and computational method for determination of a rigid body thermal diffusivity at non-stationary thermal conditions.
Infra red radiation source 1 is powered by electricity. The investigated rectangularly shaped rigid body 2 with \( \delta = 2h \) thickness is placed at a distance from Infra red radiation source 1. The central axis of infra red radiation source 1 and rigid body 2 are coincident. The thermal elements 3 are fixed at interval \( x \in [0, h] \) of a rigid body 2: \( T_0, T_1, T_2 \) are placed at points with coordinates \( x = 0, \frac{h}{2} \) and \( h \), respectively. These points are connected to a PC (isn't shown here) through analog to digital converter (ADC) and converter (aren't shown here).

At initial time \( \tau = 0 \) the temperature field of a rigid body 2 is homogeneous and is equal to ambient air temperature. At the start point electrical energy is transferred to infra red radiation source 1, where it is converted to electromagnetic radiation of \( q \) intensity. Then it is non-contact and indestructibly transferred to a front-face surface (FFS) of the rigid body 2. Radiation energy flux \( q \), which uniformly falls on FFS of the examined sample 2, is converted to internal energy, which is spent for heating of the whole rigid body 2. Infra red radiation source 1 uniformly irradiates FFS of the examined sample 2, consequently, temperature alteration takes place only along the axis 0X. Temperature remains the same for 0Y and 0Z directions, i.e. \( V_x, t = V_z, t = 0 \). Temperature alteration along the axis 0X is registered by thermal elements 3: \( T_0, T_1 \) and \( T_2 \), which transfer information through ADC and converter to nonvolatile computer memory.

Non-stationary thermal conditions duration of the rigid body 2 is determined according to the expression:

\[
\tau'_{\text{max}} = \frac{\delta^2}{a'_t} 
\]

where \( \delta \) is sample thickness, m; \( a'_t \) is preset thermal diffusivity, \( m^2/s \).

Let us assume that temperature field of a rigid body 2 is known from thermal element data. So its equation is \( t = t(x, \tau) \) for heating period \( \tau \in [0, \tau_{\text{nst}}] \), where \( \tau_{\text{nst}} \) is a segment of non-stationary thermal
conditions at sample heating, and \( \tau_{\text{nst}} \leq \tau_{\text{max}}' \). So, thermal diffusivity of a rigid body 2 can be found from differential heat equation (1), \( \text{m}^2/\text{s}^{-1} \):

\[
a_t = \frac{\left( \frac{\partial t(x, \tau)}{\partial \tau} \right)_{x=0}}{\left( \frac{\partial^2 t(x, \tau)}{\partial x^2} \right)_{x=0}}
\]

where \( t \) is temperature of a rigid body, \( ^\circ \text{C} \); \( x \) is coordinate, \( \text{m} \); \( \tau \) is time, \( \text{s} \).

**Results and Discussion**

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Let us use this method to determine thermal diffusivity of a silicate brick M150 (Russian State Standard GOST 379-95) with thickness \( \delta = 0.12 \text{ m} \) (\( h = 0.06 \text{ m} \)), Fig.2.

![Laboratory-experimental setup](image)

Fig. 2 Laboratory-experimental setup "energy source and receiver" for determination of construction material thermal diffusivity. 1 - electrical infra red source; 2 - silicate brick, 3 - a system of chromel-alumel thermocouples

Fig. 2 shows that chromel-alumel thermocouple junctions 3: T0, T1, T2 are fixed in M150 silicate brick 2. The junctions are located along the central axis at points with coordinates \( x = 0 \), 0.03 and 0.06 m, respectively. Electrical infrared source 1 is Ecoline 10 R lamp of a total power \( 3 \text{ kW} \), which is located at a distance of 0.6 m from the silicate brick FFS.

The preset value of silicate brick 2 thermal diffusivity is \( a'_{\text{t}} = 5.49 \cdot 10^{-7} \text{ m}^2/\text{s} \) [28]. According to the expression (2), heating period duration is \( \tau_{\text{max}}' = 26218 \text{ s} \). Experiment data is \( \tau_{\text{max}} = 31560 \text{ s} \) (Fig.3); average temperature alteration in interval \( x \in [0; 0.06] \text{ m} \) and time range \( \tau \in [26218; 31560] \text{ s} \) according to chromel-alumel thermocouples 3 was \( \pm 2.5 ^\circ \text{C} \). Inaccuracy of measurements is \( 0.60 ^\circ \text{C} \), thus the obtained result is acceptable.
Fig 3. To the determination of non-stationary thermal conditions duration for silicate brick

Let us consider thermal conditions for silicate brick for interval $x \in [0; 0.06]$ m and time range $\tau_{nst} \in [0; 15000]$ s. Fig. 4 presents temperature field of the silicate brick 2 of the form $t = f(x, \tau)$ at $x \in [0; 0.06]$ m and $\tau_{nst} \in [0; 15000]$ s, drawn based on experimental data.

Functional chart, which describes heating regime for silicate brick 2 at $x \in [0; 0.06]$ m and $\tau_{nst} \in [0; 15000]$ s is the following, °C:

$$t = a + b \tau + cx + dx^2 + ex^3 + fx^4 + gx^5 + hx^6 + ix^7 + jx^8, \quad R^2 = 0.9927,$$

where $a = 22.830014$, $b = 0.01062335$, $c = -481.12022$, $d = -6.1933549 \cdot 10^{-7}$, $e = 10518.343$, $f = -0.014857501$, $g = 1.2080758 \cdot 10^{-11}$, $h = -79288.783$, $i = -0.44211261$, $j = 2.4679544 \cdot 10^{-6}$ are equation parameters.

Fig. 4 Temperature field of a silicate brick for non-stationary thermal conditions
Fig. 5 presents evolution of the silicate brick thermal diffusivity in time at heating conditions at
\( x = 0 \) and \( \tau_{nst} \in [0;15000] \) s of \( a_t = a_t(\tau) \cdot 10^{-7}, \text{m}^2/\text{s} \):

\[
a_t = 5 \cdot 10^{-9} \tau^2 - 0.0004\tau + 5.0896, \quad R^2 = 0.9997, \tag{5}
\]

![Fig. 5 Thermal diffusivity evolution in time for silicate brick](image)

As it seen from figure 5, when thermal condition of a silicate brick approaches stationary condition,
the thermal diffusivity tends to zero. According to the expression (5), the thermal diffusivity \( a_t \) of
silicate brick at initial time \( \tau = 0 \) is equal to \( 5.09 \cdot 10^{-7} \text{m}^2/\text{s} \) (at brick temperature equal to that of ambient air \( t = 19.7 \, ^\circ\text{C} \)).

Conclusions

This work presents a new method for determination of rigid body thermal diffusivity at non-
stationary thermal condition. This method takes into account advantages and disadvantages of
classical techniques for determination of thermal-physical properties of construction materials. The
practical implementation of this method was performed for M150 silicate brick (Russian State
Standard GOST 379-95). Combined experiments and calculation result in material thermal diffusivity
\( 5.09 \cdot 10^{-7} \text{m}^2/\text{s} \), determined for ambient air temperature. This result agrees with specified value
\( 5.49 \cdot 10^{-7} \text{m}^2/\text{s} \) presented in [29] and data from other sources: \( 5.5 \cdot 10^{-7} \text{m}^2/\text{s} \) [6], \( 5.8 \cdot 10^{-7} \text{m}^2/\text{s} \)
[28]. The developed method can be applicable in construction and heat power engineering when
testing homogeneous construction units, thermal conductive and thermal insulating materials.

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