USE OF HOLOGRAPHIC INTERFEROMETRY FOR MONITORING HEAT TRANSFER

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In the paper is described possibility of holographic interferometry in research of heat transfer above samples. Experiments with utilization of this method enable to explain many of actions going in environment and in phase interface between material and this environment in transport of heat. The presented experiments are aimed at verifying the possibilities of safe thermal loading of wood using with metal protective plate.

KEYWORDS

Heat transfer, wood, holographic interferometry

1 INTRODUCTION

Wood is a natural material that has a very wide range of uses. Due to its advantageous physical and aesthetic properties, it is used both indoors and outdoors. It is often necessary to install various electrical devices, instruments and appliances on a wooden surface, e.g. in wooden houses, wooden tiles, furniture parts, etc. During the operation of electrical equipment, heat is generated and wood is a flammable material and this means the risk of ignition or damage to the wooden base or entire buildings.

According to STN EN 13501-1, it is possible to classify individual types of wood into three classes of flammability groups according to the reaction to fire according to the table:

Degree of flammability	Class	Kind of wood
hardly flammable	C	oak and beech wood, sawdust boards ...
moderately flammable	D, E	spruce, fir and pine wood, chipboard, cork parquet ...
easily flammable	F	poplar wood ...

Table 1. Degrees of wood flammability

When installing electrical wiring (sockets, switches, junction boxes ...) and appliances (lights, heat sources ...) it is necessary to separate these objects from the flammable wood surface with a sufficiently large air gap or non-flammable pad over the entire contact area.

Many authors study heat transfer by wood [Zhang 2013, Deliiski 2016, Younsi 2007].

To investigate the effect of heat load and heat field distribution on the surface and over combustible material, we performed experiments using wooden test specimens without the use of a protective device and with a protective metal pad on the side of the heat source. We used the method of holographic interferometry to visualize the thermal field [Brodnianska 2019].

2 HEAT TRANSFER

The issue of heat transfer is a current topic in terms of energy savings, finances, and a positive approach to the environment.

Heat transfer between substances or their particles occurs in presence of a temperature difference [Pavelek 2009].

Heat transfer by conduction takes place in bodies (solids) and in stationary fluids (liquids or gases). It takes place by transfer of molecular energy between substances or their particles which come into contact and have different temperatures. The molecules do not move, they just oscillate and transfer energy to a cooler surface. The heat flux density decreases in the direction of decreasing temperature.

The heat transfer by conduction through a simple planar wall is shown in Figure 1.

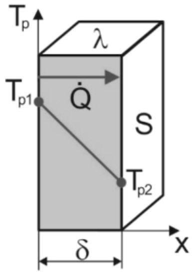

Figure 1. Heat transfer by conduction through a simple planar wall – basic scheme [Brodnianska 2018]

$\dot{Q}$ – heat flux [W] passing through a planar wall, λ – thermal conductivity coefficient [W.m^{-1}.K^{-1}], S – heat exchange surface [m^2], T_{p1}, T_{p2} – wall surface temperatures [K], δ – wall thickness [m]

Calculation of the heat flux density through a simple plane is based on Fourier's law:

$$\dot{q} = -\lambda \cdot \operatorname{grad} T = -\lambda \cdot \frac{\partial T}{\partial x} = \frac{\lambda \cdot (T_{p1} - T_{p2})}{\delta} \ [W.m^{-2}] \quad (1)$$

The heat flow passing through a planar wall with a heat exchange surface *S* is calculated by:

$$\dot{Q} = \frac{\lambda \cdot S \cdot (T_{p1} - T_{p2})}{\delta} \ [W] \quad (2)$$

Thermal resistance of the wall (resistance to heat conduction) can be calculated by equation:

$$R = \frac{\delta}{\lambda \cdot S} \ [W^{-1}.K] \quad (3)$$

The heat transfer through a planar wall, composed of n layers, is shown in Figure 2.

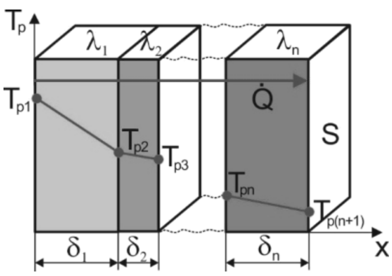

Figure 2. Heat transfer by conduction through a planar wall composed of n layers [Brodnianska 2018]

Q – heat flux [W] passing through a planar wall, λ_1, λ_2,… λ_n – thermal conductivity coefficients [Wm^{-1}.K^{-1}], S – heat exchange surface [m^2], T_{p1}, T_{p2},… $T_{p(n+1)}$ – wall surface temperatures [K], δ_1, δ_2,… δ_n, – wall thicknesses [m]

The resulting heat flux, which passes through a compound plane wall, is calculated as:

$$\dot{Q} = \frac{S \cdot \left(T_{p1} - T_{p(n+1)}\right)}{\sum_{i=1}^{i=n} \frac{\delta_i}{\lambda_i}} \qquad [W] \tag{4}$$

3 METHOD OF HOLOGRAPHIC INTERFEROMETRY

The study of many physical processes can become much easier in case of their visualization. The method of holographic interferometry was selected to watch temperature fields. It enables, using recorded field of refractive index of investigated environment, to get a complete image and idea of quantity and shape of a temperature field in a certain time and consequently to analyse and interpretate the watched effect.

A Mach-Zehnder interferometer (Figure 3) was used to visualize the temperature fields.

As the environment is in most cases transparent, it is not possible to observe these phenomena with the naked eye. By changing the temperature variables of the environment, the physical quantities of the environment change, which represents optical inhomogeneity – the refractive index changes. Deformations can be recorded, visualized and temperature profiles over the heated material can be recorded using holographic interferometry.

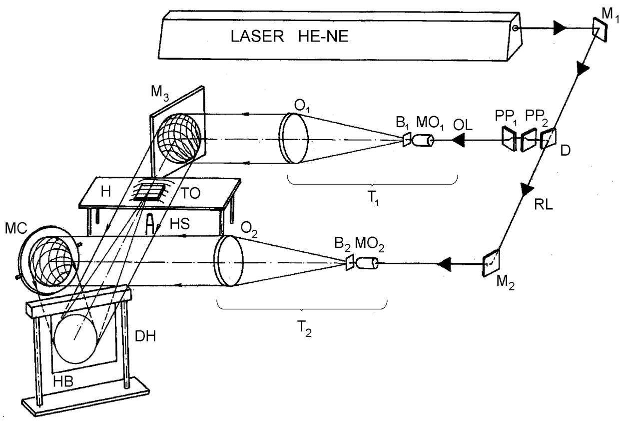

Figure 3. Scheme of the holographic variable – one-wave Mach-Zehnder interferometer

OL – object line, RL – reference line, D – divider, HB – holographic board, DH – holder of holographic board, MC – mirror in cardan suspension, O_1, O_2 – object lenses, M_1, M_2, M_3 – mirrors, B_1, B_2 – perforated blinds, MO_1, MO_2 – microscopic object lenses, PP_1, PP_2 – planparallel plates, T_1, T_2 – telescopic systems, TO – testing object, H – holder for gripping the testing object, HS – heating source

4 MATERIAL

The experiments were performed on spruce wood test specimens measuring 40 x 40 x 10 mm (5 samples), on aluminium measuring 40 x 40 x 3 mm (2 samples) and on wooden test specimens under which inserted aluminium plate (Figure 4) (5 samples).

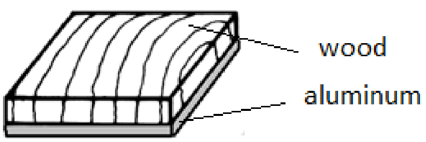

Figure 4. Test specimen with non-combustible pad

The measurement scheme is shown in Figure 5.

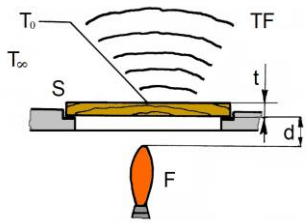

Figure 5. The measurement scheme

T_0 – temperature on the sample surface, T_∞ – ambient temperature, TF – measured temperature field, S – sample, F - flame, t – thickness of the test body, d – distance of the flame from the sample

5 RESULTS

Heat transfer occurs when the samples are thermally loaded. A thermal boundary layer is formed in close proximity above the sample, which gradually grows.

Numerical evaluation of holographic interferogram recordings of temperature fields above test specimens are recorded in Tables 2–4.

Dist	2 min	4 min	6 min	8 min	10 min	12 min
0	0.1	0.3	1.2	1.8	1.2	2.7
2	0.8	1.0	1.9	2.3	2.1	3.4
4	1.0	1.6	2.5	3.1	2.7	3.7
6	1.3	1.9	2.9	3.6	3.3	3.9
8	1.5	2.4	3.2	4.1	3.8	4.2
10	1.7	2.8	3.6	4.5	4.3	4.7
12	1.9	2.9	4.1	6.4	4.7	4.8
14	2.1	3.3	4.3	6.9	5.3	5.2
16	2.3	4.2	4.2	6.5	6.1	5.6
18	2.0	4.8	4.0	6.0	7.7	7.4
20	1.7	5.6	3.8	5.6	10.1	12.2
22	1.5	5.2	3.6	5.2	9.6	15.5
24	1.3	3.9	3.3	4.8	5.6	16.7
26	1.1	3.0	3.0	4.7	4.3	16.4
28	0.9	2.6	2.6	4.1	3.7	11.0
30	0.7	2.0	2.3	3.4	3.1	6.8
32	0.5	1.1	1.8	2.8	2.5	4.9
34	0.5	0.6	1.5	1.8	1.6	3.7
36	0.5	0.1	1.2	0.0	0.7	2.2
38	0.2	0.0	0.6		0.0	1.7
40	0.0	0.0	0.4		0.0	0.3

Table 2. Isotherms for 43 °C – spruce

Dist	2 min	4 min	6 min	8 min	10 min	12 min	14 min
0		0.0	0.7	0.5	1.5	3.7	1.7
2		0.5	1.9	1.5	2.6	3.6	2.7
4		0.7	1.6	2.2	2.7	2.6	3.1
6		0.8	1.2	2.5	2.9	2.3	2.9
8		1.0	1.4	2.7	3.0	2.1	2.8
10		1.2	1.7	3.0	2.7	2.1	3.0
12		1.3	2.1	3.3	2.6	2.3	3.9
14		1.3	2.2	3.6	2.6	2.5	4.9
16		1.4	2.5	3.7	2.6	2.8	5.3
18		1.4	2.7	3.2	3.0	3.2	4.7
20		1.5	3.2	2.8	3.1	3.3	4.4
22		1.6	3.3	2.6	3.0	3.7	4.2
24		1.5	2.9	2.6	3.0	3.7	3.9
26		1.3	2.4	2.4	2.8	3.4	3.8
28		1.1	2.3	2.3	2.7	3.0	3.7
30		0.8	2.1	2.2	2.7	3.0	3.7

32		0.7	2.2	2.1	2.5	2.8	3.7
34		0.6	1.4	2.2	2.1	2.7	3.9
36		0.5	1.4	2.3	1.9	2.5	3.1
38		0.3	1.1	1.2	0.9	2.0	2.0
40		0.0	0.0	0.0	0.0	1.9	0.9

Table 3. Isotherms for 43 ° C – aluminium

Dist	2 min	4 min	6 min	8 min	10 min	12 min	14 min
0	0.0	0.0	0.3	1.0	0.4	0.8	0.5
2	0.1	0.2	0.8	1.7	1.0	1.2	0.8
4	0.2	0.6	1.5	1.9	1.5	1.6	1.2
6	0.4	1.0	2.0	2.0	2.0	2.3	1.5
8	0.4	1.4	2.4	2.0	2.3	2.8	2.0
10	0.4	1.7	2.4	2.0	2.5	3.0	1.9
12	0.4	1.8	2.6	1.9	2.5	3.1	2.1
14	0.4	1.9	2.7	2.0	2.5	2.9	2.2
16	0.4	2.0	2.6	2.2	2.4	2.6	2.3
18	0.4	2.0	2.5	2.2	2.2	2.3	2.4
20	0.4	1.9	2.1	2.3	2.0	2.1	2.4
22	0.4	1.5	1.9	2.1	1.9	2.1	2.4
24	0.4	1.3	1.6	1.8	1.7	2.1	2.1
26	0.4	1.0	1.6	1.6	1.6	1.9	1.9
28	0.4	0.9	1.5	1.3	1.4	1.6	1.4
30	0.3	0.9	1.2	1.2	1.3	1.3	1.1
32	0.3	0.8	0.9	1.1	1.0	1.0	0.4
34	0.3	0.6	0.7	0.7	0.9	0.6	0.2
36	0.3	0.4	0.3	0.0	0.5	0.4	0.0
38	0.2	0.2	0.3	0.0	0.4	0.1	0.0
40	0.2	0.1	0.2	0.0	0.3	0.0	0.0

Table 4. Isotherms for 43 °C – spruce + aluminium

In Figure 6–8, isotherms for 43 °C are shown according to the heights above the sample (averaged values).

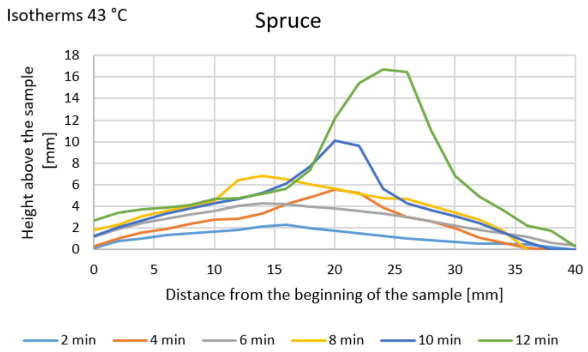

Figure 6. Temperature distribution 43 °C over spruce test specimens

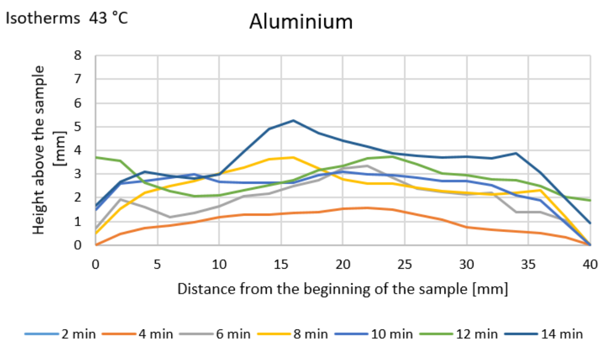

Figure 7. Temperature distribution 43 °C over aluminium test specimens

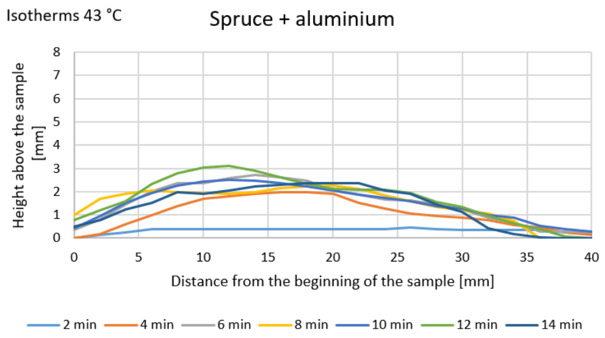

Figure 8. Temperature distribution 43 °C over spruce + aluminium test specimens

Figure 6 shows that spruce wood is a bad heat conductor. Therefore, the supplied heat does not spread from the centre to sides of the sample and over time it heated up the most. Sample centre started to burn through on average after 8 minutes and the measurement had to be completed/stopped after 12 minutes.

Figure 7 shows distribution of the received heat from the source to sample sides in a good thermal conductor (aluminium), where the temperature observed above the sample rose to a maximum of only one third of the heat above the wooden sample (from 16.7 mm to 5.3 mm).

Figure 8 shows that the addition of an aluminium plate under the spruce sample distributes the thermal energy to the sides, reducing the measured temperature to only about one fifth as in the case of spruce without an aluminium base (from 16.7 mm to 3.1 mm).

The effect of the non-combustible substrate on the reduction of the ignition risk of the combustible material due to the thermal load is shown in Table 5 and is even more clearly visible in the graph of the maximum temperature above the sample centre as a function of heating time, as shown in Figure 9.

Maximum temperatures above the center of the sample			
time	**SP**	**AL**	**AL+SP**
1	52.11	24.00	24.00
2	57.17	24.00	27.86
3	80.48	33.66	39.45
4	92.22	43.31	52.11
5	115.93	54.31	52.11
6	121.24	65.31	52.11
7	137.21	65.31	52.11
8	154.47	65.31	61.57
9	137.21	65.31	61.57
10	154.47	77.95	61.57
11	195.64	77.95	65.97
12	195.64	92.63	65.97
13		77.95	70.37
14		90.59	70.37
15		90.59	80.48

Table 5. Maximum temperatures above the center of the sample

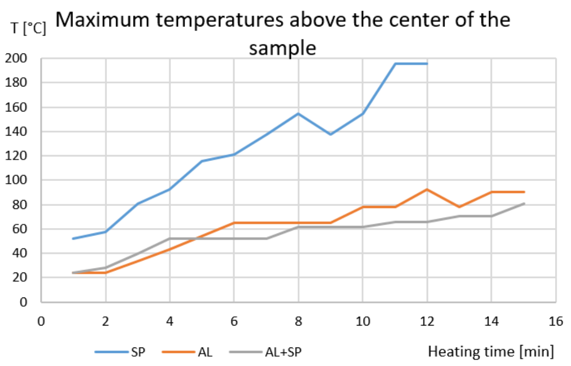

Figure 9. Maximum temperatures above the center of the sample

The course of temperature rise for spruce samples in Figure 9 shows a temperature drop between 8 and 10 minutes of heating when overheating occurred. This caused an increase in the inflow of colder air from the surroundings, followed by a sharp rise in temperature and the sample burn-through.

The temperature curves for the aluminium samples and spruce with the aluminium plate show a certain dynamic similarity. The temperature change over the spruce sample with the aluminium plate occurs after the temperature change over the aluminium sample with a delay of approximately 1 minute. A significant reduction in the maximum temperature above the spruce sample with the aluminium base is also visible, when compared to the temperatures above the spruce without the aluminium base.

It should be noted that in the experiments with a combination of wood and a metal plate, a thin air layer formed at the interface of these components. Air with a very low coefficient of thermal transferred heat by conduction and thus contributed to the reduction of heat transfer from the source through the non-combustible but heat-conducting metal plate, to the wood and through the wood into the air above the wood.

6 CONCLUSIONS

Using holographic interferometry, temperature fields of homogeneous and heterogeneous material during heating were monitored. Focus was mainly on time dependencies, the continuous course of heat transfer and observation of the whole picture of the temperature field.

The use of holographic interferometry enables observation of the shape and development of temperature fields of thermally loaded combustible and non-combustible materials and their combinations consisting of several layers. It allows visualization and evaluation of thermal processes in a transparent environment without direct interference in the processes by material sensors and sensing devices. The paper shows one of the possible applications of holographic interferometry. This method can be used also for diagnostics of electrical drives [Abramov 2015], analysis of stress fields [Frankovsky 2017], analysis of mechanical properties [Kopas 2017], diagnostics of automated technological devices [Peterka 2020].

Digital holographic interferometry [Cernecky 2015] or infrared monitoring techniques [Sfarra 2013] can be used in the future.

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