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Article

Hot-air extermination of insects: The only sustainable method for historical timber constructions

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Abstract: Wood-borer extermination by a dry heat clean-up is the essential method from the point of view of sustainability of historical wooden structures like trusses and ceilings in heritage-listed buildings. The wooden components are heated by a hot air of temperature about 100°C until the temperature in the centre of the wooden structures reaches 55°C to kill the wood-borers. In this article we review the method and present solution of the heat equation for structural wooden components. We also suggest an approximate formula that enables to estimate the necessary heating time for different cross sections of wooden components and can be used in technical application of the method.

Keywords: wooden structures; wood-borer; thermal flow; listed buildings

1. Introduction

Wood is decomposed by a variety of biological agents, including fungi, bacteria, and insects [1]. The last agent becomes responsible especially for biological degradation and destruction of timber structures in historical buildings. The insect-induced biological degradation of wooden structures has been studied e.g. in Refs. [2–5].

One possibility for wood-borer clean-up in timber structures attacked, for instance, by a house longhorn beetle (see Figure 1) is a dry heat clean-up. This method is used quite frequently in Germany and has becoming more popular in the Czech Republic. The principle of this method is that the wood borers die if wood components are heated up to at least 55°C along the whole cross-section. The heating time should be one hour at least [6]. The air is heated up in special heaters to the temperature of about 100°C and then injected through a pipe into the air surrounding the wooden structures where the wood borers are located - for instance, into an attic (see Figure 2 and 3). Because of the low heat conductivity of wood, it is necessary to supply the hot air typically for several hours depending on the cross-section of wooden components. The temperature is measured continuously in some wooden components which are the least favourable in terms of heat conduction. This method consumes rather much energy, but it is environment friendly. Therefore, it would be important for technical applications of the method to find a simple formula that enables us to compute the necessary heating time for different cross sections of wooden components. Moreover, this method is essential for historical and heritage-listed wooden structures in the case of their infestation by wood-borer insect in a large extent because it remains the only non-invasive and sustainable method to save these structures. It is impossible to apply an invasive method such as chemical injection having in mind the historical value and heritage protection. In practical applications one can deal with the whole roof-trusses constructions and large-area wooden ceilings.

The paper is organized as follows. In Sect. 2 we derive the solution of the heat equation for general wooden component dimensions. In Sect. 3 we present solutions of the heat equation for typical examples of wooden components. Then we derive an approximate formula that enables to calculate a minimum heating time to reach the temperature of 55°C in the centre of the wooden component as a function of its lateral dimensions.

Figure 1. A wooden component attacked by a house longhorn beetle.

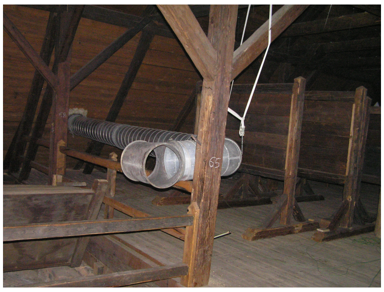

Figure 2. Distribution pipes and the outlet with the remediated area.

Figure 3. Hot air heaters and distribution pipes.

2. Solution of the heat equation

We assume a wooden tie beam of lateral dimensions x_0 and y_0, specific heat capacity $c = 2510$ J kg^{-1} K^{-1}, thermal conductivity coefficient $l = 0.18$ W m^{-1} K^{-1} and density $\rho = 400$ kg m^{-3} (spruce). The initial temperature of the tie beam and its environment is assumed to be $T_0 = 20°$C. The surface of the tie beam is heated by an air heater providing a constant air temperature of $T_1 = 100°$C.

Time evolution of the temperature field inside the tie beam can be found solving the equation of heat [7]:

$$\frac{\partial T(x,y,t)}{\partial t} = k\left[\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right] \tag{1}$$

where $k = \lambda/(\rho c)$. The initial condition reads $T(x,y,0) = T_0$. The time-dependent boundary conditions can be written as (assuming heat transfer from the air of the constant temperature T_1 to the wooden tie beam represented by the heat transfer coefficient $\alpha = 23$ W m^{-2} K^{-1}):

$$\begin{aligned} \frac{\partial T(0,y,t)}{\partial x} &= -\beta[T_1 - T(0,y,t)] \quad , \quad \frac{\partial T(x,0,t)}{\partial y} = -\beta[T_1 - T(x,0,t)]\,, \\ \frac{\partial T(x_0,y,t)}{\partial x} &= \beta[T_1 - T(x_0,y,t)] \quad , \quad \frac{\partial T(x,y_0,t)}{\partial y} = \beta[T_1 - T(x,y_0,t)]\,, \end{aligned} \tag{2}$$

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where $\beta = \alpha/\lambda$. Substituting $T(x,y,t) = T_1 + \tau(x,y,t)$ we can rewrite the heat equation (1) and the initial and boundary conditions (2):

$$\begin{aligned} \frac{\partial\tau(x,y,t)}{\partial t} = k\left[\frac{\partial^2\tau(x,y,t)}{\partial x^2} + \frac{\partial^2\tau(x,y,t)}{\partial y^2}\right] \quad &, \quad \tau(x,y,0) = T_0 - T_1\,, \\ \frac{\partial\tau(0,y,t)}{\partial x} = \beta\tau(0,y,t) \quad &, \quad \frac{\partial\tau(x,0,t)}{\partial y} = \beta\tau(x,0,t)\,, \\ \frac{\partial\tau(x_0,y,t)}{\partial x} = -\beta\tau(x_0,y,t) \quad &, \quad \frac{\partial\tau(x,y_0,t)}{\partial y} = -\beta\tau(x,y_0,t)\,. \end{aligned} \tag{3}$$

General solution of Eq. (1) can be expressed as:

$$\tau(x,y,t) = (A_x \sin k_x x + B_x \cos k_x x)(A_y \sin k_y y + B_y \cos k_y y)\exp\left[-k(k_x^2 + k_y^2)t\right] \tag{4}$$

The boundary conditions lead to equations:

$$\begin{aligned} A_x k_x = \beta B_x\,, \qquad A_y k_y = \beta B_y \quad &, \quad (A_x k_x + \beta B_x)\cos k_x x_0 = (B_x k_x - \beta A_x)\sin k_x x_0\,, \\ (A_y k_y + \beta B_y)\cos k_y y_0 \quad &= \quad (B_y k_y - \beta A_y)\sin k_y y_0\,. \end{aligned} \tag{5}$$

The solution of Eq. (3) then reads:

$$\tau(x,y,t) = \sum_{n,m=1}^{\infty} A_{nm}(\sin k_{x_n}x + \frac{k_{x_n}}{\beta}\cos k_{x_n}x)(\sin k_{y_m}y + \frac{k_{y_m}}{\beta}\cos k_{y_m}y)\exp\left[-k(k_{x_n}^2 + k_{y_m}^2)t\right],$$

where k_{x_n} and k_{y_m} are solutions of the equation derived from Eqs. (5):

$$\tan k_{x_n}x_0 = \frac{2\beta k_{x_n}}{k_{x_n}^2 - \beta^2}\,, \qquad \tan k_{y_m}y_0 = \frac{2\beta k_{y_m}}{k_{y_m}^2 - \beta^2}\,, \tag{6}$$

n, m are natural numbers. The coefficients A_{nm} are obtained from the initial conditions

$$T_0 - T_1 = \sum_{n,m=1}^{\infty} A_{nm}(\sin k_{x_n}x + \frac{k_{x_n}}{\beta}\cos k_{x_n}x)(\sin k_{y_m}y + \frac{k_{y_m}}{\beta}\cos k_{y_m}y)$$

using the Fourier transform and the orthogonality of the basis functions $\sin k_{x_n}x + \frac{k_{x_n}}{\beta}\cos k_{x_n}x$ and $\sin k_{y_m}y + \frac{k_{y_m}}{\beta}\cos k_{y_m}y$:

$$A_{nm} = \frac{\int_0^{x_0}\int_0^{y_0}(T_0 - T_1)(\sin k_{x_n}x + \frac{k_{x_n}}{\beta}\cos k_{x_n}x)(\sin k_{y_m}y + \frac{k_{y_m}}{\beta}\cos k_{y_m}y)dxdy}{\int_0^{x_0}\int_0^{y_0}(\sin k_{x_n}x + \frac{k_{x_n}}{\beta}\cos k_{x_n}x)^2(\sin k_{y_m}y + \frac{k_{y_m}}{\beta}\cos k_{y_m}y)^2dxdy} \tag{7}$$

3. Results

The heat equation (1) for the specified initial and boundary conditions (2) was solved numerically using the approach described in the previous section. Maximum values of n and m were set to be 1001 that asure fulfilling the initial condition with the accuracy of about 0.2°C at the wooden tie beam boundaries (the worst case). In practical applications the wooden tie beam dimensions span the intervals 10 – 20 cm (y-direction) and 10 – 30 cm (x-direction). In Figure 4 and 5 the temperature evolution with the step of 1 hour in the central y-cut of the wooden tie beams of dimensions 25 cm x 18 cm and 12 cm x 10 cm are shown.

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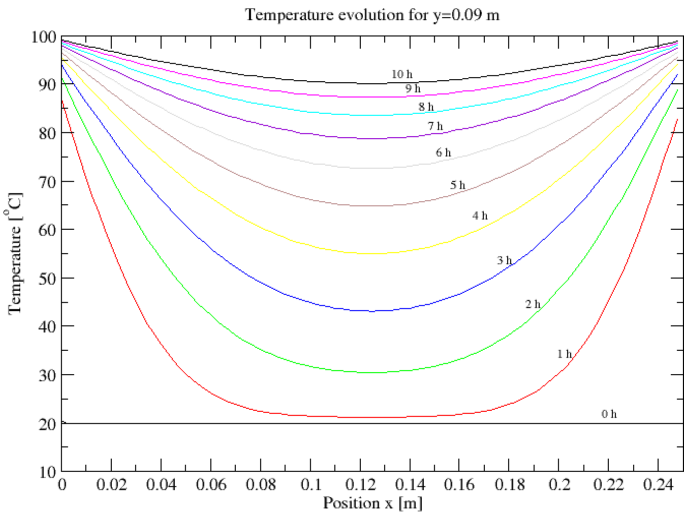

Figure 4. Temperature evolution in the central y-cut of the 25 cm x 18 cm wooden tie beam.

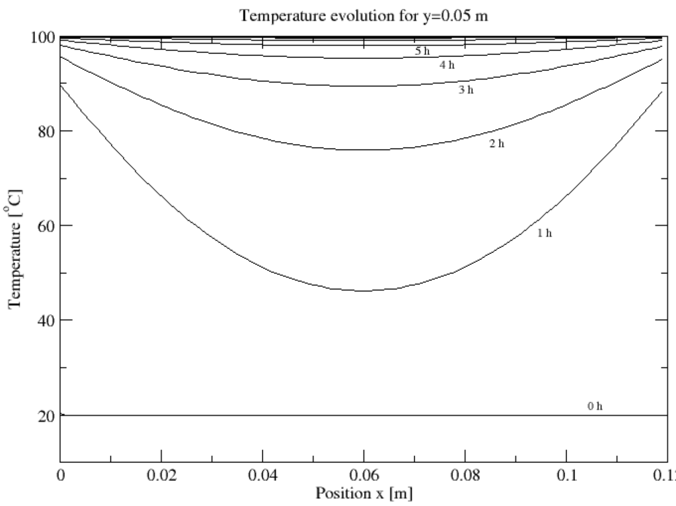

Figure 5. Temperature evolution in the central y-cut of the 12 cm x 10 cm wooden tie beam.

In Figure 6 the heating time necessary to reach the temperature of 55°C in the centre of the wooden tie beam is shown for different values of x_0 and y_0. One can see that the heating time spans quite a large interval from 30 min for wooden tie beams 5 cm x 10 cm to 14 hours for wooden tie beams 40 cm x 40 cm.

Based on the theory described in Sect. 2 (cf. Eqs. 4 and 6) we found a simple approximate formula for the heating time τ that can be used for practical purposes:

$$\tau = \frac{\rho c}{0.88 \lambda \pi^2 \left(\frac{1}{x_0^2} + \frac{1}{y_0^2} \right)} \tag{8}$$

The quality of the formula (8) is illustrated in Figure 7 where the numerical solution of the heat equation (1) is compared to the approximate one for different values of x_0 and y_0. One can see that the approximate formula (8) agrees with the numerical solution with a maximum error less than 15 min (maximum underestimation of 13 min and maximum overestimation of 6 min for the studied wooden tie beam dimensions). This is acceptable for technical applications.

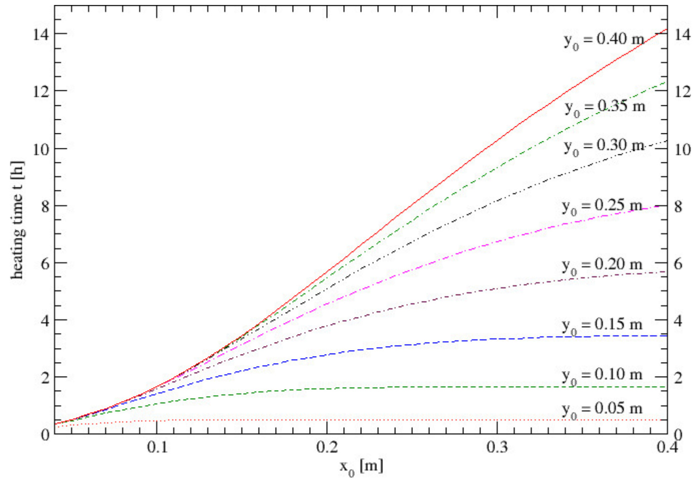

Figure 6. The heating time necessary to reach the temperature of 55°C in the centre of the wooden tie beam for different values of x_0 and y_0.

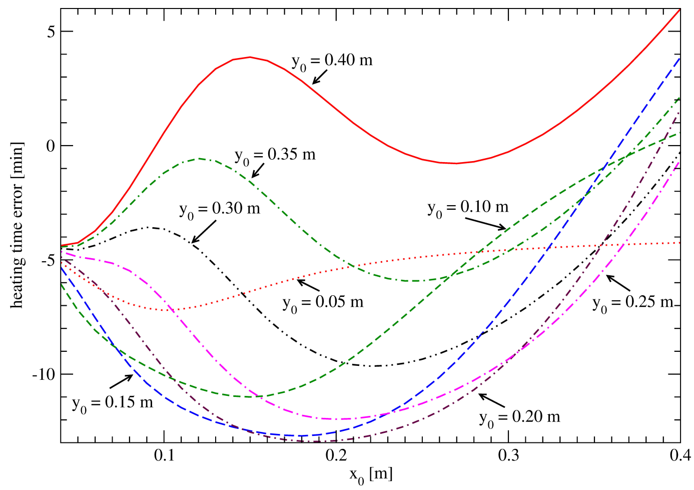

Figure 7. The heating time error of the approximate formula (8) compared to the numerical solution of the heat equation (1) for different values of x_0 and y_0.

4. Conclusions

The dry heat clean-up method as the essential method from the point of view of sustainability of historical wooden structures infested by wood-borer insect has been reviewed. The heat equation has been solved for a wooden tie beam in two dimensions (corresponding to its lateral dimensions) under the assumption that its surface is heated by an air heater providing a constant air temperature of $T_1 = 100°C$. The time evolution of the temperature field has been studied for different combinations of the wooden tie beam lateral dimensions with the aim to find a minimum heating time necessary to reach the temperature of 55°C in the centre of the beam to kill the wood-borers. The obtained heating times span quite a large interval from 30 min to several hours depending on the wooden tie beam lateral dimensions. To avoid a time-consuming solution of the heat equation and to provide a simple tool to estimate the minimum heating time we suggest an approximate formula that can be used in practical application of the dry heat clean-up method and that agrees with the numerical solution of the heat equation with a maximum error less than 15 min. The suggested formula is expected to be valuable to guarantee an environment friendly treatment of wood-borer infested historical wooden structures.

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Conflicts of Interest: The authors declare no conflict of interest.

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