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DETERMINATION OF WALL IGNITION TIME IN FIRE CONDITIONS

Alexander Suvorov[1] and Evgenia Kozhanova[2]

[1,2] Department of Computer Science and Applied Mathematics, Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia.

Email: [1] suvorovap@mgsu.ru, [2] KozhanovaER@mgsu.ru

Corresponding Author: **Alexander Suvorov**

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Abstract

This article determines the ignition time of a wall considering convective heat exchange between its surface and the fire source environment. The fire source temperature is treated as a given time-dependent function. Calculations of the wall temperature are performed using a semi-analytical method based on Duhamel's principle and the finite difference method. A novel calculation procedure is developed for the fire source temperature that is changing with time as a piecewise-linear function. It was found that accounting for a gradual temperature rise in the fire source leads to results significantly different from cases assuming an instantaneous temperature rise. The influence of the heat transfer coefficient on wall ignition time is also demonstrated.

Keywords: Ignition Time, Standard Fire Temperature, Heat Conduction In A Wall, Time-Dependent Solution, Duhamel's Principle, Finite Difference Solution.

I. Introduction

This article determines the ignition time of a wall in convective heat exchange with a fire source or heated gases from a fire. The wall ignition time, t_{ig}, is defined as the moment when the surface facing the fire reaches a specified ignition temperature, T_{ig}. For example, this could be set at 400°C for an oak wall.

Evolution of the temperature of the fire source or heated gases, T_∞ is a key parameter affecting wall ignition time. Our previous work [I] assumed an instantaneous temperature rise to a high value (e.g., 800°C). This article considers a gradual temperature increase in the fire source according to a given time-dependent function $T_\infty = T_\infty(t)$.

The Canadian Wood Council's "Fire Safety Design in Buildings" [II] notes that heated gas temperatures during furnace tests typically rise as follows:

- 538°C after 5 minutes

- 704°C after 10 minutes
- 843°C after 30 minutes
- 927°C after 60 minutes

This dependence of the fire source temperature on time will be used here for our numerical calculations. But other descriptions of standard fire conditions can also be used. For example, ISO 834 [X] or Eurocode 1 [XII] gives the temperature of the fire source in the form

$$T_\infty(t)=345 \log10 (0.133\, t + 1) + T_0 \qquad (1)$$

where T_∞ is measured in K, t is time in seconds, and T_0 is the initial temperature. ASTM E119-88 [II] provides an alternative expression of the standard fire curve as

$$T_\infty(t)=750[1-\exp(-0.0633\, t^{0.5})]+2.84\, t^{0.5}+ T_0 \qquad (2)$$

where t is time in seconds.

For modeling wall heating near fire sources, it is common to consider a convective heat exchange boundary condition [I, IV, VI, VIII, IX, XIV, XV]. In this context, specifying the right value for the convective coefficient of heat transfer h is important. It should be noted that the value of the coefficient h varies greatly in different works. For example, in [XV] it is assumed that h depends on the temperature of the fire source $T_\infty(t)$ and the temperature of the surface of the wall T_w according to

$$h=29+(3.9-0.0023\, T_w)\, ((T_\infty/100)^4 - (T_w/100)^4)/(T_\infty-T_w). \qquad (3)$$

Here, the temperature is in K. Therefore, the minimum value of h is its initial value, equal to 29 W/(m^2 K). In [XIV], the coefficient h is taken as large as 109 W/(m^2 K). On the other hand, in [VIII], the authors determine the coefficient h by solving equations of gas dynamics numerically. The program Fire Dynamics Simulator is used for calculations. It was observed that the program rarely predicts the value of h that exceeds 15 W/(m^2 K). In this work, we assume that the coefficient h is a constant equal to 20 W/(m^2 K). The same value of h is adopted in [IX].

Some approaches assume replacement of the convective heat exchange boundary condition with a Dirichlet boundary condition [XIII]. In this case, the temperature is prescribed as a power function of time.

In this paper, numerical and numerical-analytical approaches are used to solve the corresponding heat conduction equation with convective heat exchange boundary condition, so there is no need to replace or simplify the boundary condition.

II. Materials and Methods

To determine the ignition time of a wall, we treat the wall as a semi-infinite space with $x \geq 0$ (Fig. 1). The external surface of the wall, x = 0, is facing the fire source, where the temperature is prescribed to be $T_\infty(t)$.

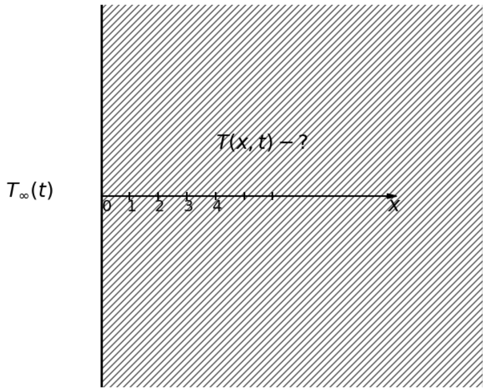

Fig. 1. Geometry of the wall. *Source:* «Made by authors».

We solve a one-dimensional unsteady heat conduction problem in the region of the wall, $x \geq 0$. The temperature $T(x,t)$ is an unknown function that satisfies the heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}, \tag{1}$$

where k is the thermal conductivity, ρ is the density, and c is the specific heat of the material of the wall. Defining thermal diffusivity $\alpha = k/(\rho\, c)$, equation (1) becomes:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}. \tag{2}$$

The boundary condition at $x=0$ incorporates convective heat exchange:

$$-k \frac{\partial T}{\partial x}\bigg|_{x=0} = h(T_\infty(t) - T(0,t)), \tag{3}$$

where h is the coefficient of heat transfer or convective heat exchange. The temperature of the heated gases in the fire source $T_\infty(t)$ is a given function of time. The initial temperature of the wall is given by

$$T(x,0) = T_0. \tag{4}$$

A simple analytical solution can be obtained only at a constant temperature of the heated gases, T_∞. In this case, it is assumed that the temperature of the heated gases increases instantaneously to a certain value, and then remains constant. Such solutions are presented in [III, V, IX, XI]. We write this analytical solution under the condition that the initial wall temperature is zero and the temperature of the heated gases is equal to one. This solution is denoted as $U(x,t)$. Then

$$U(x,t) = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - erfc\left(\frac{x}{2\sqrt{\alpha t}} + \frac{h}{k}\sqrt{\alpha t}\right)\exp\left(\frac{h}{k}x + \frac{h^2}{k^2}\alpha t\right) \tag{5}$$

where *erfc* is the complementary error function.

For a more complex dependence of the temperature of heated gases on time $T_\infty(t)$, the Duhamel principle can be used [III, XIV]. In this case, the solution can be represented as

$$T(x,t)-T_0 = \int_0^t \frac{dT_\infty(\tau)}{d\tau} U(x,t-\tau)d\tau. \quad (6)$$

To proceed with the integration of (6), we will assume that the temperature $T_\infty(t)$ is a piecewise linear function, i.e., there is a finite number of time intervals $[t_{i-1}, t_i]$, i=1,2,..., on each of which the function $T_\infty(t)$ is a linear function. Then the integral can be represented as a sum of several integrals

$$T(x,t)-T_0 = \sum_i^{t>t_{i-1}} \int_{t_{i-1}}^{min(t_i,t)} \frac{dT_\infty(\tau)}{d\tau} U(x,t-\tau)d\tau. \quad (7)$$

Here, in each integral, the upper limit is equal to t_i if $t_i < t$, or t if $t_i > t$. But on each interval, the rate of temperature change is constant. Let us denote the rate of temperature change on each (sub)interval as r_i. Then

$$T(x,t)-T_0 = \sum_i^{t>t_{i-1}} r_i \int_{t_{i-1}}^{min(t_i,t)} U\,(x,t-\tau)d\tau. \quad (8)$$

Each of the integrals of the function U in (8) can be found numerically, for example, by the trapezoid method. Instead of τ, it is convenient to use t-τ as the integration variable. In this case

$$T(x,t)-T_0 = -\sum_i^{t>t_{i-1}} r_i \int_{t_{i-1}}^{min(t_i,t)} U\,(x,t-\tau)d(t-\tau). \quad (9)$$

Let us introduce a new integration variable q=t-τ

$$T(x,t)-T_0 = -\sum_i^{t>t_{i-1}} r_i \int_{t-t_{i-1}}^{t-min(t_i,t)} U\,(x,q)dq \quad (10)$$

or by swapping the limits of integration

$$T(x,t)-T_0 = \sum_i^{t>t_{i-1}} r_i \int_{t-min(t_i,t)}^{t-t_{i-1}} U\,(x,q)dq. \quad (11)$$

This can be considered the final expression for the case when the temperature of the heated gases is a piecewise linear function. For example, if the temperature of the fire source changes over the interval [0,300] sec at a rate of r_1, and then at a rate of r_2, and we are interested in the temperature at the time of 500 sec, then the solution will be written as

$$T(x,500)-T_0 = r_1 \int_{200}^{500} U\,(x,q)dq + r_2 \int_{0}^{200} U\,(x,q)dq. \tag{12}$$

It is also possible to use the finite difference method. To solve the problem using the finite difference method, a grid is introduced along the wall depth with a step of Δ*x*. To number the points of this grid, we will use the index *i*. Thus, i=0,1,2..., considering that the point with the number 0 corresponds to the wall surface at *x*=0 (Fig. 1). Since the problem is solved on a computer, the total number of points must be limited.

We also introduce a time step Δ*t*. The time step number will be denoted by the letter *p*=0,1,2… and *p*=0 corresponds to the initial time value *t*=0. The desired temperature at a given point *i* at a given moment in time *p* will be designated as T_i^p. Replacing the differential equation (2) with its finite difference analogue, we obtain

$$\frac{T_i^{p+1}-T_i^p}{\Delta t} = \alpha \frac{T_{i-1}^p-2T_i^p + T_{i+1}^p}{\Delta x^2}. \tag{13}$$

Here we have used the explicit Euler scheme by replacing partial derivatives with their finite-difference analogues. Let us define the Fourier number

$$f = \frac{\alpha \Delta t}{\Delta x^2}. \tag{14}$$

Then the temperature at the next moment of time *p*+1 can be found knowing the temperature values at the moment of time *p*, using the formula

$$T_i^{p+1} = f\left(T_{i-1}^p + T_{i+1}^p\right) + (1-2f)T_i^p. \tag{15}$$

To satisfy the stability condition of the scheme, the coefficient next to T_i^p must be greater than zero [IX]. Thus, $1-2f\geq 0$ or $f\leq 1/2$. It follows that the time step Δ*t* must be sufficiently small.

Next, we write the boundary condition of convective heat exchange (3) in the form of a finite-difference relation. This equation is derived in detail in [IX]

$$k\frac{T_1^p-T_0^p}{\Delta x} + h(T_\infty^p-T_0^p) = c\rho\frac{\Delta x}{2}\frac{T_0^{p+1}-T_0^p}{\Delta t}. \tag{16}$$

Note that the temperature of the heated gases T_∞^p is calculated at time *p*.

Let us introduce a numerical analogue of the Biot number

$$b = \frac{h\Delta x}{k}. \tag{17}$$

Then, from (16), the temperature on the wall surface T_0^{p+1} at the subsequent time *p*+1 can be found knowing the temperatures at time *p* as follows

$$T_0^{p+1} = 2fT_1^p + (1-2f)T_0^p + 2bf\left(T_\infty^p-T_0^p\right). \tag{18}$$

For the Euler method to be stable, we must require that the coefficient in front of T_0^p on the right-hand side of the equation be greater than zero. This yields $1-2f(1+b)\geq 0$ or $f\leq 1/(2(1+b))$. This constraint on the time step size is more demanding than the one obtained earlier, $f \leq 1/2$. Therefore, the constraint $f \leq 1/(2(1+b))$ must be used to control the time step.

III. Results

Let us consider the problem of determining the ignition time of an oak wall t_{ig}, assuming that the ignition temperature of oak is T_{ig}=400°C. We will take the initial temperature of the wall to be T_0=25°C.

It is assumed that the temperature of the fire source changes gradually, as indicated in the collection "Fire Safety Design in Buildings" [VII], i.e. the temperature of the heated gases is a piecewise linear function that changes in the following way: the temperature rises from T_0=25°C to 538°C during the first 5 minutes from the start of the fire, then it rises from 538°C to 704°C during the next 5 minutes, then it rises from 704°C to 843°C during the next 20 minutes. Let us take the following values of the coefficients: h=20 W/(m^2 K), k=0.16 W/(m K), c=1255 J/(kg K), ρ=720 kg/m^3.

When using the finite difference method, the time step Δt and the step size in the coordinate Δx need to be selected. We select Δt=1 sec and Δx=0.003125 m. From here, we get f=0.018, b=0.39. These values satisfy the stability conditions of the finite difference scheme, since $0.018 < 1/(2(1+b))=0.36$. The length of the calculation area is selected to be equal to 50 mm, since outside this zone, as calculations show, the temperature practically does not change over time.

Figure 2 shows how the temperature of the wall surface changes over time. Two cases are considered: 1) the gradual increase in the temperature of heated gases in the fire source, 2) an instantaneous increase in this temperature to 800°C.

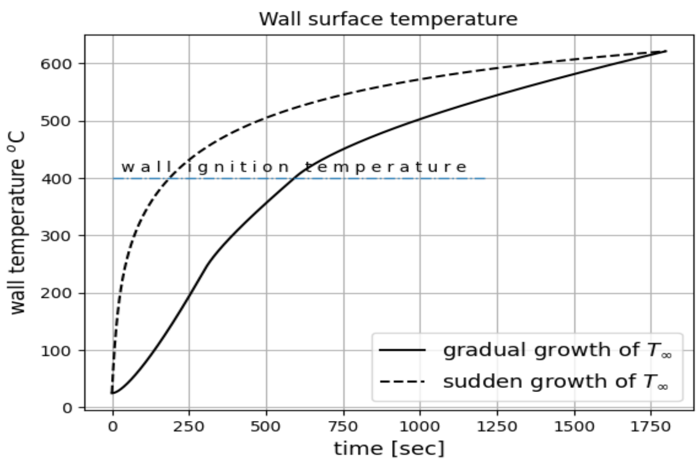

Fig. 2. Temperature increase on the surface of an oak wall, from the moment the fire has started, with the gradual increase in the temperature of the fire source and with a sudden increase to a constant value of 800°C. *Source:* «Made by authors».

It can be seen from the figure that the assumption of an instantaneous increase in the temperature of the heated gases can give a value for the ignition time that differs greatly from the standard fire conditions or from the conditions of tests to determine the ignition time. In this case, the ignition time of the wall, with correct consideration of the increase in the temperature of the fire source, turned out to be approximately 3 times higher than the ignition time of the wall with an instantaneous increase in the temperature of the fire source to 800°C. It is clear that this difference between the values could be different when another value of the instantly growing temperature is selected. For example, if we assume that the temperature of the fire source grows instantly to 610°C, then in this case, there will not be a big difference in the values of the ignition time.

The ignition time of a wall t_{ig} depends on many factors, including the value of the heat transfer coefficient *h*. The most important values of the coefficient *h* from a practical point of view lie in the range from 10 to 30 W/(m^2 K). Figure 3 shows how the ignition time depends on the coefficient *h*. The ignition time was obtained at two ignition temperatures of 300°C and 400°C. The dependence of the temperature of heated gases in the fire source on time was taken to be the same as in Figure 2, i.e., the gradual increase in this temperature was taken into account.

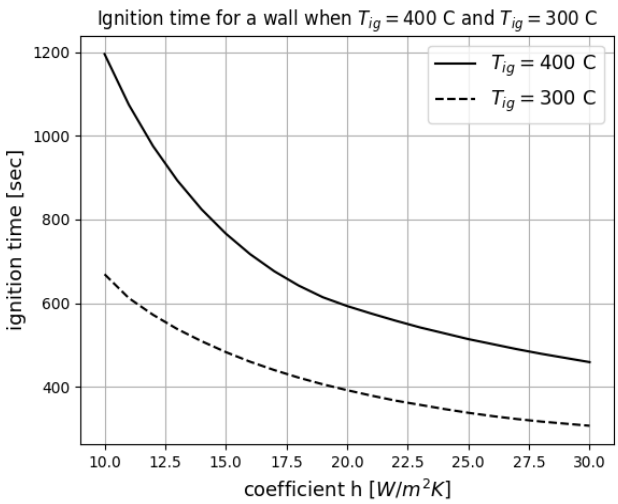

Fig. 3. Wall ignition time as a function of the heat transfer coefficient *h* at ignition temperatures of 300°C and 400°C. *Source:* «Made by authors».

We also conducted a study of the influence of the step size in the coordinate Δ*x* and in time Δ*t* on the accuracy of the results when using the finite difference method. If we fix Δ*t* and decrease Δ*x*, this may eventually lead to a loss of stability of the scheme, and consequently to an excessively rapid increase in the temperature. Therefore, in general, decreasing the step Δ*x* leads to a faster increase in wall temperature compared to the actual temperature increase and to a decrease in the estimated ignition time. Increasing the step Δ*x* leads to a slower increase in the wall temperature and to an increase in the estimated wall ignition time. Similar conclusions can be made for the case of a fixed step Δ*x* and a change in the time step Δ*t*.

IV. Discussion

As before, we assume that the fire source temperature T_∞ is defined as a piecewise-linear function of time. Let this function increase linearly with the rate r_1 at the first time interval. Then, by differentiating the formula for the wall temperature (11), constructed based on the Duhamel principle, the *rate* of increase of the wall temperature can be obtained as

$$\frac{dT}{dt} = r_1(U(x,t) - U(x,0)) = r_1 U(x,t). \tag{19}$$

It follows from this expression that the initial rate of increase in the wall temperature is zero, since $U(x,0)=0$. For a large value of time $t\to\infty$, the rate of increase in the wall temperature coincides with the rate of increase in the temperature of the fire source r_1, since $U(x,\infty)=1$.

If the temperature of a fire source increases at a rate of r_1 in the time segment $[0,t_1]$, and then increases at a rate of r_2, then in the segment $[0,t_1]$, the rate of the temperature increase is still given by the same formula

$$v_1 = \frac{dT}{dt} = r_1 U(x,t), \tag{20}$$

But on the interval $[t_1,t]$, the rate will be calculated using the formula

$$v_2 = \frac{dT}{dt} = r_1 U(x,t) + (r_2 - r_1) U(x,t-t_1), \tag{21}$$

If the temperature of a fire source increases at a rate of r_1 in the time segment $[0,t_1]$, then increases at a rate of r_2 in the segment $[t_1,t_2]$, and then increases at a rate of r_3, then in the segment $[t_2,t]$, the rate of the temperature increase is given by the formula

$$v_3 = \frac{dT}{dt} = r_1 U(x,t) + (r_2 - r_1) U(x,t-t_1) + (r_3 - r_2) U(t-t_2), \tag{22}$$

and in the first two segments, the rate is calculated using the same formulas (20), (21).

These formulas can be continued if the entire time interval has a larger number of segments in which the temperature of the fire source has prescribed rates of change r_1, r_2, r_3, etc.

The found rates of temperature growth in the wall at each time (sub)interval can be used for a rough estimate of the wall ignition time, t_{ig}. Indeed, let us find the rates of wall temperature growth in the middle of the first segment at $t_{01}=t_1/2$, in the middle of the second segment at $t_{12}=(t_1+t_2)/2$, in the middle of the third segment at $t_{23}=(t_2+t_3)/2$, etc.

These rates in the middle of each time (sub)interval can be found using the formulas given above (20)-(22). For example, the rate of temperature increase in the middle of the third segment, i.e., at $t_{23}=(t_2+t_3)/2$, is equal to

$$\frac{dT}{dt} = r_1 U(x,t_{23}) + (r_2 - r_1) U(x,t_{23} - t_1) + (r_3 - r_2) U(t_{23} - t_2), \quad (23)$$

Next, having the rates on each time (sub)interval and assuming that these rates are constant on each (sub)interval, we can calculate the wall temperature at any moment of time using a simple integration rule for a piece-wise constant function.

The result of calculating the wall surface temperature in this way is presented in Figure 4 and is shown by a dashed line. The rate of increase in the wall temperature was first found in the middle of the first time segment [0, 300] sec at t=150 sec according to (20), then in the middle of the second segment [300, 600] sec at t=450 sec from (21), and finally in the middle of the third segment [600, 1800] sec at t=1200 sec from (22) or (23). These rates are respectively equal to v_1=0.77°C/sec, v_2=0.51°C/sec, v_3=0.16°C/sec. Then, the temperature at the wall surface, for example, at t=600 sec, is found by the formula

$$T(x = 0,t = 600) = T_0 + 0.77 * 300 + 0.51 * 300 = 409. \quad (24)$$

This value is only slightly different from the precise value of 402°C. It is clear from the figure that such a rough approach to finding the wall temperature gives quite satisfactory results, since it coincides well with a more accurate calculation of the wall temperature.

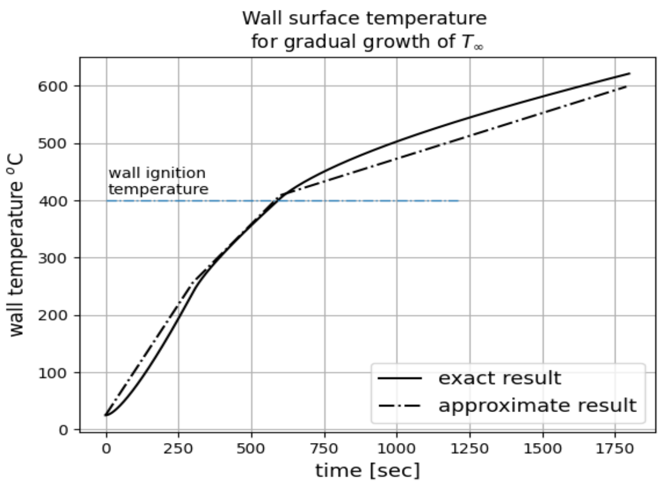

Fig. 4. Temperature increase on the surface of an oak wall with the gradual increase in the temperature of the fire source: exact and approximate calculations. *Source:* «Made by authors».

V. Python Codes

In this section, we present Python code used to evaluate the wall temperature according to the formula (11).

```
import numpy as np

import scipy.special as ss
```

```
import matplotlib.pyplot as plt
from numpy import sqrt
from scipy.special import erfc
k = 0.16
r = 720
c = 1255
alpha = k/(r*c)
dt = 1

T0 = 298-273
h=20

timea = np.arange(0,300,dt)
## fire temperature
Tfa = timea*(538-T0)/300+T0
## fire temperature
Tfa_next = timea*(704-538)/300+538

timeb = np.arange(0,1200, dt)
## fire temperature
Tfb = timeb*(843-704)/1200 + 704

timea = np.concatenate((timea,timea+300,timeb+600))
Tfa = np.concatenate((Tfa,Tfa_next,Tfb))

rate1 =(538-T0)/300
rate2 = (704-538)/300
rate3 = (843-704)/1200

def fx0(t):
return ss.erfc(0) - np.exp(0 + h**2/k**2*alpha*t)*ss.erfc(0 + h/k*(alpha*t)**(1/2))

def IntegS (a,b,f):
h = 0.5
 x = np.arange(a,b+h,h)
return h*(np.sum(f(x)) - f(a)*0.5 - f(b)*0.5)
TT = np.arange(0,1800,10)  ## results for every 10 seconds
QT = []
```

```
for tt in TT:
    if tt<=300:
        Q = T0 + rate1*IntegS(tt-tt,tt-0,fx0)
    elif tt<=600:
        Q = T0 + rate1*IntegS(tt-300,tt-0,fx0) + rate2*IntegS(tt-tt,tt-300,fx0)
    elif tt <= 1800:
        Q = T0 + rate1*IntegS(tt-300,tt-0,fx0) + rate2*IntegS(tt-600,tt-300,fx0) + rate3*IntegS(tt-tt,tt-600,fx0)

        QT.append(Q)

    QT = np.array(QT)

## approximate calculation of wall temperature
QR = []
for tt in TT:
    if tt<=300:
        v1 = fx0(150)*rate1
        Q = T0 + v1*tt
    elif tt<=600:
        v1 = fx0(150)*rate1
        v2 = fx0(450)*rate1 + (rate2-rate1)*fx0(450-300)
        Q = T0 + v1*300 + v2*(tt-300)
    elif tt <= 1800:
        ## center of first segment t=150
        v1 = fx0(150)*rate1
        ## center of second segment t=450
        v2 = fx0(450)*rate1 + (rate2-rate1)*fx0(450-300)
        ## center of third segment t=1200
        v3 = fx0(1200)*rate1 + (rate2-rate1)*fx0(1200-300) + (rate3-rate2)*fx0(1200-600)
        Q = T0 + v1*300 + v2*300 + v3*(tt-600)


    QR.append(Q)
```

```
plt.plot(TT, QT, '-')
plt.plot(TT, QR, '-.')
plt.xlabel('time [sec]', fontsize=13);
plt.ylabel('wall temperature $^o$C', fontsize=13);
plt.show()
```

Below is the code for the calculation of the temperature by the finite difference method.

```
import numpy as np
import matplotlib.pyplot as plt
from numpy import sqrt

dx = 0.003125
k = 0.16
r = 720
c = 1255
alpha = k/(r*c)
dt = 1

T0 = 298-273

h=20

alpha = k/(r*c)

b = h*dx/k
f = k*dt/(c*r*dx**2)

print('parameter ',alpha*dt/(dx**2))

L = 16*dx
X = np.arange(0,L,dx)
Temp = np.ones_like(X)*T0

timea = np.arange(0,300,dt)
Tfa = timea*(538-T0)/300+T0
Tfa_next = timea*(704-538)/300+538
timeb = np.arange(0,1200, dt)
Tfb = timeb*(843-704)/1200 + 704
```

```
timea = np.concatenate((timea,timea+300,timeb+600))
Tfa = np.concatenate((Tfa,Tfa_next,Tfb))

Ts = []

for step, time in enumerate(timea):
    for j in range(len(X)-1):
        if j==0:
            Temp[0] = 2*f*Temp[1] + (1-2*f)*Temp[0] + 2*b*f*(Tfa[step]-Temp[0])
        else:
            Temp[j]= f*(Temp[j-1]+Temp[j+1])+(1-2*f)*Temp[j]


    Ts.append(Temp[0])


timetr = h**2/k**2*alpha*timea
timetr = timea


plt.plot(timetr,Ts,'k-',label='gradual growth of $T_{\infty}$')
plt.xlabel('time [sec]', fontsize=13);
plt.ylabel('wall temperature $^o$C', fontsize=13);
plt.show()
```

VI. Conclusion

In this article, it was shown that in order to determine the wall ignition time t_{ig} it is important to correctly take into account the gradual increase in the temperature of heated gases in the fire source, that is, to take into account $T_\infty(t)$. In particular, taking into account the increase in the temperature of the heated gases in accordance with the recommendations of the Canadian Wood Council [VII] led to the fact that the wall ignition time t_{ig} increased by 3 times (up to 600 sec) compared to the value obtained under the assumption that the temperature of the heated gases T_∞ increases instantly to a value of 800°C (200 sec).

Another disadvantage of allowing the temperature T_∞ to rise instantaneously to a certain value is that the results will depend heavily on the selected value of this instantaneously rising temperature.

In this article, we also investigated the influence of the heat transfer coefficient h and the ignition temperature of the material T_{ig} from which the wall is made on the wall ignition time. It was shown that the ignition time increases with a decrease in the coefficient h and with an increase in the temperature T_{ig}.

We have developed a semi-analytical method for calculating the wall temperature when the fire source temperature is a piece-wise linear function, based on the Duhamel principle. In this case, it is only necessary to use the trapezoid method to calculate the final expression (11) in the form of an integral.

An *approximate* method for calculating the wall temperature was also developed, which assumes that the wall temperature at each time (sub)interval increases at a constant rate. These time (sub)intervals can be chosen to coincide with those time segments used to prescribe the fire source temperature, which is convenient. This approximate method gives satisfactory results, which agree well with the exact calculation (11).

Conflict of Interest:

The authors declare that there is no conflict of interest regarding this article.

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