Statyba

ISSN: 1392-1525 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcem19

DETERMINATION OF THE TEMPERATURE OF UNCOVERED STEEL CONSTRUCTIONS USING NUMERICAL METHODS

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ISSN 1392-1525. STATYBA - CIVIL ENGINEERING - СТРОИТЕЛЬСТВО, 1996, Nr. 4(8)

DETERMINATION OF THE TEMPERATURE OF UNCOVERED STEEL CONSTRUCTIONS USING NUMERICAL METHODS

Z. Bednarek

1. Introduction

Data concerning the increase in temperature of uncovered steel constructions during a fire are essential for solving stress and strain problems of these constructions and their fire resistance. These data are also very useful during an analysis of the construction condition changed after the fire in order to define the usefulness of the construction for rebuilding.

This article shows the method of determining the temperature of the uncovered steel construction, particularly floor bearing elements (beams, trusses etc.) in fire conditions using a computing technique. The whole problem was split into two different parts requiring separate solutions:

- determination of transient temperature field in the interior around the construction,
- determination of the increase in temperature of the uncovered steel construction in this temperature field.

In case of standard fire conditions the first problem can be solved without any difficulty. The increase in ambient temperature, where the construction is located, can be calculated using the formula

$$T - T_o = 345\,lg(8t + 1) \qquad (1)$$

where t - time [min], T_o - initial temperature, T_o = 20 °C.

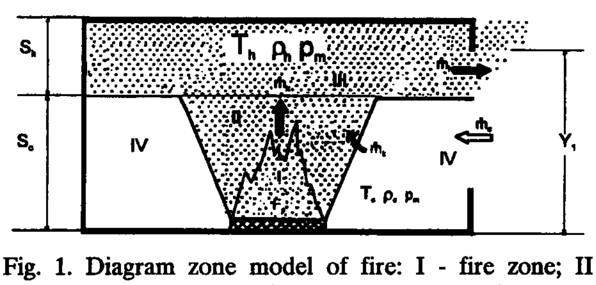

Fig. 1. Diagram zone model of fire: I - fire zone; II - convection zone (column); III -smoke zone (hot ceiling layer); IV - zone of heat radiation interaction (cool layer)

Author suggests that the determination of thermal conditions in the interior around the construction should be performed on the base of the zone model of fire. This model is simple and easy to use, especially in order to determine the increase in the temperature of floor elements.

2. Description of the inside fire development

In the zone model the whole inside space was split into four zones: fire zone, convection zone (column), smoke zone (hot ceiling layer) and zone of heat radiation interaction as shown in Fig. 1 [1]. The assumption was made that mixing of gases in each zone is good and all zones can be described with averaging parameters of fire. Internal fire is a very complicated phenomenon which can be influenced by numerous external factors. Modelling of such a phenomenon is very difficult, so following simplifications were made:

- in every room, in which fire results in generating a stream of hot gas, two layers exist - an upper layer of hot gases (hot ceiling layer - zone III) and a lower cool layer (zone IV);
- convection zone is not taken into account, it is regarded as mass and energy carrier;
- each zone is physically and chemically homogeneous;
- zones are separated with discontinuous surfaces, the flow of mass and heat is possible only through convection zone or through holes;
- heat exchange between the cool layer and constructions due to radiation and convection is not taken into account;
- fire gases are regarded as ideal gases.

We also assumed that there is a natural gas exchange between inside and external environment, and there is no gas exchange as a result of mechanical ventilation.

In case of determination of temperature field in the upper part of inside around floor elements - steel beams and trusses, the main goal is to define temperature changes during the fire in the hot ceiling layer and changes in size of this layer.

This twin-layer model of fire can be described using difference equations of mass and energy conservation.

Equation of mass conservation concerning the hot ceiling layer:

$$F_{po}\frac{d}{dt}(\rho_h S_h) = \Psi_M + \dot{m}_k - \sum_{i=1}^{N}\dot{m}_{hi} \tag{2}$$

Equation of mass conservation in the cool layer (zone of heat radiation interaction):

$$F_{po}\frac{d}{dt}(\rho_c S_c) = \sum_{i=1}^{N}\dot{m}_{ci} - \dot{m}_k \tag{3}$$

Equation of energy conservation in the hot ceiling layer:

$$F_{po}\cdot c_V\frac{d}{dt}(\rho_h S_h T_h) = \Psi_M\cdot Q_S + \dot{m}_k\cdot c_P\cdot T_C - p_m\cdot F_{po}\cdot\frac{d}{dt}(S_h) - \sum_{i=1}^{N}\dot{m}_{hi}\cdot T_h\cdot c_P - (\alpha_k+\alpha_{pr})\cdot F_{const}\cdot(T_h - T_{const}) \tag{4}$$

Equation of energy conservation in the cool layer (zone of heat radiation interaction):

$$T_c\cdot c_V\cdot F_{po}\frac{d}{dt}(\rho_c S_c) = \sum_{i=1}^{N}\dot{m}_c\cdot T_c\cdot c_P - \dot{m}_k\cdot c_P\cdot T_c - p_m\cdot F_{po}\cdot\frac{d}{dt}(S_c) \tag{5}$$

In equations (2) - (5) the following components were used:

c_P - specific heat at constant pressure, J/kg·K
c_V - specific heat at constant volume, J/kg·K
F_{const} - area of the construction contacting the hot ceiling layer, m^2
F_p - area of fire, m^2
F_{po} - area of inside floor, m^2
m_{ci} - air flow entering zone IV from outside through i-th hole, kg/s
m_{hi} - flow of fire gases leaving the hot ceiling layer through i-th hole, kg/s
m_k - air flow in convection column, kg/s
p_m - average inside pressure
Q_S - heat of combustion, J/kg
S_c - thickness of zone IV, m
S_h - thickness of the hot ceiling layer, m
t - time, s
T_C - air temperature in the cool layer (zone IV), K
T_h - gas temperature in the hot ceiling layer, K
T_{const} - surface temperature of fencing construction, K
α_k - convection surface film conductance, $W/m^2\cdot K$
α_{pr} - radiation surface film conductance, $W/m^2\cdot K$
ρ_c - air density in the cool layer, kg/m^3
ρ_h - air density in the hot layer, kg/m^3
Ψ - mass combustion rate

Formulas for mass flow m_c, m_h, m_k calculation can be found in [1] and [2].

Inside temperature calculation in the place where steel construction is located can be performed using computer program (version for PC). The block diagram of this program is shown in Fig. 2.

Symbol description in Fig. 1 and 2:

F_p - area of fire,
F_{po} - total room area,
m_h - gas flow leaving zone III,
m - gas flow entering zone IV,
m_k - gas flow entering the convection column,
T_h - temperature of gases in the hot ceiling layer (smoke zone),
S_c - height of zone IV,
T - time of calculation,
T_l - time step,
Y_l - location of upper edge of ventilating hole.

3. Determination of temperature increase in uncovered steel constructions

During the first minutes of fire thermal inertia of the construction steel results in a lower rate of steel heating, so the steel temperature will be markedly lower than that of the hot ceiling layer. Then these temperatures will be equalised and differences will be smaller. The heating rate of steel elements during fire depends on their mass factor.

This factor can be defined as a ratio of fire-exposed surface area to the volume, referred to the unit length. In case of truss members heated along the whole perimeter it is the ratio of perimeter to cross-sectional area U/F (U - perimeter, F - cross- sectional area). In case of truss member heated only partially, U is defined as part o f the perimeter exposed to fire.

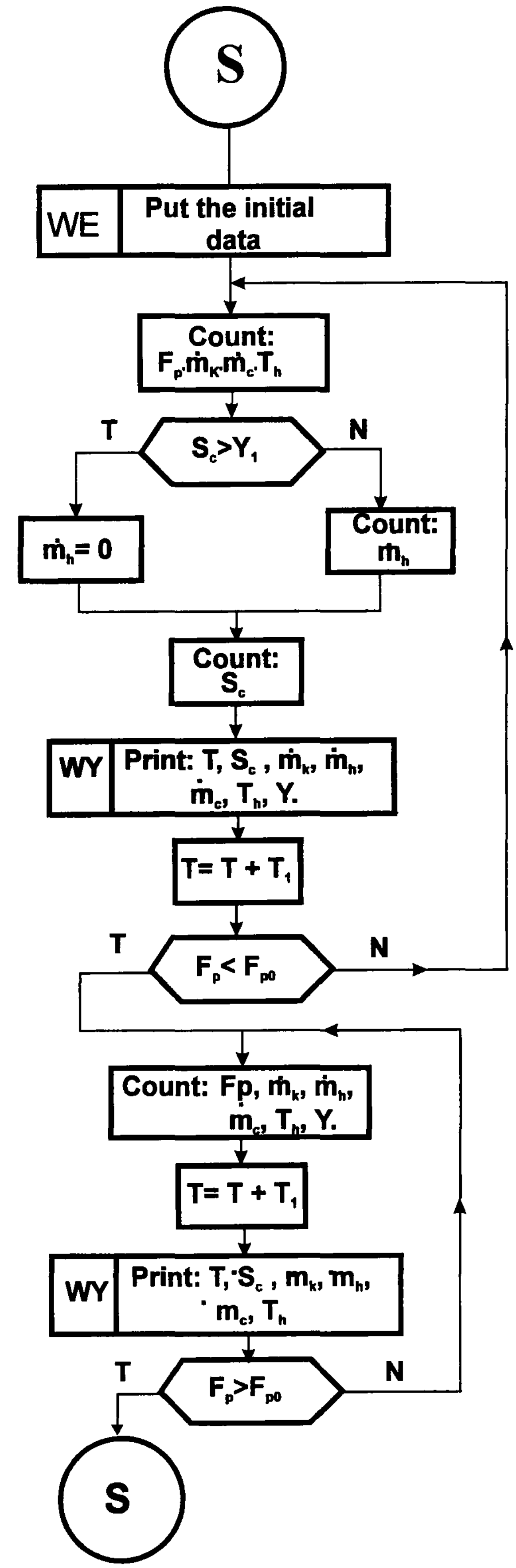

Fig. 2. Block diagram of computer program for calculating temperatures in the room during fire

Mass factor of significant part of steel constructions adopts high values (higher than 30 m^{-1}). In this case we can assume with sufficient precision that temperature of the whole cross-section is equal.

Generally the heat transfer through the cross-section is described by the Fourier equation:

$$c\rho\frac{dT}{dt} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \tag{6}$$

Boundary condition during heating the whole perimeter:

$$-\lambda\frac{\partial T_F}{\partial n} = \alpha(T_f - T_F) \tag{7}$$

Initial condition:

$$t = 0 \quad T(x,y) = T_o \tag{8}$$

in equations given above:

T_f - ambient temperature, °C, for zone model $T_f = T_h$

T_F - perimeter temperature, °C

$\frac{\partial T_F}{\partial n}$ - normal derivative to perimeter

T_o - initial temperature, °C

α - surface film conductance, W/m²·°C

Because of equalised temperature in cross-section area the Fourier equation can be transformed to the following form:

$$c\rho\frac{dT}{dt} = \frac{U}{F}\alpha(T_f - T), \tag{9}$$

where

T - equalised temperature of cross-section, °C

ρ - steel density, kg/m³

Surface film conductance α is temperature dependent and can be found using one of the following formulas

$$\alpha = 23 + \frac{5{,}77\varepsilon_r}{T_f - T}\cdot\left[\left(\frac{T_{fabs}}{100}\right)^4 - \left(\frac{T_{abs}}{100}\right)^4\right], \tag{10}$$

where

ε_r - emission factor, for floor bearing elements ε_r = 0,5-0,7 (0,7 for truss members)

$T_{fabs} = T_f + 273 \qquad T_{abs} = T + 273$

Author suggests that α can be found with sufficient precision using an approximate formula:

$$\alpha = 23{,}2 + 3{,}48\cdot 10^{-8}\cdot(T_{fabs}^2 + T_{abs}^2)\cdot(T_{fabs} + T_{abs}) \tag{11}$$

The following formula shows the relationship between specific heat and temperature:

$$c = \alpha T^2 + \beta T + \gamma \tag{12}$$

where

T - temperature, °C; c - specific heat, kJ/kg·°C

For steel:

α = 38,1·10^{-8}, β = 20,1·10^{-4}, γ = 0,473

Author suggests calculating temperature changes of uncovered steel constructions by using computerised numerical method.

4. Description of the program for determining construction temperature

4.1. Algorithm description

Program *t*-kon can be used for numerical determination of the temperature of steel construction $T_k[deg]$ for given values of ambient temperature $T_f[deg]$, specified for equal time intervals $\Delta t_f[\mathrm{s}]$. For temperature calculation the linear derivative equation of the following form was used:

$$\frac{dT_k}{dt} = a(T_f - T_k) \qquad (13)$$

where
$$a = \frac{U\alpha}{Fc\rho} \qquad (14)$$

T_f - ambient temperature [deg]

T_k - steel construction temperature [deg]

t - time [s]

ρ - steel density [kg/m^3] (ρ = 7850 kg/m^3)

The following relationships for α and c were assumed:

$$\alpha = 23{,}2 + 3{,}48 \cdot 10^{-8} \cdot \left(T_{fa}^2 + T_{ka}^2\right) \cdot \left(T_{fa} + T_{ka}\right)$$

$$c = 38{,}1 \cdot 10^{-8} \cdot T_k^2 + 20{,}1 \cdot 10^{-4} T_k + 0{,}473 \qquad (15)$$

where: $T_{fa} = T_f + 273$

$T_{ka} = T_k + 273$

Block diagram of program algorithm is shown in Fig. 3.

Numerical solution of the derivative equation the IV-th order Runge-Kutty method was applied. The algorithm of calculation of the construction temperature value $T_k[i+1]$ in every successive time step, based on the previous step value $T_k[i]$, is shown below:

$$T_k[i+1] = T_k[i] + \Delta T_k[i]$$

$$\Delta T_k[i] = (K_1[i] + 2K_2[i] + 2K_3[i] + K_4[i]) / 6 \qquad (16)$$

where: $K_1[i] = \Delta ta\left(T_f[i] - T_k[i]\right)$

$K_2[i] = \Delta ta\left(T_f[i] - T_k[i] - K_1[i]/2\right)$

$K_3[i] = \Delta ta\left(T_f[i] - T_k[i] - K_2[i]/2\right)$

$K_4[i] = \Delta ta\left(T_f[i] - T_k[i] - K_3[i]\right)$

$T_k[0] = \mathrm{T0}$

T0 - initial temperature of construction [*deg*]

Δt - assumed constant time step for numerical integration (assumed value in this program Δt = 0,05 s)

4.2. How to use this program

The following input data should be added to the program: a) value of U, b) value of F, c) initial temperature of construction $T_k[0]$ in [*deg*], d) time step Δt_f in [*s*], e) number of calculation steps N adequate to the number of entered ambient temperatures, f) ambient temperatures in successive time steps from $T_f[1]$ to $T_f[N]$, g) print step $\Delta t_w[s]$.

Then the user should select from menu the output for calculation results. The following options are available:

a) SCREEN (EKRAN) - results are displayed on the computer screen,

b) PRINTER (DRUKARKA) - results are printed (supposed that printer is on line and connected to LPT1 port),

c) FILE (PLIK) - results are sent to the text file named **dane.dat** located in the directory DANE on disk C:).

After selecting a desired option by its highlighting and pressing <Enter> key calculating procedure is activated. After finishing this process the following question appears on the screen:

Do you want to continue calculations (t/n)?

Pressing the <Enter> key results in repeating the data entering procedure and calculation is performed again for the new set of input values. Pressing <N> and then <Enter> key finishes the program.

Conclusions

- The zone model of fire shown in this article is based on the existence of two layers: a hot upper layer and a cool lower layer. This model is very useful for determining the increase in hot ceiling layer temperature, because results thus obtained are closer to reality than using other methods, for example, when standard thermal fire conditions are

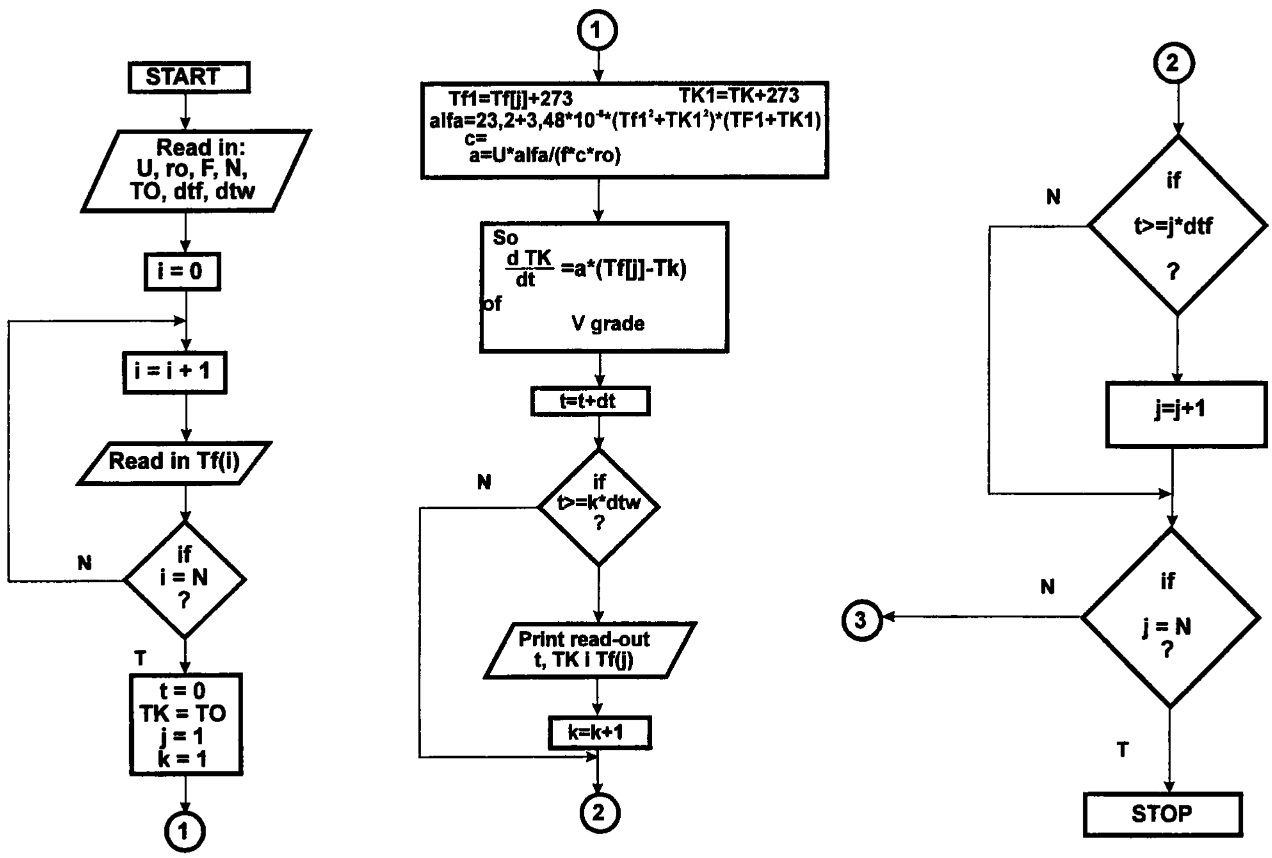

Fig. 3. Block diagram of computer program for calculating temperature of uncovered steel construction

assumed. The physical and chemical parameters of burning substances and the basic room characteristic influencing fire development are taken into account for hot ceiling layer determination.

- The article shows the numerical method of determination of the uncovered steel construction temperatures during a standard fire, or the fire described using another selected model: zone, integral or in the form of "time-temperature" distribution. This method allows a quick analysis of increase in temperature of steel trusses or other steel floor bearing elements.

References

1. W. Piórczyński, Z. Dobkowski. Porównanie zagrożenia pożarowego stwarzanego przez wybrane materiały naturalne i tworzywa sztuczne. Polimer - Tworzywa Wielkocząstkowe, 1946, 41, No 4, p. 229-232.
2. E. Sygnatowicz, J. Wolanin. Metody obliczenia grubości warstwy podsufitowej oraz przebiegu temperatury tej warstwy w warunkach pożaru wewnętrznego. Zeszyty Naukowe SGSP 1985, No 3, p. 55-66.

Įteikta 1996 06 15

DENGINIO METALINIŲ KONSTRUKCIJŲ TEMPERATŪROS NUSTATYMAS SKAITMENINIU METODU

Z. Bednarek

S a n t r a u k a

Straipsnyje pateikiamas denginio metalinių konstrukcijų (santvarų, sijų ir kt.) temperatūros nustatymo skaitmeninis metodas, kai gaisro režimas standartinis. Pagal analizuojamas teorines paklaidas ir lygtis yra sudarytas algoritmas. Pasiūlymams realizuoti naudojama T-kon programa; ji lengvai taikoma praktiniams uždaviniams spręsti. Naudojantis siūlomu metodu, greitai ir nesunkiai gali būti apskaičiuojami temperatūros pokyčiai metalinėse konstrukcijose gaisro metu.

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