Meaning of Existence of Hot Gas Layer for Determination of the Fire Plume Centreline Temperature

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Abstract – As fire develops Fire Plume occurs. The temperature characteristics of Fire Plume are described as average, axial or in the radial distance from the centerline. Common methods used for the determination of axial temperature of Fire Plume assume standard conditions of the surroundings and do not take into account the existence of an accumulated layer of hot gases below the ceiling structure that is characteristic for fires in closed premises, though. The contribution evaluates the meaning of existence of hot gas layer for the determination of Fire Plume centreline temperature. It assesses relative variability of temperatures determined by commonly applied methods which do not take the effect of a hot gas layer into account, and by a method that takes the existence of hot gas layer into account. From the assessment it is ensued that the existence of hot gas layer does play a crucial role in the determination of Fire Plume axial temperature.

Keywords – Fire, Fire Plume, temperature, gas layer, computational methods.

I. INTRODUCTION

During the development of a fire, amongst other things, burnt gases form. A characteristic accompanying then phenomenon of fire, especially in an enclosed space in the phase of its development, is Fire Plume. For various reasons, the subject of concern may be the determination of an incipient smoke temperature. From the point of view of the methods used and the extent of the details, the temperature analysis of smoke and Fire Plumes may be quite variable. The computational methods may be classified as shown in Fig. 1, see reference [1] and [2]. The smoke temperature analysis is carried out for the following reasons, in particular:

- design of a smoke and heat exhaust device,
- assessment of temperature effects on evacuated people,
- assessment of temperature effects on building constructions,
- assessment of temperature effects on stored materials,
- assessment of temperature effects on rescue crews.

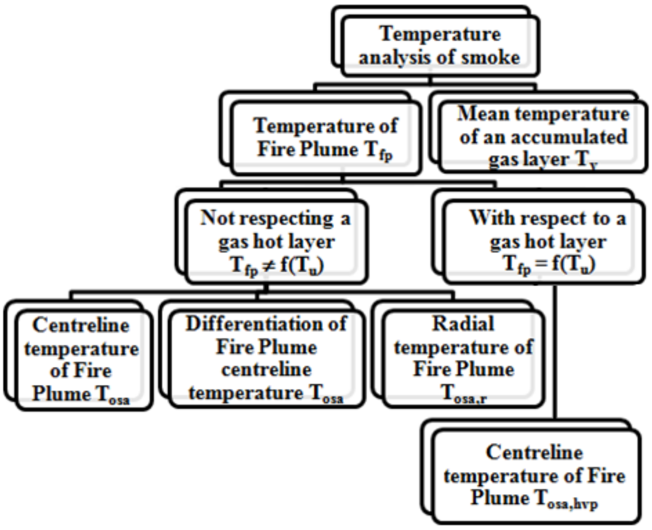

Fig. 1 Smoke temperature analysis

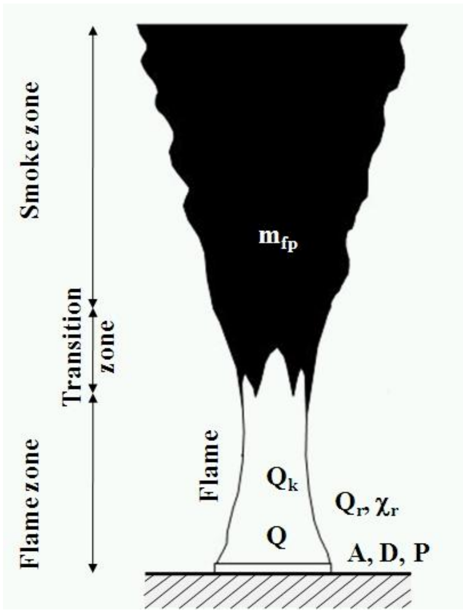

Fig. 2a Fire Plume zoning and description of temperature characteristics in the presence of a gas hot layer

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Figure 2a and b show the zoning of Fire Plumes and a schematic representation of temperature characteristics with respect to a hot gas layer. Further on, attention will be predominantly focused on the presentation of a Fire Plume centreline temperature determination method and a simultaneous consideration of the hot gas layer. The method of determination of the centreline and radial temperatures of Fire Plumes not relating to a hot gas layer will be mentioned only marginally, namely for the purposes of comparison of the computational methods.

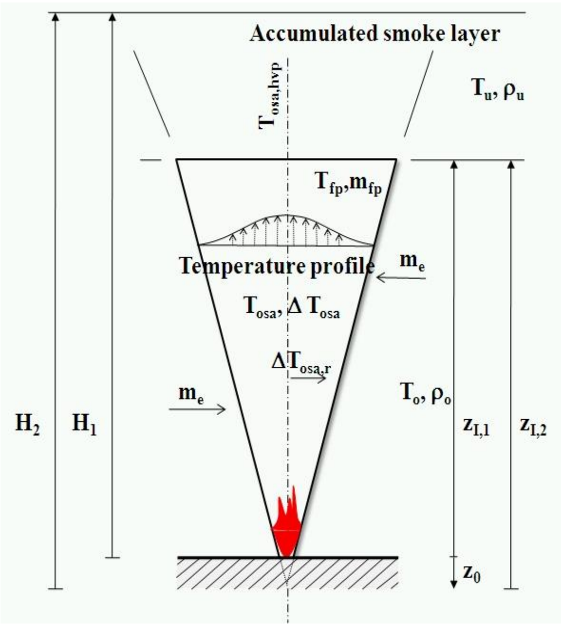

Fig. 2b Fire Plume zoning and description of temperature characteristics in the presence of a gas hot layer

Legenda for Fig. 2:

- m_e mass of air entrainment (kg×s^{-1}),
- m_{fp} mass of gases in Fire Plume (kg×s^{-1}),
- $z_{I,1}$ distance between the inflammable material surface and layer boundary (m),
- $z_{I,2}$ distance from the Fire Plume virtual start to the layer boundary (m),
- z_0 Fire Plume virtual start (m),
- A fire region (m^2),
- D fire diameter (m),
- H_1 height between the inflammable material surface and the ceiling (m),
- H_2 height from the Fire Plume virtual start to the ceiling (m),
- P fire perimeter (m),
- Q heat flux (kW),
- Q_k heat flux shared by convection (kW),
- Q_r heat flux shared by radiation (kW),
- T_{fp} Fire Plume temperature (K),
- T_o temperature of the surroundings (K),
- T_{osa} Fire Plume centreline temperature (K),
- $T_{osa,hvp}$ Fire Plume centreline temperature at a gas hot layer action (K),
- T_u gas hot layer temperature (K),
- ΔT_{osa} temperature increase in the Fire Plume centreline (K),
- $\Delta T_{osa,r}$ temperature increase in Fire Plume in the radial distance from the centreline (K),
- χ_r radiation fraction (1),
- ρ_o ambient air density (kg×m^{-3}),
- ρ_u gas hot layer density (kg×m^{-3}).

In the chapters below it is expected the reader is acquainted with the usual description of developing fire dynamics, classification into the so-called characteristic types of fire (slow, moderate, fast and very fast), basic zoning of Fire Plumes (flame zone, transition zone and smoke zone) and the significance of the virtual start of a Fire Plume.

II. CENTRELINE AND RADIAL TEMPEATURES OF FIRE PLUME NOT RESPECTING A GAS HOT LAYER

One of the most important temperatures characterizing the development of a Fire Plume is the centreline temperature. The derivation of equations for the centreline temperature determination is accompanied by a number of theoretical and experimental works [3]. To determine the proportion of $\Delta T_{osa}/T_o$ the following equation was derived

$$\frac{\Delta T_{osa}}{T_o} = \frac{5}{6}\left(\frac{9\,\pi^2\,\alpha^4}{10}\right)^{\frac{-1}{3}} g^{\frac{-1}{3}} \left(c_p\,\rho_o\,T_o\right)^{\frac{-2}{3}} Q_k^{\frac{2}{3}}\, z^{\frac{-5}{3}} \qquad (1)$$

where:

- π Ludolph number (3.1415927),
- α coefficient of air entrainment into Fire Plume (1),
- g gravity acceleration (m×s^{-2}),
- c_p gas specific heat capacity (kJ×kg^{-1}×K^{-1}),
- z height above the inflammable material surface (m).

Experimentally, to determine the centreline temperature of Fire Plumes Heskestad [1] derived the equation below [3], [4]

$$\Delta T_{osa} = \alpha \left(\frac{T_o}{g\,c_p^2\,\rho_o^2}\right)^{1/3} Q_k^{2/3}\,(z - z_o)^{-5/3} \qquad (2)$$

An acceptable coefficient value of air entrainment α in equation (1) may be considered the value of 0.0964 and value of 9.1 in equation (2). Providing normal conditions of the surroundings [2] the equation (2) may be modified to

$$\Delta T_{osa} = 25\ \frac{Q_k^{2/3}}{(z - z_0)^{5/3}} \qquad (3)$$

[1] The equation derived by Heskestad ranks among the best known equations to determine the centreline temperature of Fire Plume. However, it is not the only computational method. There are numerous methods to determine the centreline temperature of Fire Plume by various authors.

[2] Under normal conditions of the surroundings the temperature of the surroundings is considered T_o = 293.15 K, ambient air density ρ_o = 1.2 kg×m^{-3} and specific heat capacity of air c_p = 1.005 kJ×kg^{-1}×K^{-1}.

It must be pointed out that in the vicinity of the flame zone and transition zone the temperatures of Fire Plume determined by equations (2) and (3) may demonstrate unrealistically low values. A more detailed analysis of the issue is not the subject of the paper. A profile of Fire Plume temperature changes may be characterized by a Gaussian model [3]

$$\Delta T_{osa,r} = \Delta T_{osa} e^{\left[-\left(\frac{r}{\sigma_{\Delta T osa}}\right)^2\right]} \qquad (4)$$

where:

r radial distance from the Fire Plume centreline (m),

$\sigma_{\Delta Tosa}$ radial distance of Fire Plume from the centreline to a point where $\Delta T = e^{-1}\Delta T_{osa}$ (m).

For the equation (4) a sufficiently credible justification is not available. However, mainly due to a lack of other solution methods it is used to determine a change in the temperature profile and the results are considered relevant. Figure 3 shows temperature profiles of a Fire Plume. The temperatures are determined for heights of 3, 6, 9 and 12 m above the surface of inflammable materials, medium development of fire defined by a dynamic constant of its development of 300 s×MW$^{1/2}$, fire duration of 900 s, convective ratio of liberated heat flux of 80% Q, heat flux density of 250 kW×m^{-2} and normal conditions of the surroundings. Section temperatures were determined making use of equations (2) and (4).

Figure 3 implies that Fire Plume profiles have a typical cylindrical character which is approximately identical in all its heights as for its shape. A drop in the temperature towards its margins slows down along with a rise in height.

Figure 4 depicts comparison of temperature increase in the Fire Plume centerline and temperature increase in the radial distance. The illustrative picture was processed for medium development of fire, hight above the surface of flammable materials z = 3, 6, 9 and 12 m, convective ration of heat flow 80% Q, heat flow density 250 kW×m^{-2} and standard ambient conditions. The figure depicts increase in the Fire Plume centerline temperature and temperature increase in the radial distance of 0.5×m.

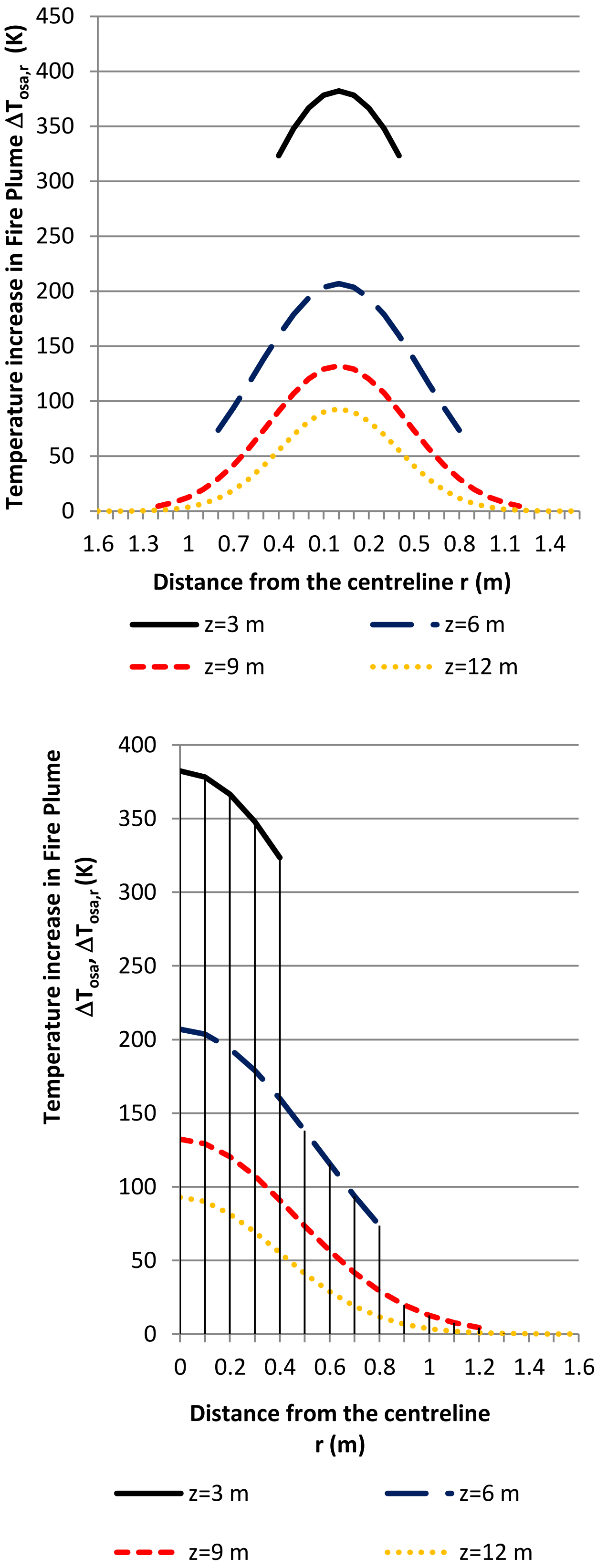

Fig. 3 Temperature profile of Fire Plume for medium development of fire

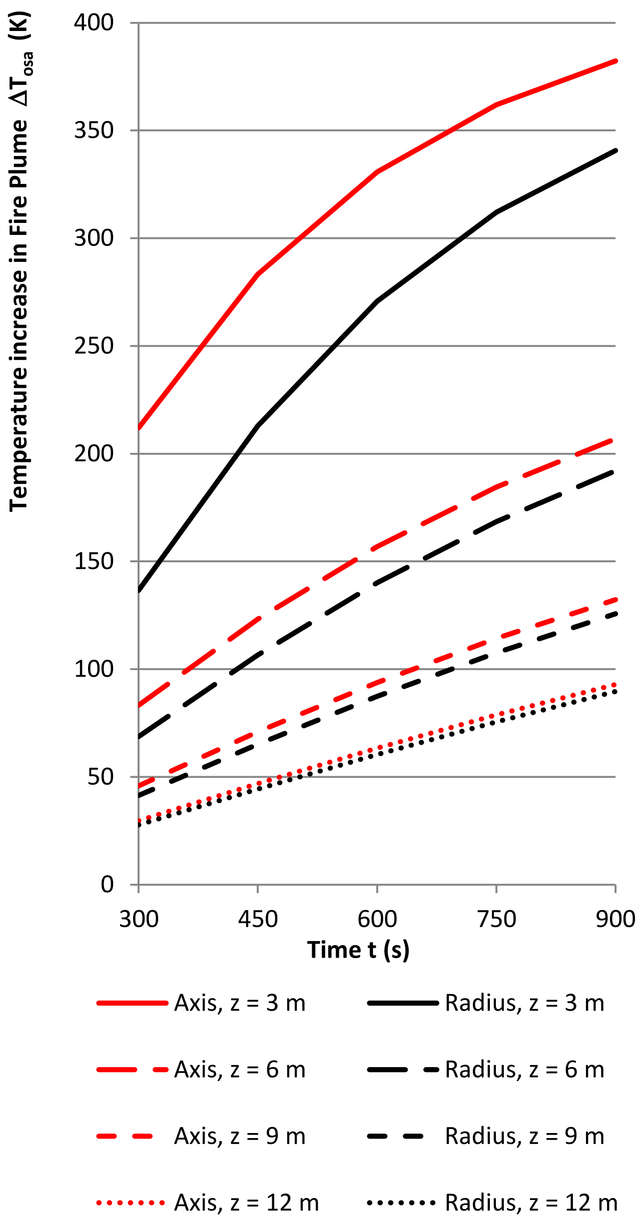

Fig. 4 Increase in Fire Plume centreline and radial temperatures

Fig. 4 indicates correct results of equations presented earlier. However, more detailed analyses indicate that the equation used for determination of temperature increase in Fire Plume centreline in radial distance can be perceived as referential only.

III. CENTRELINE TEMPEATURE OF FIRE PLUME WITH RESPECT TO A HOT GAS LAYER

The significance of the hot gas layer's action on the temperature of a Fire Plume was subjected to experimental research [5], [6]. A series of experiments were primarily carried out in Barbers Point in Hawaii and Keflavik in Iceland. Experiments were carried out in the enclosed premises of a hangar. During the experiments the Fire Plume temperature was measured using a system of thermocouples placed below the ceiling construction for heat outputs in the range from 1.4 to 33 MW. The experiments served as a basis to make theoretical relations to handle the Fire Plume centreline temperature as an action of a hot gas layer. The equations (1) and related, presented methods to determine an increase in the centreline temperature of a Fire Plume ΔT_{osa}, or temperature of the centreline in the radial distance, in dependence on liberated heat flux Q, or its convective section Q_k, height above the fuel surface z, virtual start of Fire Plume z_0 and conditions of the surroundings. However, along with a developing fire there is a gradual formation of a layer of hot gases below the ceiling construction. When a Fire Plume penetrates through the hot gas layer its overall and centreline temperatures are affected as a result of changes in the surrounding conditions. In the shaping Fire Plume gas entrainment occurs, which has a higher temperature than the ambient temperature and thus the fall in temperature slows down along with a rise in the distance above the inflammable material surface.

Mathematically, the temperature dependence of the Fire Plume centreline with respect to the presence of a hot layer may be determined by making use of the equations below. The substance of the calculation is based on the determination of the distance of the Fire Plume virtual start from the layer boundary $z_{I,2}$, distance between the surface of inflammable materials and the layer boundary $z_{I,1}$ and corrected heat flux Q_2. Auxiliary calculation values are dimensionless values of fire intensity $Q^*_{I,1}$ and $Q^*_{I,2}$. The temperature of Fire Plume centreline considering a gas hot layer may be expressed by an equation below

$$T_{osa,hvp} = T_u + 25.5 \frac{\left(\left(1-\chi_r\right) Q_2\right)^{2/3}}{H_2^{5/3}} \qquad (5)$$

where:

$T_{osa,hvp}$ Fire Plume centreline temperature at a gas hot layer action (K),

Q_2 corrected heat flux (kW).

Corrected heat flux may be determined by an equation as follows

$$Q_2 = Q^*_{I,2}\, \rho_u\, c_p\, T_u\, g^{1/2}\, z_{I,2}^{5/2} \qquad (6)$$

where:

$Q^*_{I,2}$ dimensionless value of fire intensity (1).

The distance of the Fire Plume virtual start to the ceiling can be expressed by a relation

$$H_2 = H_1 - z_{I,1} + z_{I,2}. \qquad (7)$$

The value $z_{I,2}$ may be determined by an equation

$$z_{I,2} = z_{I,1}\left[\frac{\xi\, C_T\, Q^*_{I,1}}{Q^{*\frac{1}{3}}_{I,2}\left[(\xi-1)\,(\beta^2+1) + \xi\, C_T\, Q^{*\frac{2}{3}}_{I,2}\right]}\right]^{\frac{2}{5}} \tag{8}$$

where:

ξ temperature ratio of the upper and lower layers (1)
C_T constant; 9.115 (1)
$Q^*_{I,1}$ dimensionless value of fire intensity (1)
β constant speed from the temperature ratio of a half of the Gaussian profile width; 0.913 (1)

The value of heat flux $Q^*_{I,2}$ can be specified by an equation

$$Q^*_{I,2} = \left[\frac{1 + C_T\, Q^{*\,2/3}_{I,1}}{C_T\,\xi} - \frac{1}{C_T}\right]^{3/2}. \tag{9}$$

The value of heat flux $Q^*_{I,1}$ can be determined by an equation

$$Q^*_{I,1} = \frac{Q}{\rho_o\, c_p\, T_o\, g^{1/2}\, z^{5/2}_{I,1}} \tag{10}$$

where:

Q heat flux (kW).

The centreline temperatures of a Fire Plume T_{osa} not relating to and with relating to the hot gas layer are in Fig. 5. The temperatures were set for a heat flux of 1000 to 5000 kW, temperatures of a hot gas layer from 300 to 1000 K, a distance between the inflammable material surface and the ceiling of 4 m, a distance between the inflammable material surface and layer boundary of 2 m, convective ratio of liberated heat flux of 80% Q and normal conditions of the surroundings. It is apparent from Fig. 5 that the existence and parameters of a hot gas layer have a decisive influence on the Fire Plume centreline temperature. Along with a rise in temperature of the hot gas layer T_u there is also an increase in the centreline temperature of a Fire Plume $T_{osa,hvp}$. At gas layer temperatures of 1000 K the Fire Plume centreline temperature considering this hot layer $T_{osa,hvp}$ is approximately double, in contrast to the Fire Plume centreline temperature not relating to it T_{osa}.

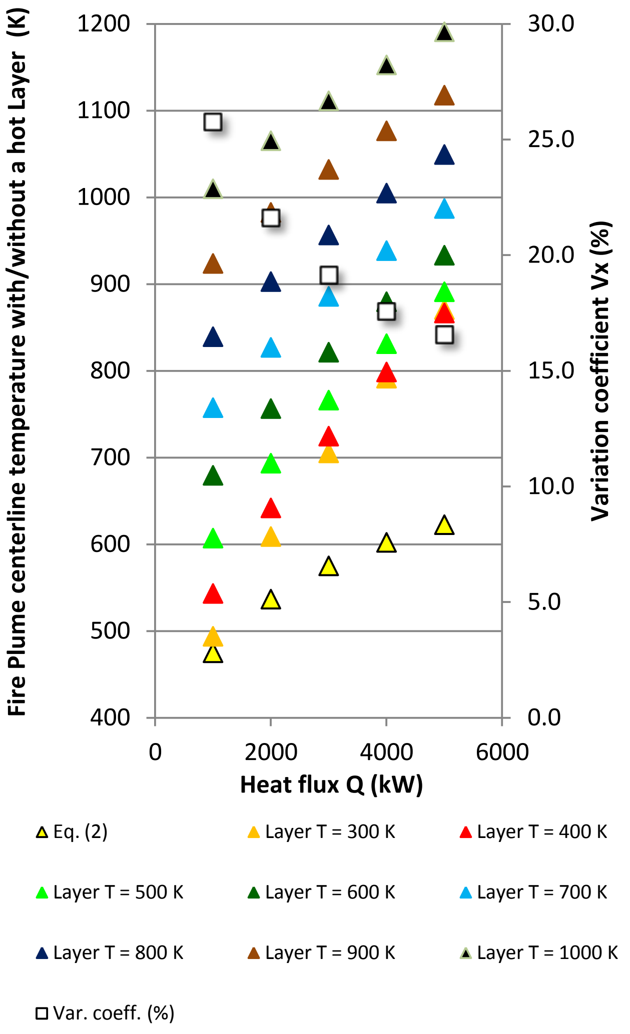

Fig. 5 Fire Plume centreline temperature with/without respect to a gas hot layer

A suitable statistic parametre of compared values is a variation coefficient expressed by equation:

$$V_x = \frac{100\, s_x}{\bar{x}}, \tag{11}$$

where

V_x variation coefficient (%)
s_x nominal deviation (1)
$\bar{x}$ arithmetic average (1)

The variation coefficient represents a relative variability rate which expresses the difference between monitored values. Undoubtedly, the relation of variation coefficient V_x for individual values of released heat flows Q is worth attention. Figure 5 implies that the variation coefficient value and thus also the degree of relative variability between the specified values decrease along with a rise in the liberated heat flux value. From the variation coefficient values it is possible to deduce that along with an increase in the liberated heat flux value the presence or absence of the gas hot layer gains an importance over and against the temperature of such a layer.

IV. FUTURE DEVELOPMENT

In the future, the methods suitable for the temperature analysis of Fire Plumes should be based on the probabilistic approach too. Let us consider the Simulation-Based Reliability Assessment (SBRA) Method, a probabilistic direct Monte Carlo approach, in which all inputs are given by bounded histograms. Bounded histograms include the real variability of the inputs and outputs, see references [7] and [8] and Fig. 6. Application of the SBRA Method is a modern and innovative trend in mechanics.

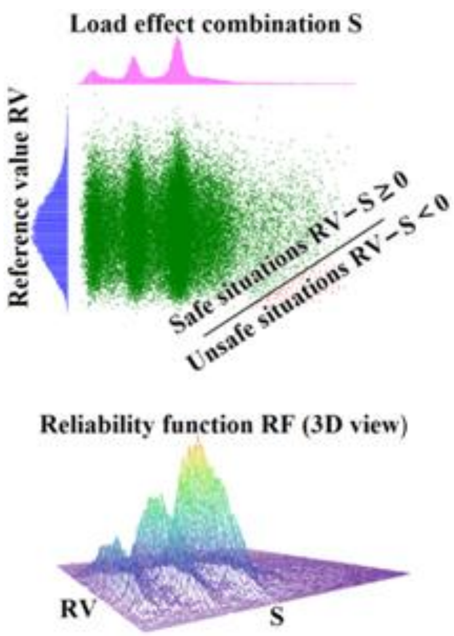

Fig. 6 Monte Carlo approach (SBRA Method)

Some application of SBRA Method (mining, fatigue testing, biomechanics, geomechanics, civil engineering, mechanical engineering etc.) are presented in [7] [8], [9], [10], [11], [12], [13], [14], [15] and [16], for example see Fig. 7, 8 and 9.

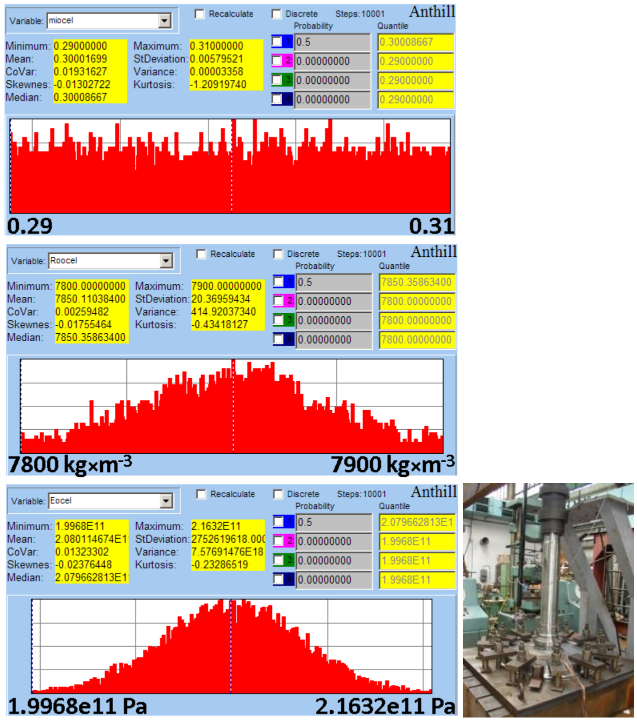

Fig. 7 Examples of histograms and applications of the SBRA Method – stochastic inputs (design study of machine for fatigue testing of railway axles, see reference [7] and [9])

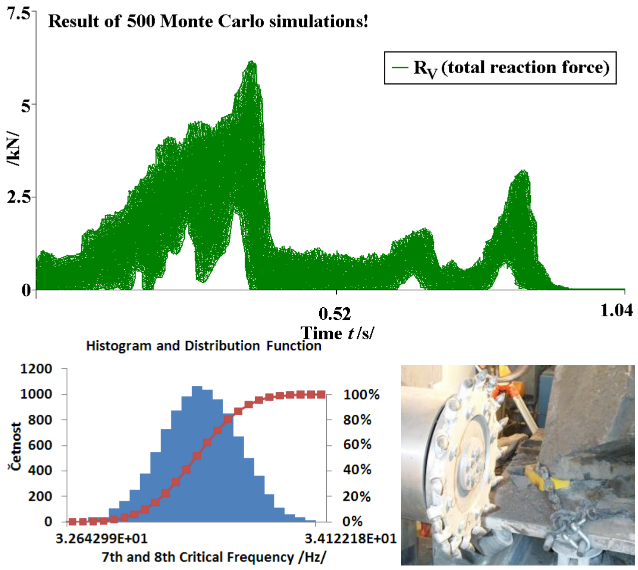

Fig. 8 Examples of histograms and applications of the SBRA Method – stochastic outputs (solution of a hard rock disintegration process, see references [7] and [9])

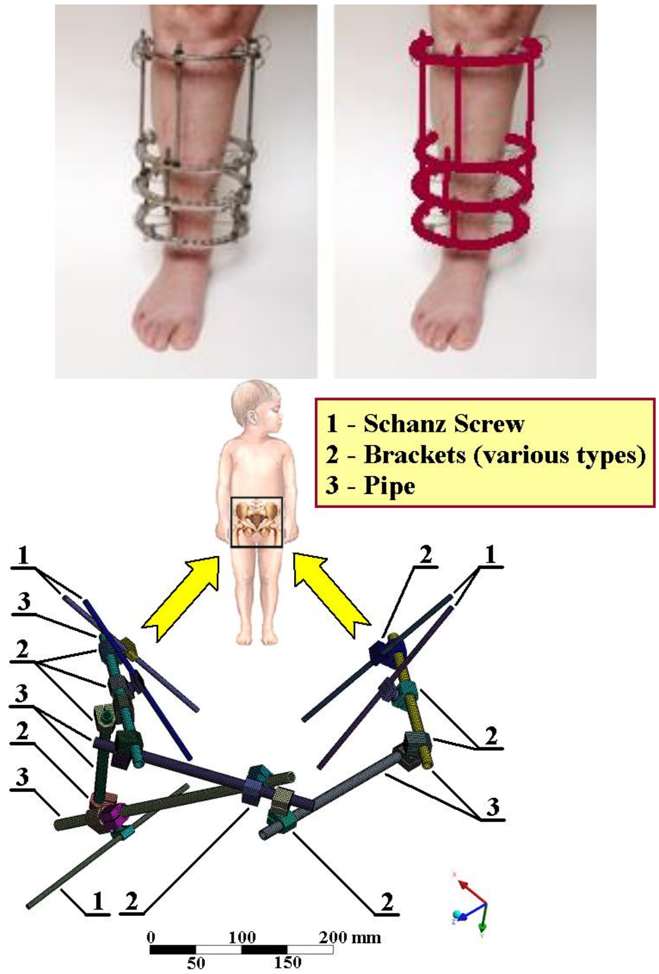

Fig. 9 Examples of application of the SBRA Method (designing of external fixators applied for the treatment of open and unstable fractures, see references [12] and [13])

V. CONCLUSION

The paper describes a systematic classification of methods suitable for a temperature analysis of Fire Plumes and has presented some of the methods to determine centreline and radial temperatures of Fire Plumes. In particular, attention was paid to the presentation of a method suitable to determine the Fire Plume's centreline temperature with respect to an accumulated hot gas layer. It is clear from the text that in cases with a formation of a hot gas layer, it is vital to analyze its temperature and the identified value must be taken into consideration in the determination of the Fire Plume centreline temperature. Making use of the described method of the Fire Plume centreline temperature determination considering a hot gas layer requires sufficient information on the temperatures and distribution of the layers in the space. The required values are functions of time and need not be always determined with a sufficient accuracy, which may be a reason for the limited utilization of the presented method. In the future, the methods suitable for the temperature analysis of Fire Plumes should be based on the probabilistic approach too, i.e. via Simulation-Based Reliability Assesment (SBRA) Method.

ACKNOWLEDGEMENT

1. This work was supported by the Ministry of Industry and Trade of the Czech Republic as the part of project № MPO FR-TI3/818.

2. This work was supported by the project of the Interior Minister of the Czech Republic No. VG 20122014074 "Specific Assessment of High Risk Conditions for Fire Safety by Fire Engineering Procedures".

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