STUDY OF THE NECESSITY OF USE OF VIRTUAL ORIGIN IN ASSESSMENT OF SELECTED FIRE PLUME CHARACTERISTICS

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The introduction of this article describes the significance and characteristic of the Fire Plume virtual origin, which is used in the assessment of certain local fire parameters. Based on selected characteristics for determining the rising of axial temperature, gas flow rate and mass volume of smoke in a Fire Plume, the necessity of the use of virtual origin was assessed. The results were compared using selected statistical methods. The study was done for a fire thermal outputs from 1000 to 5000 kW and heights above the flammable material surface from 5 to 50 m. Based on the delimitation of deviation acceptability limits, where the variation coefficient value was selected up to 10% and the percentage deviation up to 15%, regression power and linear functions were derive, which, based on magnitude of the released heat flow, determine the minimal height above the fuel surface at which the Fire Plume virtual origin can be omitted under presumed conditions. At the same time, there are principles affecting the necessity of use of Fire Plume virtual origin in practical applications presented which may be designs of smoke and heat systems, respectively other fire safety equipment.

KEYWORDS
local fire, virtual origin, functional relation

1 INTRODUCTION

During assessment of the fire propagation phase we typically speak of so-called local fire [ISO/TS 16 733 2006]. A developing fire is accompanied by the origin and evolvement of a flue gas column, which is called a Fire Plume.

A Fire Plume can be divided into three basic zones, i.e. flame zone, transition zone and smoke zone. The Fire Plume was studied from different viewpoints, e.g. geometry, temperature, gas flow rate and gas mass volume. [Heskestad 2016, Hosser 2013]

The original research of the Fire Plume was developed by numerous researchers. The correlation of flame height and volume of sucked air into the Fire Plume was assessed by G. Heskestad [Heskestad 2016], significance and volume of sucked air into the Fire Plume, or sucking of air in the near and far part of the Fire Plume was solved by E. E. Zukoski, T. Kubota and B. Cetegen [Zukoski 1981, Cetegen 2007], the Fire Plume in terms of development dynamics was studied by G. Heskestad [Heskestad 1998], etc. The original researches of the Fire Plume were follow-up by further research, e.g. a recent work by X. Zhang and coll., involving the relationship between flame height and axial temperature of a turbulent line source of Fire Plume [Zhang 2014]. Specific current research works include work by T. Beji and coll., involving the assessment of rate of smoke filling in large volume spaces [Beji 2012] or H. Miloua and coll., focused on evaluation of different numerical approaches for ventilation of tunnel structures [Miloua 2011].

The Fire Plume virtual origin z_v is used for assessment of the characteristics of the respective zones. [Heskestad 2016, Hosser 2013]

Works done by G. Heskestad can be especially ranked among the original works focusing on the Fire Plume virtual origin. The works involved mainly the correlation between the Fire Plume virtual origin and the mean flame height [Heskestad 1983]. Works by other authors follow-up onto the work of Heskestad, focusing on researching the Fire Plume virtual origin under specific conditions. For example, the work focused on researching the Fire Plume virtual origin in a turbulent environment done by G. R. Hunt and N. G. Kaye [Hunt 2001] or experimental works related to deriving sub-ceiling gas temperature affected by a cumulated gas top layer, where a modified Fire Plume virtual origin was derived, authored by Z. H. Gao and coll. [Gao 2015], or the study involving the relationship of flame height from openings during insufficiently ventilated fires, which required additional determination of the Fire Plume virtual origin, authored by F. Tang and coll. [Tang 2012].

It is clear that the Fire Plume virtual origin was, and no doubt, will continue to be the subject of interest of experts in this field of research. [Malerova 2014]

The aim of this article is to assess, on selected Fire Plume characteristics, the necessity of use of virtual origin for local fire.

2 SIGNIFICANCE OF FIRE PLUME VIRTUAL ORIGIN

Originally (historically) so-called point sources of fires with low thermal outputs were researched. However, in real situations we also encounter different geometrical shapes of fires with large thermal outputs. The Fire Plume virtual origin enables the transformation of originally derived expressions in relation to real fires. [Heskestad 2016, ISO 16 734 2006]

The virtual origin “demonstrates” a Fire Plume point source, above which flames are “starting to appear”. The virtual origin is located above the surface of flammable materials (reaches positive values) or under the surface of flammable materials (reaches negative values). [ISO 16 734 2006]

3 METHOD

3.1 Characteristic of Fire Plume Virtual Origin

The Fire Plume virtual origin in dimensionless form is typically described by the equation [ISO 16 734 2006]:

$$\frac{z_v}{D} = -1.02 + 15.6(X-Y)\frac{Q^{2/5}}{D} \tag{1}$$

where	z_v	Fire Plume virtual origin (m)
	D	fire diameter (m)
	X	coefficient ($m.kJ^{-2/5}.s^{2/5}$)
	Y	coefficient ($m.kJ^{-2/5}.s^{2/5}$)
	Q	thermal flow (kW)

The coefficients in equation (1) can be determined using the following equations [ISO 16 734 2006]:

$$X = \left[\frac{c_p \cdot T_\mathrm{a}}{g \cdot \rho_\mathrm{a}^2 \cdot \left(\frac{\Delta H_c}{s} \right)^2} \right]^{1/5} \tag{2}$$

$$Y = 0.158 \left[\left(c_p \rho_a \right)^{4/5} \cdot T_a{}^{3/5} \cdot g^{2/5} \right]^{-\frac{1}{2}} \cdot \alpha^{2/5} \cdot \frac{T_{OL}^{1/2}}{\Delta T_{OL}^{3/5}} \tag{3}$$

$$T_{OL} = \Delta T_{OL} + T_\mathrm{a} \tag{4}$$

where		
	c_p	specific thermal capacity (kJ.kg^{-1}.K^{-1})
	T_a	ambient temperature (K)
	g	gravity acceleration (m.s^{-2})
	ρ_a	density of ambient air (kg.m^{-3})
	ΔH_c	combustion heat (kJ.kg^{-1})
	s	stoichiometric ratio of air and fuel (-)
	α	convective ratio of released heat flow (-)
	T_OL	axial temperature of mean flame height (K)
	ΔT_OL	increase of axial temperature of mean flame height (K)

Under normal atmospheric conditions, i.e. g = 9,81 m.s^{-2}, c$_\mathrm{p}$ = 1,00 kJ.kg^{-1}.K^{-1}, ρ_a = 1,2 kg.m^{-3}, T_a = 293 K, α = 0,7, ΔT_OL = 500 K and $\Delta H_s/s$ = 3000 kj.kg^{-1}, equation (1) can be modified to [ISO 16 734 2006]:

$$\frac{z_V}{D} = -1.02 + 0.083 \frac{Q^{2/5}}{D} \tag{5}$$

or

$$z_V = -1.02D + 0.083Q^{2/5} \tag{6}$$

Equation (6) is used most frequently in practice.

Under normal atmospheric conditions the Fire Plume virtual origin, dependant on the flame height, can be described by equation [ISO 16 734 2006]:

$$z_V = L - 0.175Q_C^{2/5} \tag{7}$$

$$Q_C = \alpha \cdot Q \tag{8}$$

where		
	L	flame height (m)
	Q_c	convective heat flow ratio (kW)

3.2 Method of Assessment of Necessity of Use of Fire Plume Virtual Origin

The necessity of use of the virtual origin was assessed for:

- increase of Fire Plume axial temperature,
- Fire Plume flow rate,
- Fire Plume smoke mass volume.

The said areas were compared for a release heat flow of 1000, 2000, 3000, 4000 and 5000 kW and height above flammable material surface of 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 m. The convective ratio of heat flow was 0.7, heat flow density 250 kW.m^{-2}. The values were intentionally selected in areas which are characteristic for a developing, i.e. local, fire. In principle, they correspond to conditions presented in common technical standards [VDI 6019 2006].

The results of selected Fire Plume characteristics were assessed using the following simple statistical methods:

- arithmetic mean,
- dispersion,
- standard deviation,
- variation coefficient Vx and
- percentage difference of values.

The significance of use of the virtual origin for the increase of the Fire Plume axial temperature was assessed using the following equations, which are modified for normal atmospheric conditions [ISO 16 734 2006, Karlsson 2000]:

$$\Delta T_{axis} = 25 \cdot \frac{Q_c^{2/3}}{\left(z - z_v \right)^{5/3}} \tag{9}$$

where		
	ΔT_axis	increase of Fire Plume axial temperature (K)
	z	height above flammable material surface (m)

By omitting the Fire Plume virtual origin, equation (9) can be modified to:

$$\Delta T_{axis} = 25 \cdot \frac{Q_c^{2/3}}{(z)^{5/3}} \tag{10}$$

The increase of Fire Plume axial temperature and variation coefficient of these values determined by equations (9) and (10) are illustrated in Figure 1.

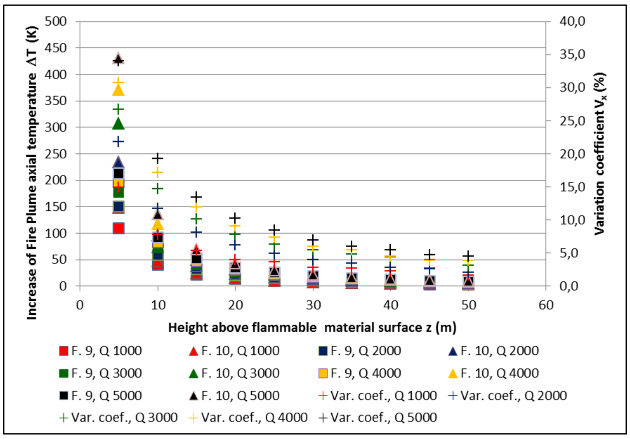

Figure 1. Increase of Fire Plume axial temperature and variation coefficient for compared equations

The significance of use of the virtual origin for the Fire Plume flow rate was assessed using the following equations, which are modified for normal atmospheric conditions [ISO 16 734 2006, Karlsson 2000]:

$$u_{axis} = 1.03 \cdot \frac{Q_c^{1/3}}{\left(z - z_v \right)^{1/3}} \tag{11}$$

where		
	u_axis	Fire Plume flow axial rate (m.s^{-1})

By omitting the Fire Plume virtual origin, equation (11) can be modified to:

$$\Delta T_{axis} = 1.03 \cdot \frac{Q_c^{1/3}}{(z)^{1/3}} \tag{12}$$

The flow rate of gases in the Fire Plume and variation coefficient of these values determined by equations (11) and (12) are illustrated in Figure 2.

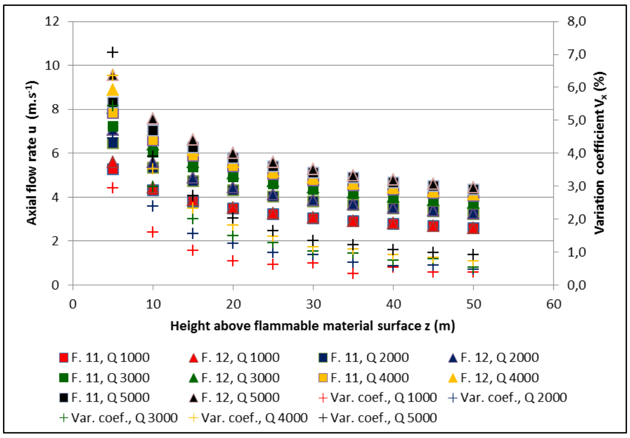

Figure 2. Axial flow rate of gases in the Fire Plume and variation coefficient for compared equations

The Fire Plume smoke mass volume can be determined using equations [Hosser 2013, Kucera 2009, Heskestad 1984]:

$$m_e = 0.071 \cdot Q_c^{1/3} \cdot (z - z_v)^{5/3} \tag{13}$$

where m_e volume of sucked air (in the sense of [Heskestad 2016], it can also be considered as smoke mass volume) (kg.s^{-1})

By omitting the Fire Plume virtual origin, equation (13) can be modified to:

$$m_e = 0.071 \cdot Q_c^{1/3} \cdot z^{5/3} \tag{14}$$

The Fire Plume smoke mass volume and variation coefficient of these values determined by equations (13) and (14) are illustrated in Figure 3.

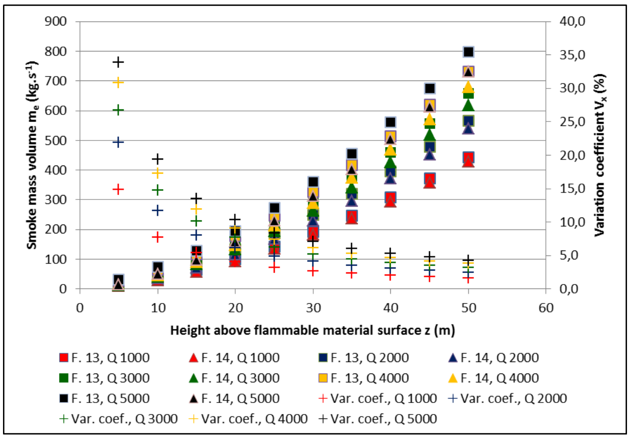

Figure 3. Fire Plume smoke mass volume and variation coefficient for compared equations

4 EVALUATION OF RESULTS, FUNCTIONAL RELATION DESIGN

The results presented in Figures 1, 2 and 3 demonstrate that the change in variation coefficient V_x is functionally dependent on $f = (Q; z)$.

To derive the functional relation it was necessary to define the “tolerance zone”, i.e. acceptable difference between the compared values by considering or omitting the Fire Plume virtual origin. A 10% variation coefficient, which corresponds to approximately 15% difference between values in the compared cases, was selected as the acceptable difference. The said limits were selected based on the presumption that the difference in values in the said interval is practically negligible.

Based on the defined limits, two functional relations were derived. The first relation can be described by a regression power function:

$$\frac{Q^2 \cdot 10^{-3}}{z^3} = 1 \tag{15}$$

The minimum height above the flammable material surface z, at which the Fire Plume virtual origin can be omitted, can then be described using equation:

$$z \geq \sqrt[3]{Q^2 \cdot 10^{-3}} \tag{16}$$

The second relation can be described by the regression linear function:

$$\frac{Q}{z} \leq 0.0267 \cdot Q + 76.5 \tag{17}$$

The minimum height above the flammable material surface z, at which the Fire Plume virtual origin can be omitted, can then be described using equation:

$$z \geq \frac{Q}{0.0267 \cdot Q + 76.5} \tag{18}$$

Equations (16) and (18) determine the minimal height above the flammable material surface z, at which maximum 10% variation coefficient is achieved while omitting the Fire Plume virtual origin when determining two out of three characteristics, i.e. heat increase of Fire Plume axial temperature and Fire Plume mass volume. As was said above, the difference in compared values is approximately 15%.

For the third Fire Plume characteristic, which is the axial rate, a variation coefficient up to 2% and percentage deviation up to 5% are achieved when applying equations (16) and (18).

5 DISCUSSION

The possibility of omitting the virtual origin was assessed in selected Fire Plume characteristics, i.e. increase of axial temperature ΔT_{axis}, axial flow rate u_{axis}, and Fire Plume smoke mass volume m_e. The said characteristics can be considered representative and typically used to characterise a Fire Plume.

The results obtained by the compared equations were evaluated using selected mathematic-statistical methods. The variation coefficient V_x, which is the ratio of the standard deviation and arithmetic mean, can be considered as a suitable indicator characterising the deviation between compared values. The increasing value of the variation coefficient indicates a higher deviation between the values. The deviation was also additionally expressed by percentage difference. The selected methods can be considered adequate for the purpose of assessing the deviation between the compared equations.

Figures 1, 2 and 3 clearly show that the variation coefficient value significantly decreases with the increasing height above the flammable material surface z. The variation coefficient value decreases in the case of increase of the axial temperature and Fire Plume mass volume from tens of percent to units. In the case of Fire Plume axial rate the value drops from units to tenths of units. The Fire Plume virtual origin loses significance with an increasing height above the fuel surface.

From the figures it is also evident that the variation coefficient reaches lower values in all cases at lower heat flow values. On the contrary, higher heat flow values lead to higher variation coefficient values and thereby also higher deviations between compared equations. The Fire Plume virtual origin loses significance with the decreasing heat flow value.

Providing the acceptance of the “defined limits of deviation acceptability”, which are variation coefficient value 10% and percentage deviation value 15%, it can be stated that for heat outputs from 1000 to 5000 kW and heights above the flammable surface from approximately 10 to 25 m the Fire Plume virtual origin can be omitted (depending on the value of the heat flow). For higher heat output the height above the flammable material surface for possible omission of the Fire Plume virtual origin will be greater (e.g. for heat output 1000 kW the Fire Plume virtual origin can be omitted at a height of 10 m, for heat output 5000 kW the Fire Plume virtual origin can be omitted at a height of 25 m). The described relations for omission of the virtual origin relate to the increase of the axial temperature and smoke mass volume of the Fire Plume.

The significance of the Fire Plume virtual origin is substantially lower than for the characteristics presented above. Using derived functional relations and discussed heights above the flammable material surface from 10 to 25 m, the variation coefficient value will not exceed 2%. The presented results lead to the consideration whether it is at all necessary to consider the virtual origin when determining the axial rate of a Fire Plume.

The functional relation for determining the minimum height above flammable material surface at which the virtual origin can be omitted, were derived for heat outputs from 1000 to 5000 kW and heights above the flammable material surface from 5 to 50 m. Their use was verified with a positive result also for fire lower heat outputs at the defined heights. On the contrary, the presented functional relations are not usable for higher heat outputs.

6 CONCLUSION

The article describes the mathematical expression, significance and possible use of the Fire Plume virtual origin. The possible omission of the virtual origin was evaluated for selected Fire Plume characteristics using defined mathematical-statistical methods.

Based on assessment of deviations, general principles were described at which the Fire Plume virtual origin loses significance, i.e. increasing height above flammable material height and decreasing heat output.

At the same time, functional relations were derived for determining the minimum height above flammable material surface at which the Fire Plume virtual origin can be omitted. The derived functional relations have a practical use.

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