Fire Growth Rate Strategies in FDS

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ABSTRACT

The HRR curve is characterized by four phases: the incipient phase, the growth phase, the fully developed phase and the decay phase. A central parameter in the design of buildings and the provision of fire protection measures, is the rate at which the fire develops. Therefore the speed at which a space becomes untenable is mainly dependent on the fire growth rate, which is also closely related to the risk profile selection. To reproduce the fire growth phase, it is generally recommended the use of the t-squared fires [1].

Fire Dynamics Simulator (FDS) 6.6.0 [2] enables us to reproduce the t-squared fire in several ways, by using different “fire growth functions”, i.e. RAMP-function and SPREAD_RATE function. These functions use different approaches. While the RAMP function associates the time history of the HRR curve with the entire surface, the SPREAD_RATE function is similar to a cellular automaton approach and it mimics a radially growing fire along the surface with a constant speed.

In this paper the behavior of the dimensionless heat release rate $Q^*$, during the fire growth phase, has been studied for both the fire growth rate functions. Furthermore, a numerical study of the “growth function dependency” of some important outputs has been carried out, in order to quantify the implications on safety design. If on one hand, in accordance with the Swedish Best Practice [3], the SPREAD RATE should be preferred, seeing that the burning surface is small when the HRR is low and therefore it is possible to maintain applicable values of the $Q^*$ during the fire growth, on the other the case studies performed, using the RAMP function, have shown to be the worst case scenario analysing the gas temperature and the visibility in order to evaluate the Available Safe Egress Time.

KEYWORDS:

Modeling; performance-based design; Fire Safety Engineering, FDS 6.6.0; flame spread; fire growth; heat transfer; fluid dynamics; CFD; Froude number.

NOMENCLATURE LISTING

$c_p$ specific heat (J mol$^{-1}$ K$^{-1}$) $Q_c$ rate of heat release (kW)
$D$ Fire source diameter (m) $T_\infty$ ambient temperature (K)
$Fr$ Froude number $t$ time (s)
$g$ gravity acceleration (m/s$^2$) $U$ velocity of the fuel vapours
$\Delta H_c$ heat of comb. of the fuel vapour $\alpha$ fire growth rate (kW/s$^2$)
$HRR_{PUA}$ Heat Release Rate per unit area $\rho_\infty$ Fuel density (kg m$^{-1}$·s$^{-1}$)
$L$ Flame height (m)
INTRODUCTION

In a life safety analysis that evaluates the ability of the occupants to escape from the enclosure of fire origin, it will normally only be the incipient and growth phases of the fire that are of relevance (after a flashover or full involvement, the possibility of escape can be discounted) [4].

For design purposes, fires are often assumed to grow proportionately to time squared (t-squared fires). The t-squared fire growth can be reproduced by FDS using different approaches, but this paper is going to focus on SPREAD_RATE and RAMP functions. Although the RAMP function is widely used, the Swedish Best Practice guideline [3] recommends the use of the SPREAD_RATE function.

In this report the theoretical consequences of the use of these two methods have been explained, introducing the significant parameters related to the fire growth. Since the aim of this paper is to assess a responsible and informed use of these two approaches, the growth function dependency of some output parameters has been analysed for simple case studies, showing discrepancies and similarities.

A SIGNIFICANT PARAMETER RELATED TO THE FIRE GROWTH

The surface area of the fuel source is a matter of great concern during the fire growth phase. A high HRR generated over a small surface area, will cause the fire plume to be driven by momentum instead of buoyance, similar to a jet flame. Jet flames are more structured than buoyance driven flames which usually occur in building fires and are also less affected by surrounding air flows [4]. If the surface area of the fire source is large with a low HRR, the flame will break up into smaller, separate, flames. This will not represent a “real” fire. Therefore the momentum (or inertia) and buoyancy in the flame will determine the type of fire.

The Froude number (Fr) may be used as a means of classification. It is a measure of the relative importance of inertia and buoyancy in the system, and is conveniently expressed as:

\[ Fr = \frac{u^2}{gD} \]  
(1)

A vast number of experiments have been carried out that relate flame heights to energy release rate and source diameter. The scientific community has found it convenient to express the data in terms of a non-dimensional energy release rate, denoted \( \dot{Q}^* \), and given by the following expression:

\[ \dot{Q}^* = \frac{\dot{Q}_c}{\rho_o c_p T_o \sqrt{gDD^2}} \]  
(2)

The \( \dot{Q}^* \) represents the square root of the Froude number and has been found to be very important in controlling the geometry of fire plumes. So it is important to define an optimum value for the engineering applications [5]. Cox and Kumar [6] define that dimensionless HRR (\( \dot{Q}^* \)) should be in the range of 0.3 to 2.5 for natural fires in buildings. Using this range, along with the recommended design fires in the national guidelines, a range of applicable fire diameters can be calculated. With a known fuel surface diameter, the heat release rate per unit area (HRRPUA) can also be calculated.

T-SQUARED FIRE GROWTH

The growth phase begins when the fire exhibits a heat release rate that increases beyond a negligible level. Flame spread is the typical mechanism that governs fire growth. Flame spread is the phenomenon of flames moving across an object, igniting that which with they come into contact. When the growth stage is calculated analytically, it is done with the power low equation in engineering applications:

\[ \dot{Q}_c = at^p \]  
(3)

A fire growing outward radially at a constant rate should have an exponent of \( p=2 \) because the area of the involved circular surface grows with the square of the radius, where the radius is predicted to grow linearly in time. Testing has shown that this exponent is valid for a wide range of material and objects. These fires are commonly referred to as t-squared fires [7].

There are several ways to reproduce these t-squared fires in FDS 6.6.0 using the simple pyrolysis model. This paper is going to discuss the following functions, characterized by two different approaches:

- RAMP function;
- SPREAD_RATE function (hereinafter referred to as S_R);
It is worth mentioning that there is also a third method that achieves the S_R behavior, using the RAMP function with a control logic. Since the aim of this paper was to study these two “pure” approaches that are mainly used, this hybrid method has not been analysed.

The RAMP function controls the heat release rate of the burner, by specifying the time history of the RHR curve. Using this function, the fuel area is constant during the whole fire phenomenon. On the contrary the HRRPUA and \( \dot{Q}^* \) vary during the fire growth phase. Fig. 1 shows the typical flame variation of a fire source modeled with the RAMP. It is clear that the flame behavior varies over time. Therefore the \( \dot{Q}^* \) of the fire, during the first seconds, is outside of the above-mentioned range defined by Cox and Kumar [6], but then it increases until it reaches optimum value.

\[
Q^* = 0.03, 0.141, 0.31, 0.56
\]

The disadvantage of using the above mentioned function is that the fire source needs to be properly resolved for the HRR to resemble a continuous function[3].

Instead the S_R function mimics a fire that is growing radially at a constant speed. In particular, the surface of the burner is discretized with a regular square array and flame spread occurs as a series of cell ignitions, using a sort of cellular automaton technique. The advantage of using the S_R function is that the burning surface is kept small when the HRR is low. Therefore it is possible to maintain applicable values of the dimensionless HRR (\( \dot{Q}^* \)) during the fire growth. To calculate the S_R value, the following equation can be used [3]:

\[
SPREAD\_RATE = \frac{\alpha \cdot 1}{\sqrt{n \cdot HRRPUA}}
\]

The phenomenon is more obvious when larger grid cells are being used. Thus it is recommended that a square shaped fire source is modeled with an odd number of grid cells covering each side of the fire source. [3]
COMPARISON BETWEEN RAMP AND SPREAD_RATE FUNCTIONS

The S_R and RAMP functions have been tested on three different geometrical shapes (so six simulations have been performed). Table 1 shows the comparisons between three pairs of scenarios (S_01 - S_02, S_03 - S_04, S_05 - S_06), where each pair compared has the same inner geometry. Furthermore, each comparison differs from the others in size, in order to perform a sensitivity analysis. The aim of this sensitivity analysis is to assess if the differences, in terms of effect, between the two fire growth functions, are affected by building size and inner geometry.

Table 1. Different fire scenarios studied

| Simulation | S_01 | S_02 | S_03 | S_04 | S_05 | S_06 |
|------------|------|------|------|------|------|------|
| Function   | S_R  | RAMP | S_R  | RAMP | SP_R | RAMP |

In each one of the three comparison the fixed parameters, in addition to the enclosure size, are mesh size, number of ventilation openings, fire position and fire size. The output devices position is a fixed parameter as well in each one of the three comparison. Some fixed parameters, such as mesh size, were defined by performing sensitivity analysis (it has been ensured that all the ASET parameter are well resolved using this mesh size). Mesh size is 0.2x0.2x0.2 m³. Regardless of the function used to perform the fire growth, the fire size was selected using the Italian Fire Code [8] that advices of the characteristics of the burners that can be applied to different occupancies. The occupancy selected was the “civil occupancy” and the characteristics of these fire case studies are presented in the following table.

Table 2. Fire Characteristics

| Parameter            | Civil occupancies |
|----------------------|-------------------|
| Fire Growth Rate     | 150 s (fast)      |
| RHR_MAX              | 5 MW              |
| Fire Dimensions      | 1,8 x 1,8 m²      |
| Q⁺ (at RHR_MAX)      | 0,8               |

The three comparisons between the HRR curves of the two fire growth function have been shown a similar behavior regardless of the enclosure geometry. In the first 50 seconds (highly significant for the ASET analysis) the HRR curves produced by the S_R show a plateau trend with higher values than the RAMP Curves (see figure 3, on the left), due to the first cell ignition that produces a flat Heat Release Rate trend. Furthermore the fire growth modeled with the S_R function has shown a discrepancy with the RAMP function as the fire HRR curve approaches the maximum HRR. This discrepancy occurs because the chosen fire source is square shaped whereas the fire spread over the fire source surface is radial. In order to avoid this discrepancy and to only study the growth phase of the fire, the following comparisons are evaluated during the first 300 seconds.

Fig. 3. HRR comparison between the SPREAD_RATE cases and RAMP cases
Seeing that the fire growth is a matter of concern for life safety, we analysed smoke layer height, visibility and gas temperature. The comparison of the graphs between the outputs of the smoke layer height devices (they were measured in multiple points and then averaged) of the two growth functions are represented below. The smoke layer for S1/S2 and S5/S6 drops below head height faster with S_R than without, but after 75 seconds, in all three comparisons, the layer heights of the S_R function cases are slightly higher than the ones of the RAMP function cases.

Furthermore the comparisons have been assessed for the visibility at 1.8 m off the ground. The scenarios that use S_R, after approximately 75 seconds, show a higher visibility than the ones that use RAMP. Fig. 5 shows the comparison between S_05 and S_06. This pair of scenarios has been chosen because the enclosure obscuration by the smoke is more gradual and the results are clearer than in the other comparisons. As a result it is clear that the visibility of the scenario S_05 (S_R) is always higher than the S_06 (RAMP).

Another important parameter related to life safety is gas temperature at 1.8 m off the ground. In all three comparisons the gas temperatures in the case studies that use the S_R are slightly lower than the ones that use the RAMP. This is clearly reflected in Fig. 5 that shows the gas temperature comparison between S_05 and S_06.
Temperature | SPREAD_RATE | RAMP | Time
--- | --- | --- | ---
See previous page | | | t=165

Fig. 6. Gas temperature slice comparison between the scenarios S_05 and S_06

Finally, the growth function dependency of the adiabatic surface temperature (AST) trend has been analysed to evaluate the fire resistance of structures. The curve trends have shown that there are no significant differences between the two functions of fire growth utilized.

**CONCLUSION**

Based on the information above, the following conclusions can be drawn.

- Since the $S_R$ function associates a radial diffusion on a surface with a t-squared function of the HRR Curve, this behavior can be considered consistent with the real behavior of a fire. Moreover using the $S_R$ function, the burning surface is kept small when the HRR is low and therefore it is possible to maintain applicable values of the $Q^*$ during the fire growth. On the contrary the HRR curve produced by this function has shown some discrepancies compared to the theoretical t-squared function, which have not been noticed in the RAMP function (excluding the small oscillations).

- As the $S_R$ function, during the fire growth, generates a more structured flame than the RAMP-functions, the smoke produced is expected to layer in a more orderly manner, slowing down the fall of smoke level. This has been confirmed by the visibility and gas temperature analyses at 1.8 m off the ground. Therefore in all three comparisons the visibility and gas temperature slices have shown that the untenable conditions (related to this parameters) for occupants of the room occur before using the RAMP function using the $S_R$ function.

- The smoke layer for S1/S2 and S5/S6 drops below head height faster with $S_R$ than without, but after 75 seconds, in all three comparisons, the layer heights of the $S_R$ function cases are slightly higher than the ones of the RAMP function cases. The phenomenon emerged during the first seconds could be due to the fact that, in the first 50 seconds, the HRR curves produced by the $S_R$ show a plateau trend with higher values than the RAMP HRR Curves, where the trend is t-squared and start from 0 (see figure 3).

- The growth function dependency of the AST trend has been analysed to evaluate the fire resistance of structures, but the comparisons have not shown any significant differences between the two functions.

**REFERENCES**

[1] PD 7974-0:2002, Application of Fire Safety Engineering Principles To The Design Of Buildings. Guide To Design Framework And Fire Safety Engineering Procedure, British Standards Institution

[2] McGrattan K., Hostikka S., McDermott R., Floyd J., Weinschenk C., Overholt. K. “Fire Dynamics Simulator User’s Guide. FDS Version 6.6.0”, NIST, Gaithersburg, USA. 2017.

[3] Norén N., Rosberg D., “Developing a Swedish Best Practice Guideline for Proper use Of CFD-Models When Performing Aset-Analysis”, Proceedings, Fire and Evacuation Modeling Technical Conference (FEMTC), 2014

[4] PD 7974-1:2003, Application of fire safety engineering principles to the design of buildings. Initiation and development of fire within the enclosure of origin (Sub-system 1), British Standards Institution

[5] Drysdale, D., An Introduction to Fire Dynamics, John Wiley and Sons, Chichester, 1985, p. 136.

[6] Cox G., Sumar K., “Modeling enclosure Fires Using CFD,” The SFPE Handbook of Fire Protection Engineering, 3rd edition, Society of Fire Protection Engineers, 2002, pp. 3-205 till 3-207.

[7] Hurley M. J., Rosenbaum E. R., Performance-Based Fire Safety Design, CRC Press Book, 2015. p18.

[8] Decree of the President of the Republic, August 1, 2011, no. 151. Regulations for simplified application of the discipline procedures relating to fire prevention activities (in Italian).