NUMERICAL SIMULATION EVALUATION OF FIRE SPREADING IN A BUILDING USING FIRE DYNAMICS SIMULATOR (FDS)

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ABSTRACT:

The 3D model of a building was built to analyze the scene of a fire with reference to thereal situation. The process of evolution of a fire was simulated with FDS. The evolution time of the fire, the degree of danger, the temperature as well as the visibility was analyzed. Architectural solutions that could be considered for the prevention and evolution of fire in the presented situations were also analyzed. The results of the simulations in the proposed scenarios showed that solutions could be found to prevent the spread of fire. The results of the study provide a real base for improving the evacuation conditions and limiting the damage caused by fire in single-family buildings.

1.INTRODUCTION

1.1 Overview

Fire is a natural phenomenon, which from the beginning of human existence and until today has posed a serious threat to people. Fire definition: self-sustained burning, which takes place without control in time and space, resulting in loss of life and/or damage to property and requiring organised intervention to interrupt the burning process (Law No.10 of 18/01/1995). Combustion is when fuel reacts with oxygen to release heat energy (P118/2015).

Combustion can take place slowly or quickly depending on the amount of oxygen available. Fuel: solid, liquid or gaseous substance capable of initiating and sustaining combustion. Phenomena of: transfer, transport, transmission.

Conduction fires spread through direct contact between two materials. A conduction fire spreads when a fire heats up a material that is a good heat conductor, like metal when it comes into contact with a combustible material (Nurul L.H. et.al. 2017). Then the fire can travel further across a room or building in this manner (Law No.307, 2006).

Convection is the most common cause of fire spreading in domestic and commercial buildings and it is also the most dangerous (Jianyong Shi et.al. 2019).
Radiation: a fire can be spread by radiation when the heat travels through electromagnetic waves in the air. When a fire breaks out, heat will travel in all directions until it reaches an object that will absorb it. When it reaches a combustible material, it will smoulder and eventually burn (Labiba M.A. et.al. 2018).

Fig. 1 is presenting the burning triangle (ISU 01, ISU 04):
- heat / trigger energy;
- fuel;
- oxygen / the comburent.

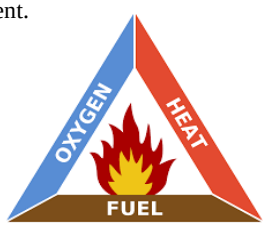


Figure 1. The burning triangle (ISU 01, ISU 04)

These three elements are needed simultaneously in time and space for initiating and maintaining combustion. The removal of a constituent element of the burning triangle leads to the interruption of the burning process (Chang Liu et.al. 2020).

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Fire classes:

- class A - solids (wood, cotton, paper, fabric rolls, charcoal);
- class B - liquids (liquefied liquids or solids: hydrocarbons, paints, alcohol, tar,varnish);
- class C - gases (represented by fires of combustible products that are in a gaseous state at an ambient temperature above 15 ℃);
- class D - metals (aluminum, zinc, magnesium, potassium, white phosphorus);
- class E - electrical fires;
- class F - cooking fats and oil fires (vegetable or animal fats, vegetable and animal oil).

1.2 FDS (fire dynamic simulation) programme

General Fire Dynamics Simulator (here after FDS) is a calculation program CFD model-based computational software for the numerical simulation of fire development. The program is based on fluid flow theory applied to fire dynamics and solves the mathematical equations describing thermally driven low-velocity flows, with emphasis on the scattering and heat transport (CFPA-E no. 19/2009).

The FDS program is being developed in the United States by the National Institute of Standards and Technology NIST (National Institute of Standards and Technology). The FDS program was originally intended for research use by NIST.
Since 2000, the program has been distributed to the general public, and is currently distributed to free of charge by the manufacturer (McGrattan et. al., 2019). FDS being only a computational processor, requires a graphical preprocessor (PyroSim) as well as a graphical post-processor (Smokeview).
Main features of the FDS program:

➢ the FDS hydrodynamic model solves numerically a form of the fitted Navier-Stokes equations to low-velocity (0.3 Ma ≈ 100 m/s), thermally driven flows, with emphasis on smoke dispersion and heat transport (Taher Halava 2021).;
➢ FDS combustion modelling addresses simple combustion chemistry by monitoring only fuel (O2, CO2, H2O, CO, N2) and soot particles. Air and reaction products are considered from the mathematical model point of view as a single mixture of gases moving and reacting together;
➢ radiative heat transfer is included in the model by solving the equation (Radiation Transport Equation) for a grey gas and for some limiting cases using the Wide Band Model. The equation is solved using a technique similar to the Finite Volume Method. Using about 100 discrete angles, the subroutine for the radiative heat transfer calculation requires about 20% of the total calculation time, considered to be a low cost considering the complexity of the radiative heat transfer phenomenon (Fang Liu. et. al. 2020);
➢ combustion and radiation FDS is a specialized program for fire simulation because it incorporates terms and boundary conditions describing turbulent combustion of fuel material and oxygen, thermal radiation transfer through hot soot-containing gases, thermal decomposition of real materials, activation of sprinklers and smoke detectors, water droplet scattering (in the case of sprinklers) as well as other phenomena describing the evolution of a real fire (Fengzhu M. et. al. 2017).

2. THEORETICAL CONSIDERATIONS

Performance criteria - (the dwelling studied in Fig. 2) on fire safety: the foundation is made of concrete, the resistance structure consists of brick masonry structural walls with a 12 cm thick reinforced concrete floor and a wooden roof.



Figure 2. Proposed dwelling for study
(Ground Floor + First Floor + Attic)

Building features:

-Building importance class III;
-Category of importance of the building "C";
-Fire stability level III
-The nature of the activities taking place in the built environment: "Residential building".

The kitchen can be included in the medium fire risk category; according to it is intended use. Therefore all access doors delimiting the kitchen area will have fire resistance EI minimum 15 minutes, the wall are made of 25 cm thick brickwork with REI minimum 180 minutes.

The FDS User Manual (McGrattan et. al., 2019) recommends that the size of a cell/discretization volume be in the range $\left[\frac{D^*}{16}, \frac{D^*}{4}\right]$ where D* is the characteristic fire diameter obtained with Eq.1 (McGrattan et. al., 2019):

$$D^* = \frac{Q_{max}}{\rho_\infty * C_p * T_\infty * \sqrt{g}} \quad [m] \qquad (1)$$

Q - max - is the maximum heat output, in kW;
ρ_∞ - air density with value 1,204, in kg/m3;
C_P- specific heat of air with value 1.005, in kJ/(kg K);
T_∞- air temperature with value 293, in K;
g - gravitational acceleration of 9.81 in m/s^2.

Heat load - (Eq.2) - the amount of heat that can be released by complete combustion of the total combustible materials, both fixed and mobile, in the space affected by the fire (Antonio Galhardo et.al.2022). The heat load is the physical quantity given by the heat released by the totality of the combustible materials housed and building elements by their complete combustion.

$$S_Q = \sum_{i=1}^{n} Q_i * M_i \ [MJ] \qquad (2)$$

-M_I- mass of combustible material of the same kind in the space under consideration [kg];
-Q_i-is the lower heating value of a material [MJ/kg or MJ/m^3 N].

The values depending on the material are presented in Table 1.

Room name	Material	Q_i Calorific value (MJ/kg)	M_I Quantity (kg)	S_Q heat load (MJ)
Kitchen	wood (furniture)	19,25	250	5390
	plastics	42,6	180	7668
	paper, cards	16,3	25	407

Table 1. Material properties

Heat load density (Tab.2) - is the most important parameter of the hazard (risk) of Fire.

$$q_s = \frac{S_Q}{A_s} \ [MJ/m^2] \qquad (2)$$

S_Q - thermal load $[MJ]$
A_s - the sum of the floor areas of the rooms from the space under consideration [m^2].

$$q_s = \frac{13465}{16} = 839{,}20 \ [MJ/m^2] \qquad (3)$$

Risk of Fire	Thermal Heat Density (MJ/mp)	
low level	q<420 MJ/mp	
medium	q=420-840 MJ/mp	**839,20 MJ/mp**
high level	q<420 MJ/mp	

Table 2. Kitchen (medium fire risk)

Parameters (Tab.1) entered in the simulation program - heat load density (Fig.3):

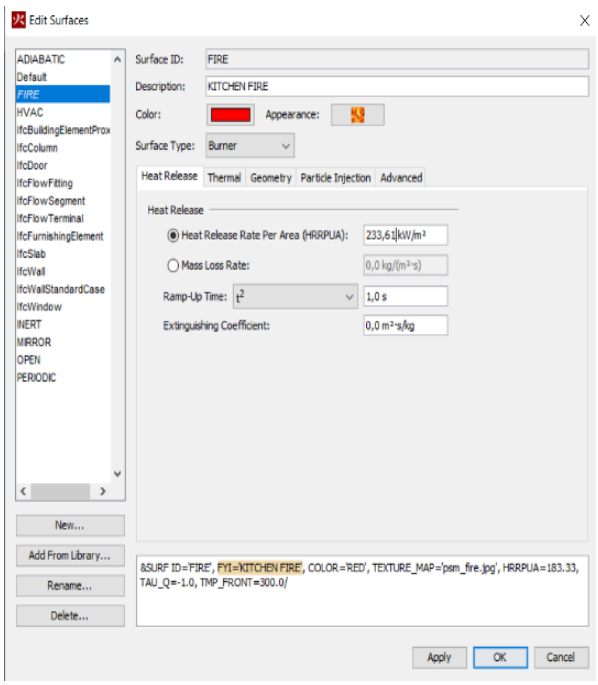


Figure 3. Fire kitchen – heat load density - Pyrosim Software

The fire parameters were entered into the simulation program after the calculations (heat load, heat load density).

3. MATERIALS AND METHODS

The real situation exposed (open space ground floor: living room, hall and stairwell – Fig.4) through the fire development phases:

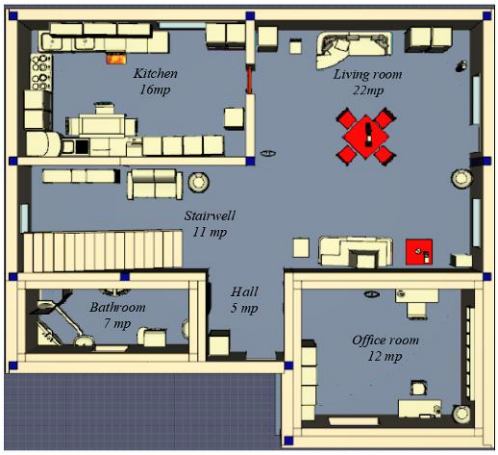


Figure 4. Actual situation (ground floor)

3.1 Getting to know the fire proposed for study

Phases of fire development:

- incipient;
- growth;
- fully developed;
- decay.

Fire initiation presented in Fig.5 - is the process of ignition of combustible products, the initial phase of combustion is directly related to the amount of fuel being burned. At this stage the heat released is moderate and the smoke has not reduced visibility.

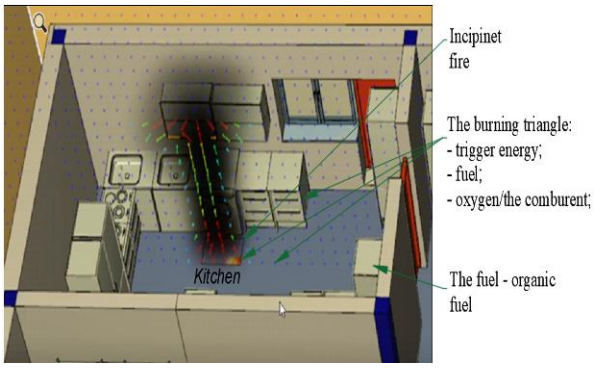


Figure 5. Incipient phase (Pyrosim FDS)

Only the fuel influences the development of the fire. It can be said that the fire is limited by the fuel in the burning space. At this stage, the volume of the room in which the phenomenon develops has no influence on the fire development.

Growth - the growth stage is where the structures fire load and oxygen are used as fuel for the fire. The airflow increases considerably, which leads to a progressive increase in the room temperature.

At the same time, the volume of smoke produced by combustion is becoming significant and is accumulated by convection at the top of the burned space.

This phase can be accelerated by the following factors which are affecting the burning rate:
- the degree of looseness, splitting or granularity of matter;
- geometric arrangement of materials in the room;
- temperature;
- other factors;

The factors (Fig.6) listed directly above are of particular importance in this phase, (development of fire).

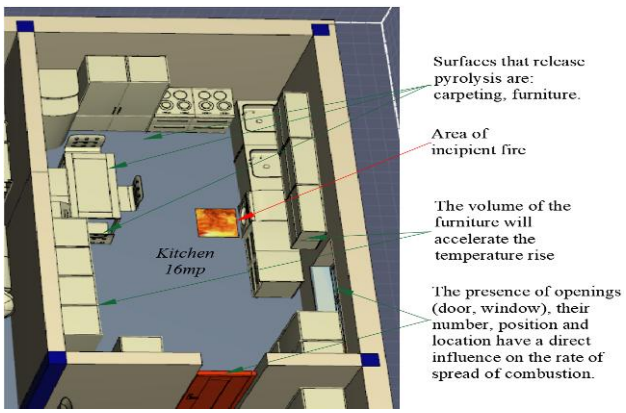


Figure 6. The factors affecting the burning rate in fire development (Pyrosim program simulation)

The spread velocity of the combustion of a material depends on its geometrical shape and its arrangement in space and in relation to other elements in the room. The growth stage is presented in Fig.7.

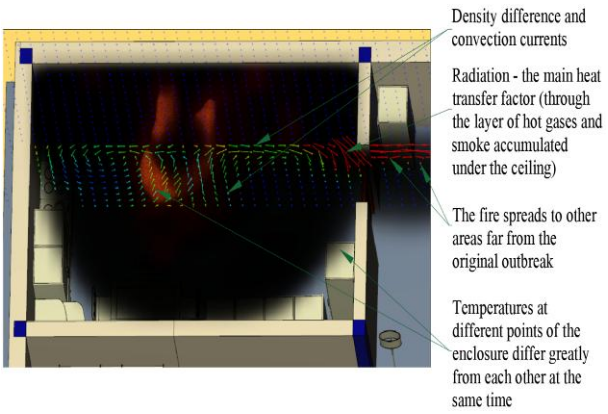


Figure 7. The growth stage (Pyrosim Program Simulation)

Smoke, through its components, is a new fuel source in the development equation of fire. Objects that come into contact with the heat released by the fire through radiation and conduction heat up and ignite. The fire development stage is the most unstable time in the development of a fire (Fig.8).



Figure 8. Flash-Over Phenomen (ISU 01)

Fully developed (Fig.9) - when the growth stage has reached it is maximum and all combustible materials have been ignited, a fire is considered fully developed. The phase referred to as widespread burning is the most important stage of the fire, so the intensity and risk of fire spread are maximised. This is the hottest phase of a fire and the most dangerous for anybody trapped within.

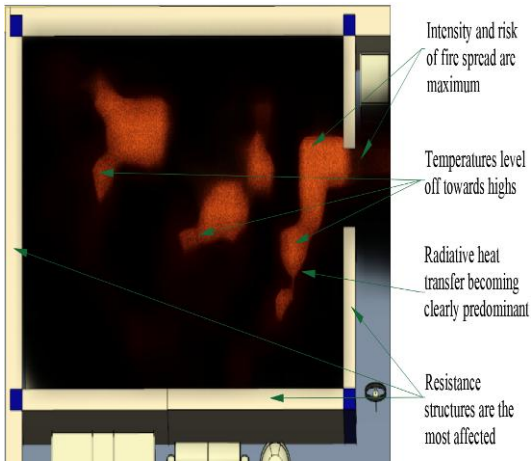


Figure 9. Fully Developed

Temperatures are levelling off towards maximum values, radiative heat transfer becoming clearly predominant. During this phase, the load-bearing structure is the most affected by the fire: walls crack and dislocate, openings widen, causing the fire to spread to adjacent rooms and then to the whole building.

The combustion regime stabilises and is conditioned by either the surface area of the combustible materials, either the dimensions of the openings, and therefore the air intake regime.

a) In the first case, the combustion speed is limited by the size of the fuel surface, when air circulates excessively in relation to the contact surface between fuel and air (ventilated fire - which is intense and short-lived).

b) In the second case, when the amount of air in the enclosure is less than the critical value required for combustion (unvented fire) the burning rate depends on the size of the openings (windows) in the enclosure.

Decay (Fig.10) - usually the longest stage of a fire, the decay stage is characterized by a significant decrease in oxygen or fuel, ending the fire. During this phase the temperature stops rising, then it begins to decrease, but the decrease is not sudden, still acting destructively on structures.



Figure 10. Decay (real image from the studied fire)

The evolution of fire in confined spaces is shown in the following diagram (Fig.11).

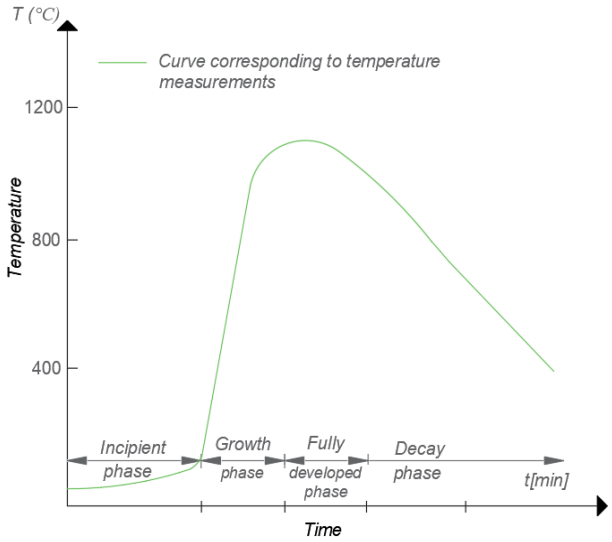


Figure 11. Estimated temperature variation during a fire

The diagram shows the correlation between temperatures, hot gases and the conventional fire duration which breaks out in an enclosed space. In the development phase of the fire, the main cause is the spread of the fire, with a 5-7% weight loss of combustible materials.

During burning, the burned area increases, the burning area are fully developed, the temperature exceeds 900°C; weight loss of combustible materials reaches 80-85%.

3.2 Proposed situation

The proposed situation is achieved by dividing the living room from the hallway and stairwell by a masonry wall and a normal interior door.

Fire compartmentation (Fig.12) - means the construction or part of a construction containing one or more rooms or spaces, delimited by construction elements intended to isolate the fire, for the purpose of limiting the spread of fire, for a given duration.



Figure 12. Proposed situation (ground floor plan)

3.3 Results

Actual situation - fire (smoke, temperature, combustion compounds) spreads from the initial area (kitchen) to the living room area, then into the hallway and stairwell area (upper spaces).

In this situation the evacuation time of people caught in the upstairs and attic is reduced due to the spread of smoke to the stairwell on the ground floor and then to the upstairs and attic (Fig.13).

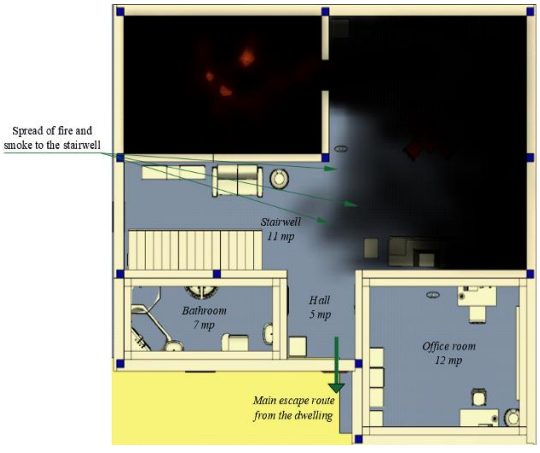


Figure 13. Fire develops and spread (actual situation)

The expansion of combustion compounds (component particles of smoke) towards the main escape route from the dwelling is observed, making it difficult for people to evacuate safely.

Proposed situation (Fig.14) - fire (smoke, temperature, combustion compounds) spreads from area (kitchen) to the living area, and then is temporarily bounded by the partition wall in the hallway and stairwell.

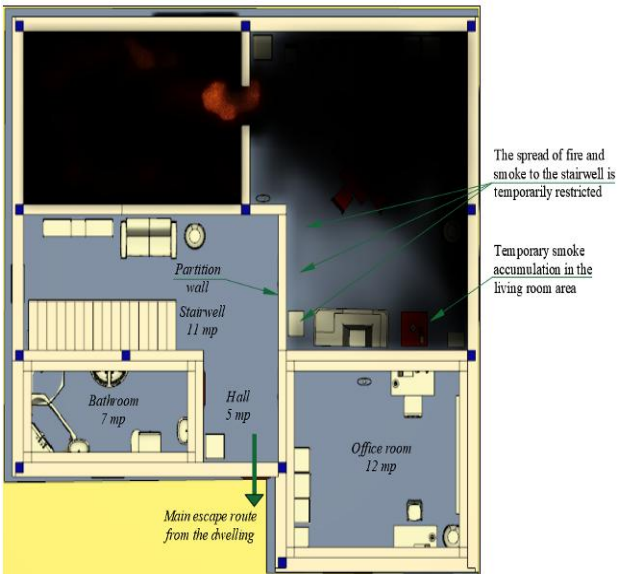


Figure 14. Fire develops and spread (proposed situation)

It can be observed the temporary limitation of fire spread to the hallway and stairwell area. Due to this limitation, people caught inside the dwelling on the first floor and attic can safely evacuate themselves.

Temperature evolution during the fire - *(proposed situation)* - Fig.15.

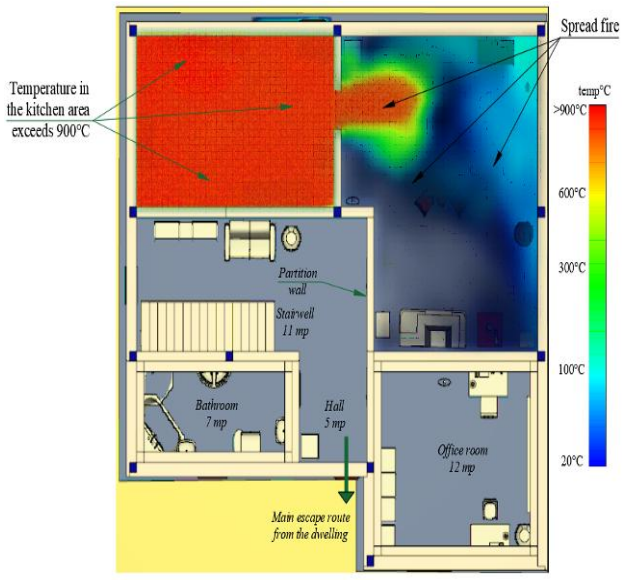


Figure 15. Temperature spread during the fire development (proposed situation)

4. CONCLUSIONS

4.1 Elements for determining the probable cause of the event

- the place of the outbreak: - the kitchen;

- likely source of ignition (in fire): - thermal effect of electric current;

- the causative agent of ignition: - electric cable, electric conductor;

- the first material to ignite: - plastics;

- determined circumstance: - faulty, uninsulated conductor, electrical cable properly or with damaged insulation due to mechanical or physical action;

- conditions that favoured the development and spread of the fire: the amount of combustible materials and their arrangement in the room.

4.2 Analysis of results

Through FDS type simulation of a fire, as well as by adding another architectural solution, the result can be seen immediately: the level of safety is increasing, the requirement of safe evacuate on can be fulfilled and the effects caused by a fire are limited (Figs.16, 17, 18, 19).

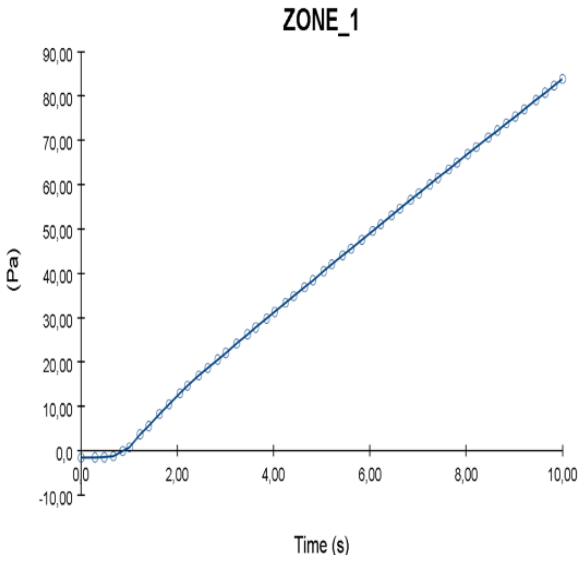


Figure 16. Pressure variation during fire (FDS)

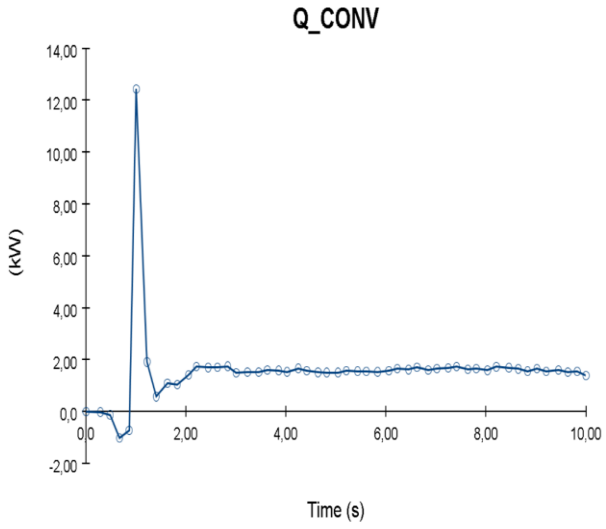


Figure 17. Variation of convective heat transfer (FDS)

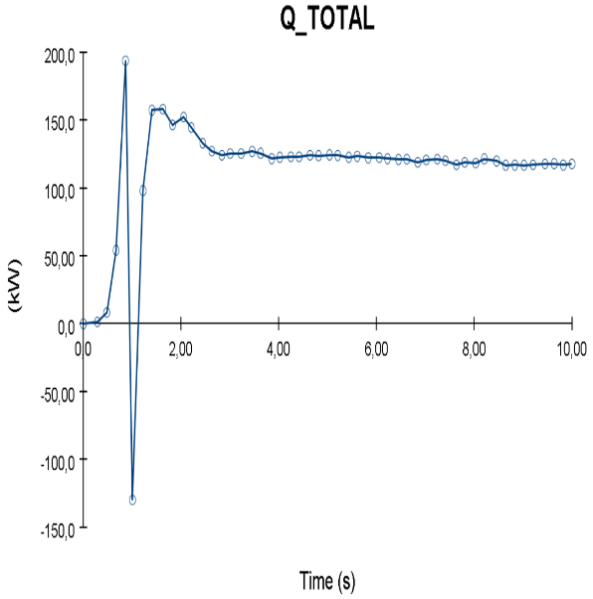


Figure 18. Total amount of heat transmitted (Q_{TOTAL}) (FDS)

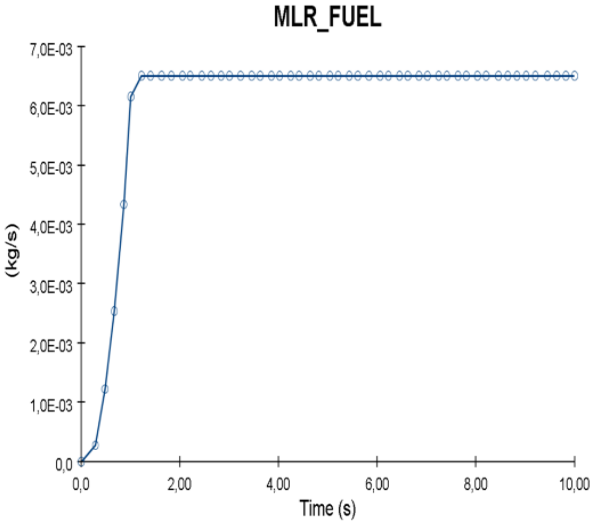


Figure 19. Total amount of material in the burnt area (FDS)

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