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Modeling of fire suppression by fuel cooling

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ABSTRACT

Fire suppression with water spray was investigated, focusing on cases where fuel cooling is the dominant suppression mechanism, with the aim to add a specific suppression model addressing this mechanism in Fire Dynamics Simulator (FDS), which already involves a suppression model addressing effects related to flame cooling. A series of experiments was selected, involving round pools of either 25 or 35 cm diameter and using both diesel and fuel oil, in a well-ventilated room. The fire suppression system is designed with four nozzles delivering a total flow rate of 25 l/min and injecting droplets with mean Sauter diameter 112 μm. Among the 74 tests conducted in various conditions, 12 cases with early spray activation were especially considered, as suppression was observed to require a longer time to cool the fuel surface below the ignition temperature. This was quantified with fuel surface temperature measurements and flame video recordings in particular. A model was introduced simulating the reduction of the pyrolysis rate during the water spray application, in relation to the decrease of the fuel local temperature. The numerical implementation uses the free-burn step of the fire to identify the relationship between pyrolysis rate and fuel surface temperature, assuming that the same relationship is kept during the fire suppression step. As expected, numerical simulations reproduced a sharp HRR decrease following the spray activation in all tests and the suppression was predicted in all cases where it was observed experimentally. One specific case involving a water flow rate reduced such that it is too weak to allow complete suppression was successfully simulated. Indeed, the simulation showed a reduced HRR but a fire not yet suppressed. However, most of the tests showed an under-estimated duration before fire suppression (discrepancy up to 26 s for a spray activation lasting 73 s), which demonstrates the need for model improvement. In particular the simulation of the surface temperature should require a dedicated attention. Finally, when spray activation occurred in hotter environments, probably requiring a combination of fuel cooling and flame cooling effects, fire suppression was predicted but with an over-estimated duration. These results show the need for further modeling efforts to combine in a satisfactory manner the flame cooling model of FDS and the present suggested model for fuel cooling.

1. Introduction

Fire suppression by water sprays involves several combined phenomena. They are now well known, as described in [1] or [2] for example. These mechanisms act on the gas phase (including the flame), the fuel or both of them. In particular, flame cooling and inerting effects result from a strong evaporation. Considering the high value of the water latent heat of vaporization, particle evaporation leads to a strong heat sink effect which reduces the flame energy and its temperature. The evaporation of water particles produces a large amount of vapor, which also penalizes the mixing between fuel vapor and oxygen. This affects the combustion process and can lead to the fire suppression. When the particle diameter is large enough, their momentum can also allow them to penetrate the plume and the flame and to reach the fuel surface to cool and to wet it. The consecutive fuel cooling affects pyrolysis rate and can lead to suppression for solid fuels and liquid fuels with flashpoints above ambient temperature.

These mechanisms were studied by CNPP and LEMTA in the frame of an experimental campaign, involving 74 pool fire tests, aiming at a better understanding of the physical phenomena occurring during water application on a fire. By varying the application conditions of the water mist (in particular the time between fire ignition and mist application) the two regimes of dominant mechanisms were observed: i.e. (i) fuel cooling for early application in an environment which is not hot enough to result in a strong particle evaporation, thus requiring the fuel cooling before obtaining the fire suppression, and (ii) late

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Nomenclature

a	empirical parameter ($m^2\ kg^{-1}$)
A	pre-exponential factor ($kg\ s^{-1}\ m^{-2}$)
B	pre-exponential factor ($kg\ s^{-1}\ m^{-2}\ T^{1/x}$)
c	specific heat ($J\ kg^{-1}\ K^{-1}$)
E	exponential factor (J)
h_s	solid heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
HRR	Heat Release Rate ($kJ\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$k(t)$	model pyrolysis reduction factor (s^{-1})
$\dot{m}_f$	pyrolysis rate ($kg\ s^{-1}\ m^{-2}$)
$\dot{m}_{p,f}$	water mass reaching the fuel surface ($kg\ s^{-1}\ m^{-2}$)
$\dot{q}''$	heat flux ($W\ m^{-2}$)
$\dot{q}''_c$	convective heat flux ($W\ m^{-2}$)
$\dot{q}'''_r$	radiative heat flux ($W\ m^{-2}$)
R	ideal gas constant ($J\ K^{-1}$)
t	time (s)
t_0	fire ignition moment (s)
T	temperature (K)
x	exponent (dimensionless)

Greek

ΔH_c	heat of combustion ($kJ\ kg^{-1}$)
χ	combustion efficiency (dimensionless)
ρ	density ($kg\ m^{-3}$)

Subscripts

app	property when mist application starts
exp	experimental data
f	fuel property
ign	ignition
num	numerical result
p	particle property
s	solid contribution
sup	data related to fire suppression
vid	result obtained from video recording

application in a hot environment producing a strong evaporation and a consecutive efficient cooling of the flame, leading to the fire suppression while the fuel surface temperature was still above the ignition point [3].

Beside the observation of the suppression mechanisms, the goal was also to improve the suppression models in order to allow predictive simulation of fire suppression in numerical codes, using FDS [4,5] in particular which is mainly used in fire safety engineering studies. In the case of suppression dominated by flame cooling and inerting effects, some recent improvements [6] were brought to the models in FDS.v6 for the evaluation of the suppression criterion. This model was evaluated in various situations, not restricted to mist action on the fire, but also in this particular case [7].

FDS allows users to use either a full pyrolysis model where pyrolysis rate and HRR are calculated thanks to the physical properties of the fuel material or a prescribed evolution of the pyrolysis rate. To use the full pyrolysis model properly, the user should have a good knowledge on the fuel he uses, which may not be the case in many situations. A consequence of this is that a prescribed evolution of pyrolysis rate is usually used in fire safety engineering studies where combustible materials are not always known enough to use a complex model. However, the engineer is expected to have at least a good understanding of the HRR evolution and propagation in his scenario and basic knowledge on the used combustible material. Using the full pyrolysis rate also leads to a higher computational cost which is a sensible matter in fire safety engineering.

The full pyrolysis model is able to calculate reduction of pyrolysis rate that may occur when water suppression system is activated. A dedicated model currently allows the user to simulate fire suppression by water application when a prescribed pyrolysis rate is used instead of the full model. This dedicated model is based on an a priori fire power reduction through an exponential law. The pyrolysis rate is assumed to be affected as follows [8]:

$$\dot{m}_f = \dot{m}_{f,app}\ e^{-\int k(t)\mathrm{d}t} \tag{1}$$

where $\dot{m}_{f,app}$ is the pyrolysis rate when water mist application starts and $k(t)$ is related to the liquid mass per unit area that reaches the fuel surface $m''_{p,f}$ as follows:

$$k(t) = a\ m''_{p,f}(t) \tag{2}$$

where a is an empirical parameter. The exponential nature of fire suppression by water was suggested by Yu et al. [9] after dozens of rack storage commodity fires of different geometries and for various water application rates. Although it was derived from this particular application of rack storage, it is usually applied in various cases of water applications whatever the fuel type and the fire conditions in engineering studies, which lead to some doubts on the reliability of this relationship, should it be used in any fire suppression scenario. Another important problem related to this model is that this a coefficient has to be set prior to the simulation, making prediction impossible. Some sensitivity tests carried out on this parameter did not provide clear trends allowing to set a in a confident manner without calibration or arbitrary choices [10] as the range for a for the tests detailed in this paper is [0.15;1] while the experimental setup remained the same. Hence, the present work aimed at observing dedicated experiments where fuel cooling is the main suppression mechanism and at developing a different model. Two qualities were expected for the model that would be developed: it should have a predictable ability (i.e. it can be used without the need of a specific test) and it could be used in a fire safety engineering situation, i.e. it is used when the user prescribes the HRR and it does not lead to a significant increase of computational cost compared to the current model. The new models presented here are based on experimental observations especially focused on the pyrolysis rate, the HRR and the fuel temperature.

In this paper, the experimental setup that was used and some specific suppression cases involving fuel cooling as the main suppression mechanism will be presented first. A particular attention will be paid to the evaluation of the fuel surface temperature and of the pyrolysis rate. It should be noted that fuel surface temperature only is considered here because tests involve liquid fires where evaporation occurs at the fuel surface. Temperature within the fuel should be explored too in the case of solid fires. Experimental results will be discussed and several suppression models dedicated to fuel cooling will be suggested. Explanations on how they can be introduced in FDS will also be given. Validation results will be presented for one of these models, based on simulations where it was implemented into the code, investigating its capability to predict suppression and evaluating its accuracy in terms of time at which suppression occurs.

2. Experimental study

2.1. Experimental setup

The experimental setup was detailed in [3]. Only the main characteristics of the experimental configuration are recalled here.