Experimental study of smoke/mist interactions in a configuration combining a corridor adjacent to a room

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Abstract:
This work deals with the influence of water mist involved in case of fire, focusing on the mist/smoke interactions. Real scale experiments are conducted in a configuration of fire occurring in a room with smoke flowing in an adjacent corridor. The smoke flow is characterized through a set of thermocouples and opacimeters, while the fuel mass loss is registered at the same time for the HRR determination (one hundred sensors involved as a whole). The complete setup provides an evaluation of the smoke stratification before water mist activation and the de-stratification related to the smoke mixing when the mist is activated.

Keywords: optical and thermal stratification, fire, smoke, experimental study.

1 Introduction
The fire safety strategy involved in France in case of fire consists in keeping a smoke free environment near the floor, as long as possible, using ventilation systems. This is aimed at promoting the self-escape of persons on one hand and at allowing firefighters to reach the fire load on the other hand. Although the activation of fire-fighting system may penalize this strategy, the use of sprinkler systems is allowed in buildings in order to increase the acceptable heat load, while warranting a limited fire growth, or even fire extinguishment. The drawback of such systems is a huge water flow rate, which may induce environmental or material damages. Therefore, water mist can be expected to be a good compromise for building protection as compared to traditional sprinkler systems. This technique involves smaller droplets, with typical diameter below 1mm at 1m from the nozzle for 90% of the whole water volume. The corresponding water flow rate is also really weaker as compared to sprinkler systems (reduced by a factor 10 according to manufacturers). The use of such small droplets promotes a high evaporation rate, which results in a heat sink that cools the surrounding medium and an inerting effect which penalizes the combustion reaction. Moreover, the water mist also induces radiation attenuation through absorption and scattering phenomena which limits the radiative transfer from flame to fuel or any surfaces. This radiative shielding effect has been demonstrated and evaluated in recent works by the authors in particular in the frame of the use of water mist systems ([1], [2], [3]). Some new problems may be raised by this technique in relation with the fire control concerns and with the smoke flow however. Only the smoke/mist interactions are addressed in the present work. The injection of water droplets induces a smoke mixing and downward drag effects, which may penalize the visibility, making the escape conditions worse. Few studies may be found in the literature on such stratification vs de-stratification effects in case of water mist activation (see Blanchard [4] and Tang et al. [5,6] for recent contributions).

In real scale situations, all the above-cited effects are combined, with relative importance depending on numerous parameters including droplet size, water flow rate, type of fuel, etc… Blanchard [4,7] evaluated these phenomena in case of a mid-scale tunnel. Some similar features are found in the present work, since a
longitudinal smoke flow is also observed, but in a corridor adjacent to a room where an heptane pool is burning. The whole experimental setup involves numerous sensors aimed at studying the smoke flow with and without water mist activation. The study focuses on the quantification of the water mist effects on the smoke stratification, based on measurements involving optical and thermal criteria through temperature distributions and opacity profiles obtained with transmissivity measurements in the visible.

2 Case study

2.1 Experimental setup

The real scale setup (Figure 1) corresponds to a room and a corridor. The room has a surface of 12 m² and is 2.15 m high. The corridor length is 9 m, its width is 1.4 m and its height is 2.35 m. An opening is located near the floor of the room with a height of 20 cm and a width of 90 cm in order to favour the oxygen supply to the heptane fire pool and to avoid any supplementary problem of under-ventilated fire. This also limits any reversed flow of air from the corridor which could alter the smoke stratification through a counter flow of air in the bottom part. A 40cm high lintel in the upper part of the corridor exit allows to improve the smoke stratification ability and to get a homogeneous smoke thickness. Figure 1 also presents an aspiration device at the exit which will be used in future tests as a possible way to evaluate the gas concentration in smoke (for a dedicated quantification and possible evaluation of the fire heat release through oxygen consumption).

The water mist system is a real scale one provided by the manufacturer PROFOG. A CEN OH1 water mist nozzle is used under water pressure feed 110 bars. The injection point is located in the corridor 3.5 m downward from the wall near the room door. The nominal flowrate is 27.5 l/min and a polydisperse spray is generated with a mean Sauter diameter \(D_{32}\) equal to 23.5 µm.

The heptane pool fire (with surface 0.09 m² and fuel height 15 cm) is placed in the room, which produces smoke flowing in the upper part of the corridor. This choice for fire location is motivated by the objective to limit the interaction between mist and fire load and only to study interactions occurring between mist and smoke.

2.2 Instrumentation

The heat release rate (or HRR) is deduced from fuel mass loss measurements with weight recorded every second. According to [8] the mass loss rate \(\dot{m}_{comb} = \frac{dm}{dt}\) is proportional to the HRR:
\[ HRR = \eta \Delta h_c \]  

(1)

Involving the combustion yield (\( \eta \)) and the heat of combustion (\( \Delta h_c \)).

Three vertical profiles based on 18 K-type thermocouples are registered in the corridor (every 3m from the wall near the room door) in order to characterize the thermal stratification. The thermocouples are spaced every 20cm vertically from the floor up to 1m, then spaced 10cm in the upper part up to the ceiling. The surrounding opacity is studied through opacimeters made of a laser diode (635 nm) coupled to a photodetector. They are located at 3 m and 6 m from the corridor entrance (Figure 2). All the opacimeters used for the result analysis are located below the vertical position 1m from the floor, where a smoke free environment is expected before water mist activation, as their measurement data would not be taken with confidence in surroundings with temperature higher than 50°C. The goal is to evaluate the smoke free height and to observe the stratification alteration due to mist/smoke mixing after nozzle activation (the mist injection and the consecutive cooling warranting that the surroundings will stay below the limiting temperature of 50°C). The transmissivity is calculated as the ratio between the radiation intensity measured during the experiment \( I \) and a reference value \( I_0 \) registered at the initial instant:

\[ \tau = \frac{I}{I_0} \]  

(2)

3 Results

3.1 Heat release rate

The HRR is plotted in Figure 3 as a function of time. A dotted line shows on the same graph the instant of water mist activation. HRR growth phase is followed by a level-off period at 300 kW after 360 s. The water mist system is activated at 360s for a 300s time period. The operating period corresponds also to the stationary phase. Thus, water mist does not affect the fire activity in the room in a straightforward manner. However the smoke flow alteration in the corridor may have a non–direct influence on the fire regime. By comparing with HRR recorded without mist activation (not shown here), the only perturbation lasts few seconds before the activation instant, was very close and the stationary regime development was not penalized.
3.2 Gas temperature

The smoke produced by the fire quickly fills the room volume and flows out the room into the upper part of the corridor. The thermal stratification is obvious in Figure 4a where vertical profiles of temperature are provided, before water mist activation. The high values in the upper part traduces the hot smoke flowing above a colder smoke-free. The interface height is close to 1.10 m. The smoke layer is homogeneous along the corridor: temperature profiles are the same whatever the longitudinal position. The mist activation alters this stratification due to a mixing induced by the downward water injection which homogenizes the temperature profiles. Note that the T_1 profile (located upstream from the nozzle location, 3m from the corridor extremity) still presents a thermal stratification, while the T_2 profile (located downstream from the injection, 6m from the corridor extremity) is almost constant. At the other extremity of the corridor outlet, T_S profile illustrates the environment tends to be thermally stratified, gas temperature in the upper part being close to 40°C like profile T_2.

![Figure 3](#) HRR as a function of time during 660 s

![Figure 4](#) Temperature profiles before (on the left) and during (on the right) water mist activation. T_1, T_2 and T_S correspond to profiles at 3m and 6m from the corridor extremity (room side) and at the other extremity.

Figure 5 shows the time evolution of the same temperatures at the locations T_1 and T_2. The water mist activation instantaneously stops the increasing step of the temperatures and cooling occurs. A slight further
increase is still observed while fire keeps burning. The homogenization of the temperatures is the second obvious effect with all curves gathering in a close temperature range, still with a small discrepancy for the profile upward from the injection which confirms a remaining thermal stratification there. Note that temperature uniformity illustrates that in the bottom part, which was smoke-free before mist activation, is now hotter and smoky.

![Temperature Profiles](image)

**FIG. 5** – Temperature evolution with time (thermocouple vertical position from floor indicated in the legend)

### 3.3 Opacimetry

The transmissivity measurements during the test lead to the mist influence on the visibility. Emission source and detector are 10 cm distant. Figure 6 shows the transmissivity as a function of time at the longitudinal position corresponding to the above-seen temperature distributions: T_1 and T_2. Before mist activation, the transmission level of all opacimeters located at a vertical position below 1m from the floor is equal to 1. This confirms that this area near the floor is smoke free (as also confirmed by simple observations during the test).

The mist spraying affects the transmissivity. However, the opacity evolution depends on the location. It appears on the left hand side figure (upstream from the injection) that a de-stratification occurs, decreasing the transmissivity progressively (the opacimeters detecting the visibility alteration one after the other), starting with the opacimeter located at the upper position (transmission instantaneously fallen down to 20%) down to the one located near the floor. The smoke-free layer thickness decreases with time. On the contrary, the effect is quite instantaneous downstream from the nozzle (Figure 6b), probably due to the fact that smoke is suddenly dragged near the floor due to the mist injection and finally flows near the floor toward downstream, weakly able to re-stratify as the cooling effect prevents from actual buoyancy effects. Another explanation comes from the droplets themselves which induce scattering effects. During this early stage of mist system operation, the transmissivity is even higher (smaller opacity) at higher positions (0.80 and 1.0 m from the floor). This could be explained by a higher droplet concentration near the floor. It is interesting to note that temperature measurements would lead to the idea of a quite homogeneous mixing of smoke and mist, whereas optical data show a more complex environment probably heterogeneous in concentrations.
4 Conclusion

A smoke flow has been studied in a corridor adjacent to a room where an heptane pool is burning, focusing on the alteration of the smoke due to a water mist injection. The present test led us to a characterization of the smoke stratification with a hot and opaque upper layer (evidenced with thermocouples and opacimeters) above a cool and transparent layer on the bottom part. Thermal and optical properties have been investigated here (species concentration would be another complementary way to study the stratification in a next step). A 1.1m high smoke-free layer has been obtained in the present conditions before mist activation, quite homogeneous and confirmed whatever the investigation means (through optical or thermal data). The mist injection instantaneously alters the stratification, inducing drag effects toward the floor, mixing and cooling of the smoke plus mist flow. Thermocouple measurements show a quite homogeneous flow in particular downstream the injection point, clearly demonstrating a de-stratification, while optical data show a more complex situation. The corridor is obviously homogenized in temperature but the opacity varies in a complex manner indicating heterogeneities in the concentrations of smoke particles and droplets. Further tests and analysis of numerical simulation results will now help us to complete the analysis of these smoke/mist interactions.

References