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Experimental Investigation on Flow and Thermal Characteristics of a Pool Fire in an Engine Compartment

Ilyas Sellami[1], Khaled Chetehouna[1], Antonin Robinet[1], Souria Hamidouche[2], Antoine Oger[3]
[1]INSA Centre Val de Loire, Université d'Orléans, PRISME EA 4229
88 boulevard Lahitolle, F-18022 Bourges, France
ilyas.sellami@insa-cvl.fr; khaled.chetehouna@insa-cvl.fr; antonin.robinet@insa-cvl.fr
[2]IMT Nord Europe, Institut Mines Télécom, Univ. Lille
Center for Energy and Environment, F-59000 Lille, France
souria.hamidouche@imt-nord-europe.fr
[3]DGA Techniques Terrestres
Echangeur de Guerry, F-18021 Bourges, France
antoine.oger@intradef.gouv.fr

Abstract **-** Despite the considerable body of work on pool fires taking place in confined and mechanically ventilated environments, there are still important uncertainties in our comprehension of such phenomena and in our ability to forecast their behavior. In this context, experiments are carried out to investigate the impact of airflow velocity on the flow and thermal characteristics of a pool fire in a full-scale engine compartment of an industrial vehicle. Two-component velocity measurement using Particle Image Velocimetry (PIV), heat release rate (HRR) evolution, and temperature profiles are presented. The results exhibit detailed flow structures around the flame in terms of direction and intensity. A high ventilation flow rate can lead to a significant increase in HRR as well as a reduction in temperatures inside the compartment.

Keywords**:** Experimental, pool fire, engine compartment, ventilation, particle image velocimetry, velocity field.

1. Introduction

Fires in vehicle engine compartments remain a major concern for users, leading to serious impacts on people, property, the environment, and their operational capabilities. In the USA alone, in 2018, over 200,000 vehicle fires were recorded, resulting in 560 deaths, 1,500 injuries, and over $2 billion in direct property losses [1]. In propulsion machinery rooms, fuel storage compartments, or ship engine spaces, fires can result from the leakage of fuels in the presence of various ignition sources such as static electricity, electric sparks, overheated engine blocks, etc. Such accidental fires can be simulated by pool fires, as they almost replicate the combustion process that occurs following fuel spills [2]. Pool fires are a frequent occurrence in the process industries as well as in the transportation and storage of chemicals and hazardous materials. According to a study of 224 recorded accidents, fires accounted for 43% of causes, among which 80% were pool fires [3].

One of the most important parameters describing motion in the combustion flow field is the velocity field [4]. Among the various approaches capable of measuring the velocity field, Particle Image Velocimetry (PIV) has emerged as a more preferred technique due to its ability to provide a more accurate approximation of the characteristics of physical phenomena. This in-field technique, is characterized by its high investigative productivity, enabling the measurement of instantaneous velocities in a selected flow cross-section [5], [6]. The PIV technique, which is based on the imaging of tracer particles illuminated by the incident laser, has made great progress in recent years in terms of practical applications, measurement principles, and system implementation [2], [7], [8], [9].

In this context, the aim of this study is to investigate the flow and thermal characteristics of a heptane pool fire inside an engine compartment. This study uses optical measurement techniques such as two-component Particle Image Velocimetry (PIV), mass loss rate, and temperatures measured in a mechanically ventilated configuration to characterize velocity fields and assess the effect of ventilation on flow and thermal characteristics in the neighborhood of the flame.

2. Material and methods

The experiments are carried out using the full-scale engine compartment of an industrial vehicle. The test bench measures 2.44 m^3 in volume, with dimensions of 1.30 m in length, 2.54 m in width, and 1.25 m in height [10]. The compartment has a large main window and two smaller side windows for operating PIV instruments (laser and camera) and providing visual feedback during experiments (see Fig. 1). A pool fire from a 24 cm-diameter cylindrical steel pan containing 155 g of n-heptane, representing the fire source, is positioned in the center of the compartment floor. A radiator fan is positioned on the front grille of the test bench to simulate the ventilation effects. Two airflow velocities are applied: 0 and 3.2 m/s. Temperature measurements are carried out using 15 type-K thermocouples, spaced 6 cm apart, and vertically positioned above the pan. The evolution of fuel mass is measured using a Scaime load cell positioned beneath the fuel pan. The velocity field around the flame is measured using the Dantec Dynamics PIV system. The illumination source used is a Nd:YAG laser, delivering two pulses (120 mJ/pulse) at a wavelength of 532 nm. Laser pulse separation time (Δt) is set to 200 µs. A light sheet is generated at the center of the pan, while the measurement window, 0.4 m high and 0.4 m long, is located 0.5 m above the fire pan. In order to record velocity fields, a HiSense 4M camera with high spatial resolution is located at a distance of 1.69 m, perpendicular to the laser sheet (Fig. 1). As tracers, we have used particles based on a mixture of polyhydric alcohols and water generated with a mist machine. Consequently, two sets of 1200 instantaneous velocity fields are acquired with a frequency rate of 5 Hz.

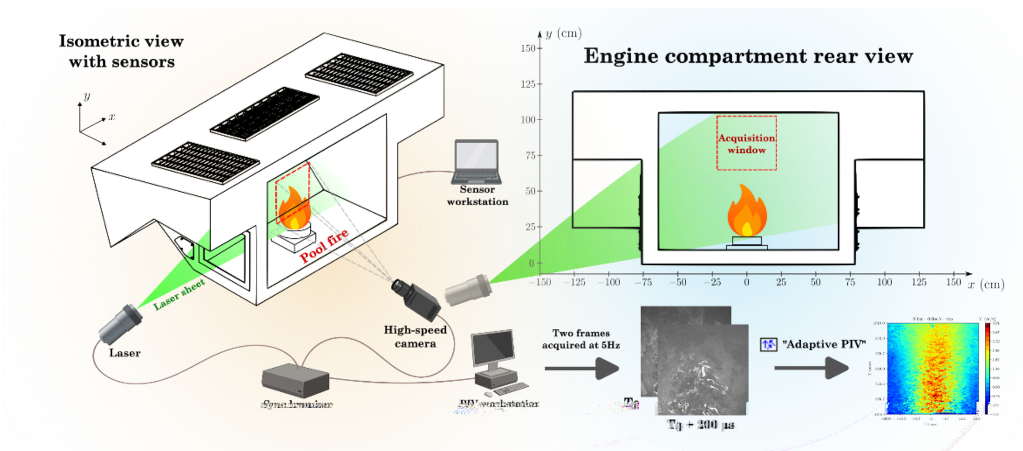

Fig. 1: Schematic diagram of the experimental set-up.

3. Results and discussion

3.1. Mean flow properties

Fig. 2 shows color contours of the vertical and horizontal mean velocity's components (noted *V* and *U*) obtained using the described method and equipment for the natural and mechanical ventilation conditions (airflow velocities of 0 and 3.2 m/s, respectively). According to the 2D velocity fields obtained, the vertical velocity component is dominant compared to the horizontal component, with a pseudo-symmetrical distribution between the left-hand and right-hand sides under natural ventilation (Figs. 2a and 2c). In these conditions, the flow regime strongly responds to the high buoyancy forces generated by the fire. However, in the case of mechanical ventilation, the mean velocity values observed on the right-hand side are higher. This is due to the additional flow forcing generated by the mechanical ventilation (3.2 m/s), which distrusts the initial flow structures. As a result, the mean magnitude of the vertical and horizontal velocity components decreases with height. The time-averaged vertical velocity shows higher values around the central position ($X = 0$ mm) and lower values at locations further away from the central position under natural ventilation. Nevertheless, under high ventilation, the mean vertical velocity shows high values on the right-hand side, exceeding 6 m/s, while it exhibits values lower than 4 m/s on the left-hand side (Fig. 2b). The time-averaged horizontal velocity is much lower than the vertical velocity, with a maximum value of approximately 2 m/s for high ventilation conditions. Clearly, horizontal velocities approach zero near the compartment ceiling. As illustrated in Fig. 2d, alternating locations of positive and negative horizontal velocity can be identified, indicating the entrainment of air from the environment through the compartment's front grille.

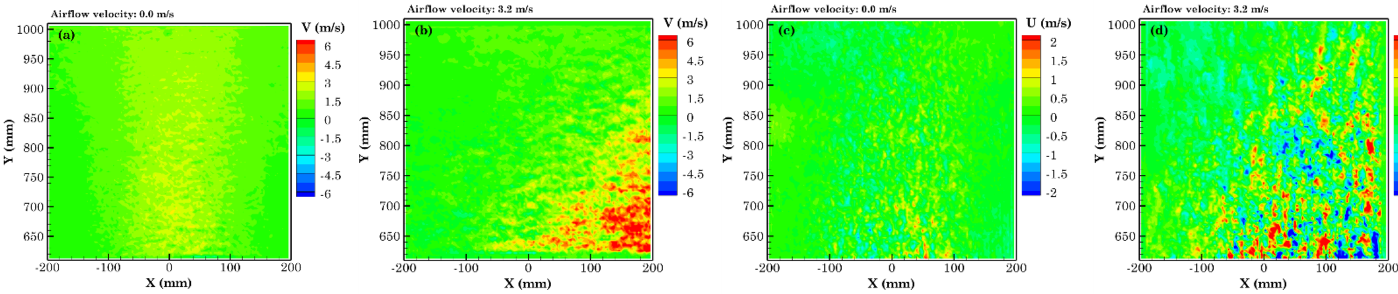

Fig. 2: Time-averaged velocities: (a) contours of the vertical velocity under natural ventilation; (b) contours of the vertical velocity under an airflow velocity of 3.2 m/s; (c) contours of the horizontal velocity under natural ventilation; and (d) contours of the horizontal velocity under an airflow velocity of 3.2 m/s.

3.2. Thermal characteristics of the pool fire

The heat release rate (HRR) is one of the most important variables in fire safety analysis. As a common approach, the HRR can be derived from the measured mass loss rate (MLR). The effects of ventilation conditions on the HRR are illustrated in Fig. 3(a). The behavior of the pool fire inside the experimental set-up can be divided into the following stages:

(1) Growth stage: this short phase occurs after ignition. The HRR increases gradually as the fuel pool heats up. At this stage, there is no significant change in HRR. This means that the development of an incipient fire is largely dependent on the characteristics and configuration of the fuel involved (fuel-controlled fire).

(2) Quasi-steady burning stage: the HRR increases significantly with increasing ventilation flow rate. Under an airflow velocity of 3.2 m/s, the maximum HRR value is doubled, from around 36 to 69 kW. In general, ventilation systematically restricts fire at this stage.

(3) Extinguishing stage: this phase is characterized by reduced evaporation and a weaker flame due to the fuel burnout. Unlike the case of natural ventilation, the HRR decreases rapidly towards zero under high ventilation conditions. This variability in extinguishing duration depends on the maximum MLR value reached under the effect of ventilation. Usually, a low peak value leads to a longer burning period, and conversely, a high peak value results in a reduction of the decay phase delay.

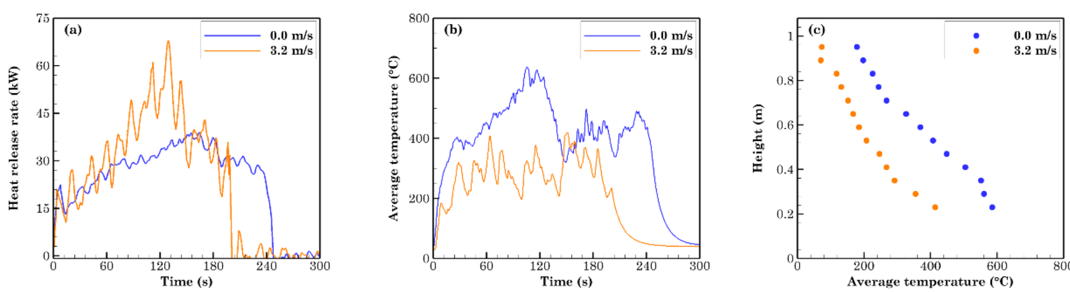

Fig. 3: Influence of ventilation on the burning behavior of the pool fire: (a) HRR evolution; (b) average temperature along the vertical thermocouple tree above the fire; and (c) vertical distribution of time-averaged temperature.

Temperature analysis plays a crucial part in understanding compartment fires. Fig. 3(b) illustrates the effect of ventilation on the average temperature measured across the vertical thermocouple tree above the pan. Generally, the average temperature increases progressively after the fire ignition, reaching its peak during the quasi-steady period. Mechanical ventilation results in lower average temperatures inside the compartment, reaching a plateau during 180 seconds with a time-averaged value of around 293 °C. This cooling effect is due to the entrainment of a strong fresh-air jet from the environment. Nevertheless, natural ventilation leads to higher temperatures, with an average peak of around 630 °C after 107 seconds from ignition, followed by a rapid drop in temperature. This drop suggests a significant partial suppression, resulting in a depression and air supply, and subsequently in the re-ignition of hot gases at the flaming surface. Moreover, temperature profiles in both ventilation cases follow a similar trend, in which gas temperature decreases with height in an almost linear relationship, as shown in Fig. 3(c). During natural ventilation, the average temperature drops from around 585°C at 0.23 m above the pan to 175°C near the ceiling. Meanwhile, when mechanical ventilation is applied, the temperature drops from approximately 415°C near the floor to 70°C below the ceiling.

4. Conclusion

This study investigated the burning behavior of a pool fire within an industrial engine compartment, focusing on the impact of airflow velocity through the 2D PIV technique and the measured mass loss rate. The experimental findings exhibit a detailed description of the flow structures in terms of direction and intensity. A high ventilation rate can lead to a significant asymmetrical distribution of the velocity field. As a result, vertical velocity was the dominant velocity component for most locations. The results revealed that HRR increased significantly with increasing ventilation. At an airflow velocity of 3.2 m/s, the HRR peak doubled from around 36 to 69 kW. It was also noted that an increase in ventilation rate induced a significant decrease in temperatures inside the compartment.

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