EXPERIMENTAL ANALYSIS OF GEOMETRY AND TEMPERATURE IN LAB-SCALE DIESEL POOL FIRES UNDER CROSSWIND CONDITIONS

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Abstract. *Smoke dispersion from a major fire in Santos Port in 2015 forced many people leave their residences, causing health problems and financial losses.. Considering this kind of accident, the smoke dispersion in function of wind speed is experimentally modelled here. This article presents the experimental analysis of the smoke column dispersion in a diesel pool fire, using a wind tunnel in a lab simulation. The influence of different wind speeds over the tilt, height,d length, and temperatures of the flame was analyzed. Experimental analysis results were compared to correlations available in the literature. For the initial part of study it was used a scaled-down model of an actual tank of diesel storage, from a large refinery in Canoas – RS. An accidental fire in this kind of tank can produce a huge quantity of smoke, the prediction of the intensity and dispersion to the surroundings may help to guide the prevention and remediation procedures.*

Keywords*: pool fire, flame tilt, smoke, fire safety*

1. NOMENCLATURE

μ_a ambient air viscosity (kg m^{-1} s^{-1})
ρ_a ambient air density (kg m^{-3})
ρ_g fuel vapor at boiling point density (kg m^{-3})
θ flame tilt angle (deg)
C_{pa} specific heat of air at constant pressure (J kg^{-1} K^{-1})
C_f specific heat of liquid fuel (J kg^{-1} K^{-1})
D fuel pool diameter (m)
Fr Froude number
g gravitational acceleration (m s^{-2})
$\dot{m}''$ fuel mass burning rate per unit area (kg m^{-2} s^{-1})
Re_D Reynolds number
T_a ambient air temperature (K)
T_f flame temperature (K)
T_{bp} fuel boiling point (K)
U wind speed (m s^{-1})
U_c minimum wind speed required for flame tilt to occur (m s^{-1})
$U_{c,mod}$ minimum wind speed required for flame tilt to occur (m s^{-1})

2. INTRODUCTION

A recent headline was the huge fire and explosions in fuel storage tanks located in Santos seaport, at São Paulo. That kind of accident usually leads to many problems to local residents and firefighters, besides the environmental and financial losses. In another accident, G1 (2016a), a leakage of gaseous fuel in Santos Port complex released a toxic cloud, as seen in Figure 1a, that reached many cities causing various health problems. G1 (2016b) reported also that some anhydrous alcohol and gasoline storage tanks exploded and created a column of smoke (Figure 1b) that could be seen from many kilometers and spread to neighbor cities.

Because of that kind of accident, it is very important the study of phenomena involved in gases and smoke dispersion by wind and its influence in the consequences of events like those previously mentioned.

Crosswind that blow over a flame modify its characteristics, the wind speed determining its tilt angle and influencing the distance it reaches. The determination of those dimensional characteristics can help to predict the direction and the area the smoke, and consequently, the hazardous matter/pollution, could reach. . An experimental test in lab-scale is a feasible way to understand the phenomena of smoke dispersion. and can be employed to create a model to estimate its impact on the regions surrounding an accident and to delineate an action plan to maximize the security of the local population.

In the leakage of toxic gases shown in Figure 1a, the gas cloud traveled many kilometers transported by the wind; a correct determination of the region- affected by that accident could avoid health problems to people living there. Figure 1b shows the smoke column provoked by a fire in fuel storage tanks. Those accidents spread hazardous materials (as soot and toxic pollutants) into the air stream, affecting residents not only near to, but also some kilometers away from the fire.

(a)

(b)

Figure 1. (a) Leakage of toxic gas and (b) fire in gasoline and alcohol anhydrous at Santos Port, São Paulo.

3. METHODOLOGY

This paper presents measurements of temperature and geometrical effects of crosswind in a lab-scale diesel oil pool fire in a wind tunnel. As demonstrated further, the experimental setup performed comparisons of several empirical correlations in order to determine their agreement with measured values in practical experiments. It is well-known that the use of empirical correlations can lead to discrepancies but this type of study is very important to understand their validity and, if necessary, to adapt the boundary conditions of new experiments or to modify the correlation.

3.1 Experimental setup

The current pool fire investigation in lab-scale employed a wind tunnel to obtain experimental data. The experimental workbench consisted in the following equipment and materials:

a) a wind tunnel 1250 mm long, with rectangular cross-section of 250 mm high and 280 mm wide;
b) an infrared camera model Flir A320;
c) a digital spit thermometer Incotherm 6132;
d) a handheld digital anemometer Icel AN-10;
e) a digital thermometer with thermocouple type K probe Minipa MT-520;
f) a steel tank scaled with 110 mm in diameter and 57.6 mm in height (the lab-scale tank was scaled-down at 1:250 of the actual storage tank).

Figure 2 shows the test section and the instrumentation. The wind tunnel was used to create the cross wind; the infrared camera to determine the flame and hot gases temperatures (uncertainty of ±2 K or ±2% of reading); the digital spit thermometer to determine the reference temperature of the wind leaving the tunnel (uncertainty of ±1 K). A handheld anemometer was used to determine the speed of the wind in the test section exit (uncertainty of ±3% + 0,1), the thermometer together with the probe of thermocouple type K mounted at 40 mm in radial position near the tank in its left side were used to determine the surrounding temperature (uncertainty of ±0.2% of reading + 1D).

The cross air flow in the tunnel is generated by a fan with a variable-frequency drive to provide wind speeds ranging from 0 m/s to 6.2 m/s, but in the current study it was varied up to 3.6 m/s. A honeycomb was also installed in the tunnel for turbulence regularization. The other end of the tunnel was open. Figure 3 presents a detail of the front side view of the experimental setup.

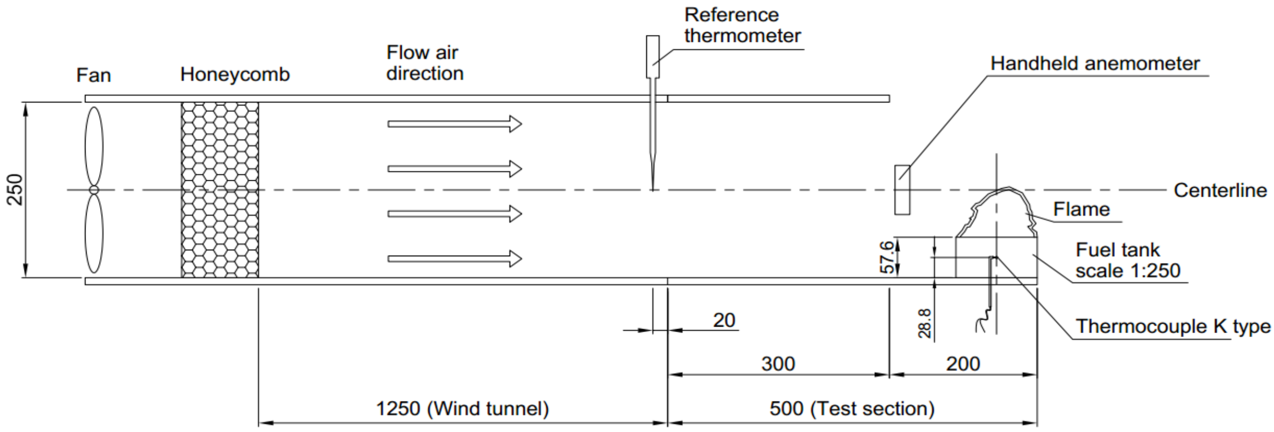

Figure 2. Schematic view of the experimental setup (dimensions in mm).

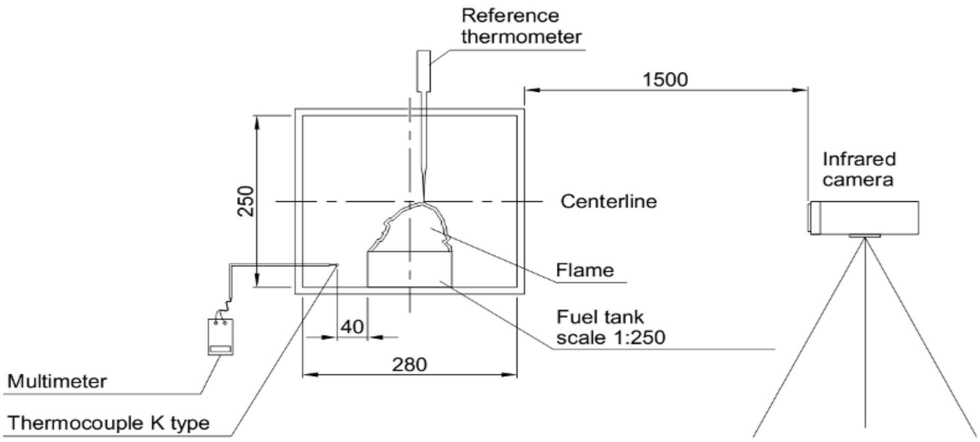

Figure 3. Schematic view of front side section of the experimental setup (dimensions in mm).

3.2 Semi-empirical determination of correlations

According with a recent work by Lam and Weckman (2015a), one of the most important motivations to conduct researches about fire is to improve the ability to predict hazards from a fire in a given scenario. In order to analyze a scenario, one must first determine how large the fire is and how intensely it is burning, requiring knowledge of characteristics as flame geometry, flame temperature and heat release rate. Collection of quality experimental data is critical to the accuracy of such predictions, and model validation is indeed an important part for fire model development. Therefore, experimental simulation of realistic, yet controlled, accidental fire scenarios is necessary for improvement of existing fire models and development of new models.

Lam and Weckman (2015b) discussed various researches about wind-blown pool fires where the main focus was on parameters that describe flame geometry, particularly those needed to estimate radiative heat transfer and thermal hazard from the fire. In most previous studies, flame geometry has been characterized using photo or video images of the fire, while in their recent studies values for flame drag, flame tilt angle and flame length are obtained based on video frames, and the temperature of flame and surroundings were given by a set of thermocouples and are compared to values predicted using semi-empirical correlations available in the literature. Results are compared to measured data to determine sources of discrepancy and thereby identify weaknesses in the physics modeled by the correlations. This same method was used to describe the value found in the experimental analysis in present work, and then corrections were made to predict the experimental data for the scaled pool fire.

The correlations for the tilt angle that were used in the analysis can be seen in Table 1. The correlations were obtained from many references and were summarized by Lam and Weckman (2015b). Table 1 presents, for each correlation, the main conditions in which the corresponding data was obtained, as wind speed range, burner shape and size, and fuel.

Hereafter, it is defined some auxiliary equation, that were used in the correlations from Lam and Weckman (2015b). Equation (1) is the minimum wind speed required for flame tilt to occur, Eq. (2) is a minimum wind speed modified, Eq. (3) is Froude number and Eq. (4) is the Reynolds number.

$$U_c = \left(\frac{g \cdot m''.D}{\rho_a} \right)^{1/3} \tag{1}$$

$$U_{c,\text{mod}} = \left(\frac{g \cdot m''.D}{\rho_g} \right)^{1/3} \tag{2}$$

$$Fr = \frac{U^2}{g.D} \tag{3}$$

$$\text{Re}_D = \frac{\rho_a.U.D}{\mu_a} \tag{4}$$

Table 1. Correlations for analysis of flame tilt, adapted from Lam and Weckman (2015b).

Eq.	Correlation	Wind speed	Burner size	Fuel
(5)	$\cos\theta = 0.7\left(\frac{U}{U_c}\right)^{-0.49}; \quad \frac{U}{U_c} \geq 1$	1.5–5.6 m/s	0.91 m × 0.13 m to 0.91 m × 0.61 m, adapted for line source of fuel	Wooden cribs
(6)	$\cos\theta = \left(\frac{U}{U_{c,mod}}\right)^{-0.5}; \quad \frac{U}{U_{c,mod}} > 1$	1.3–7.9 m/s	1.8–24.4 m diameter	LNG
(7)	$\cos\theta = 0.87\left(\frac{U}{U_c}\right)^{-0.272}; \quad \frac{U}{U_c} \geq 1$	1.8–14.4 m/s	6.1 m × 6.1 m to 15.2 m × 12.2 m	LNG
(8)	$\cos\theta = 0.86\left(\frac{U}{U_c}\right)^{-0.250}; \quad \frac{U}{U_c} \geq 1$	1.8–14.4 m/s	6.1 m × 6.1 m to 15.2 m × 12.2 m	LNG
(9)	$\cos\theta = 0.92\left(\frac{U}{U_c}\right)^{-0.26}; \quad \frac{U}{U_c} \geq 1$	0–2.3 m/s	1.5–6 m diameter	Gasoline, diesel oil
(10)	$\cos\theta = 1.06\left(\frac{U}{U_c}\right)^{-0.73}; \quad \frac{U}{U_c} \geq 1$	0–3 m/s	0.21 m × 0.21 m, 0.29 m × 0.15 m, 0.45 m × 0.11 m, 0.58 m × 0.07 m	Acetone

4. RESULTS

All measurements were made in an ambient temperature between 17-18 °C. For each test case 40 readings of each parameter (tilt angle, flame height, flame length, temperatures) were collected to perform a statistical analysis.

In the case of speed, the stabilized value was taken after 5min with the anemometer in the wind tunnel outlet. This time value was taken by empirical observation.

The mass burning rate of diesel, $\dot{m}''$ necessary to compute the equations in Table 1 was defined by empirical analysis as reported in USNRC (2016), and the value is considered constant by 0.045 kg m^{-2} seg^{-1}. The volume of fuel was considered constant, since the fuel film was maintained at 5 mm in relation to top of tank, with a variation of approximately ±5%, the volume of fuel is given by $5.474 \cdot 10^{-4}$ m^3.

Figure 5 shows the variation of the tilt angle as the wind speed increases obtained both from the current experimental data and from the correlations previously presented in Table 1. The rise of values in the figure means that the flame lay down with the increase of the wind speed. The tilt angle is measured using the orthogonal to the pool plane as reference. Experimental results presents better agreement with correlations for higher velocities. This is due to larger uncertainties in low velocity measurements.

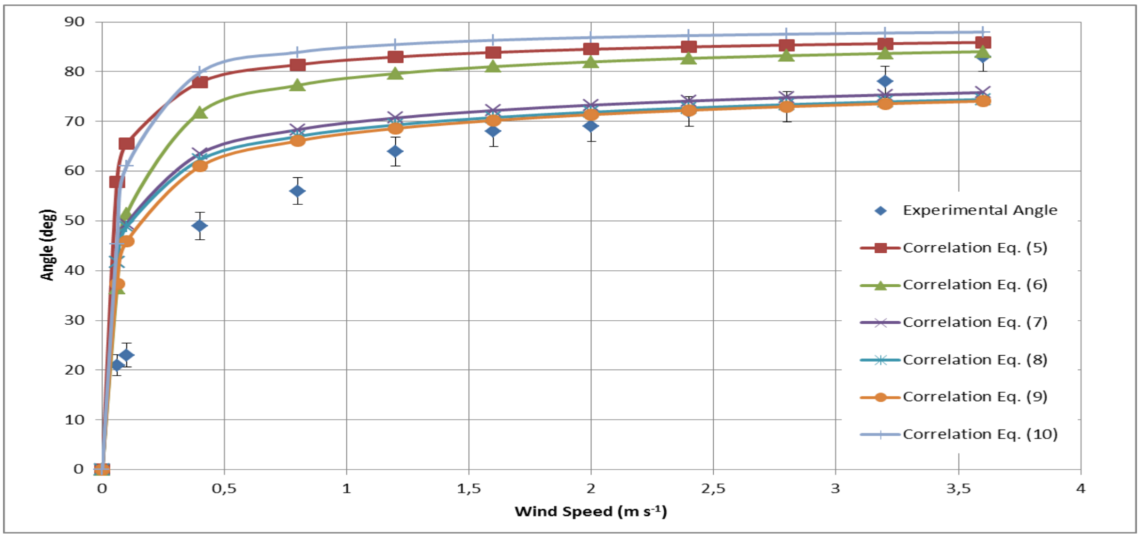

Figure 5. Comparison between the angle with correlations and experimental vs wind speed.

Figure 6 presents the thermographic images for wind speeds of 0 m/s, 0.06 m/s and 1.2 m/s. It is possible to observe the initial tilt angle of the flame of 0° in relation to the normal direction of the pool surface. As the crosswind speed increases, the flame is getting more inclined, with a higher tilt angle. This behavior was also observed in Figure 5.

In Figure 6 the temperature color scale corresponds to temperatures measured some instants after, a delay characteristic of the thermal camera. In the top left corner, box 1 and box 2 show actual temperature. Therefore, the maximum temperatures in the boxes are bigger that the ones showed in color scale.

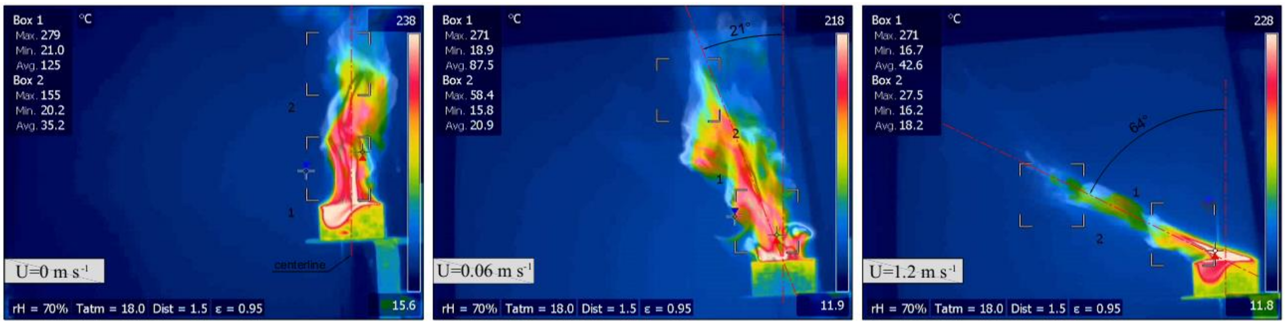

Figure 6. Tilt angle schema to make the analysis

Figure 7 depicts sequential thermographic images for wind speeds ranging from 0 m/s to 3.6 m/s. The images show wind speed and correspondent tilt angle of the flame increasing. At higher speeds, flame comes near to horizontal and presented a length reduction.

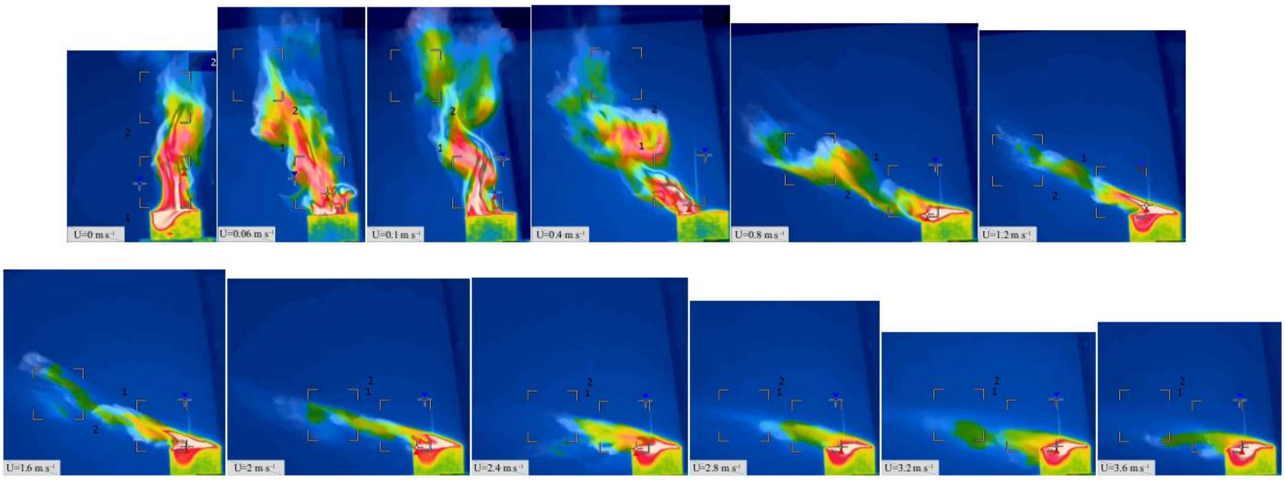

Figure 7. Tilt angle with wind speed variation.

Figure 8 presents the temperature at the pool centerline at the top of the tank as a function of the cross-flow speed. These data were obtained from the analysis of the thermographic figures, and values are approximate. It is observed the tendency of the temperature to increase as the wind speed increases. . That effect is expected since more oxidizing fluid (air) is carried into the flame (in direction to the pool center), so the location where combustion takes place is continuously modified as the cross-flow speed is modified. This leads the flame front closer to the pool center and thus the temperature increased.

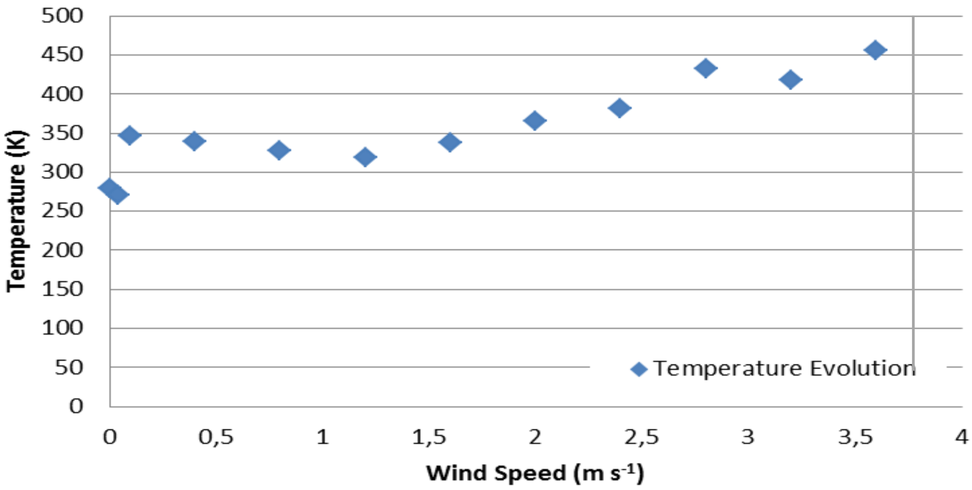

Figure 8. Flame temperature versus wind speed

Figure 9 shows the evolution of temperature in the centerline region of the plume, 40 mm far from the pool top. These data were obtained from the analysis of the thermographic figures, and values are approximate. As the wind speed (and consequently the turbulence) increases, the temperature decreases faster and almost reaches the ambient temperature, since as more air is carried to the fire, the speed change the density values of the vapor gases of the fuel making the temperature of the plume to decrease. That probably occurs because the thermal exchanges with the surrounding environment are bigger.

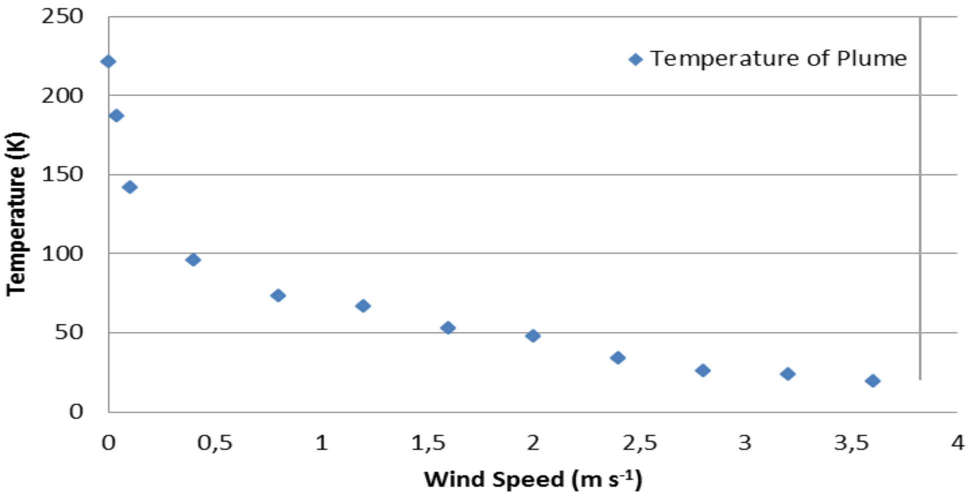

Figure 9. Plume temperature versus wind speed

The determination of flame height and length is schematically shown in Fig. 10. Figure 10a was obtained for a cross-flow speed of 0.06 m s^{-1} and Figure 10b for 1.6 m s^{-1}. In each figure, the vertical measurement is the flame height, and the measurement aligned with the flame axis is its length. In both cases, the reference location is the pool top position.

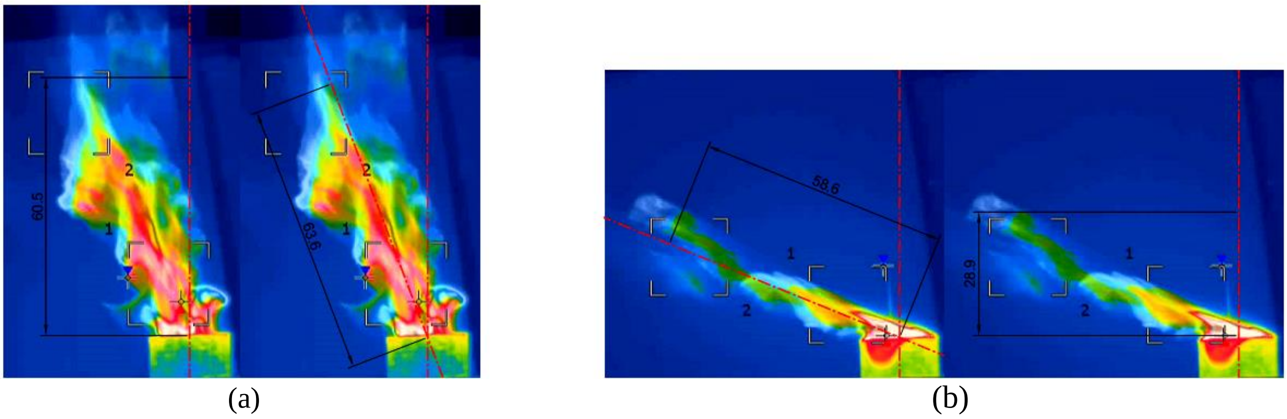

Figure 10. Measurement of flame height and length: (a) cross-flow speed 0.06 m s^{-1}; (b) 1.6 m s^{-1}

Flame heights as a function of cross-flow speed are shown in Figure 11a, while Figure 11b presents flame length. Both heights and lengths generally decrease as the speed is increased. It is interesting to note that the height gradient is steeper than the length gradient, i.e., the flame tilted more rapidly than it became shorter in length. This is due to the low momentum of the flame in relation to the cross-flow momentum, since it is a primarily buoyancy-driven fire. According to other investigations, like (Mudan, 1984; Moorhouse, 1982; Welker and Sliepcevich, 1966; Raj, 2010; Lautkaski, 1992; Tang et al, 2015) the flame length should grow with the wind speed, because it would be stretched, but this was not verified in the current experiment. A possible reason for these shorter flames could be that the flame became over-ventilated so the combustion was impaired, which is a situation very close to flame blowout/extinction. These results can also be verified in Figure 7.

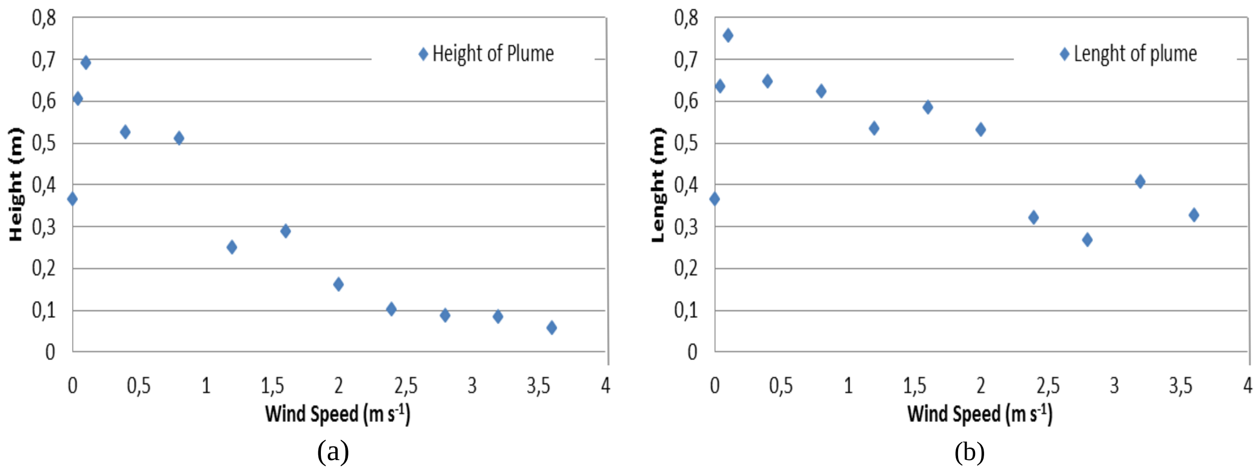

Figure 11. (a) Evolution of height as function of wind speed and (b) length as function of wind speed.

5. CONCLUSIONS

This paper presented a first step to characterize the thermal and geometric behavior of a diesel pool fire under controlled turbulent crosswind conditions. The scenarios were intended to simulate outdoor casualties like fires in fuel tanks.

The temperature contour plots (thermographic images) were successfully used to enhance visual analysis of the fire geometry and of the tilt angle. Estimates of plume tilt were obtained from the temperature contour plots and were consistent with images of the fire.

The results obtained in the present experiments provide valuable insight into the phenomena that affects the geometry of the wind-blow fire plume. As the wind speed increased from 0 m s^{-1} to 3.5 m s^{-1}, the horizontal momentum of the wind became increasingly important relative to buoyancy effects in the fire, resulting in increased plume tilt.

The experiment made possible to verify the influence of wind speed in tilt angle, the faster is the cross-wind, the more inclined is the flame, independent of the method used in their determination, experimental or correlations. Higher wind speeds led to higher angles, decreases in the flame height and modified temperature profiles inside and outside the pool.

The flame length presented a behavior that was not expected in accordance to other works, since it became shorter as the wind speed increased, instead of being elongated. That can be explained possibly because the flame reached its near-blowout limit, but this must be studied further.

Besides the refinement of the current experimental data, including pollutant dispersion, the continuity of this research will be also focused on the numerical simulation of this pool fire. That simulation will work as a validation for the numerical code and in the future simulations of actual scale tanks will be performed.

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