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Critical heat flux for ignition of dead and live *Pinus halepensis* needles. Influence of moisture content

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Abstract

Wildland fire spread has been shown to exhibit unexpected behaviors depending on the fuel roughness, wind and land topography. Fire outbreak has attracted for a long time both wildland fire scientists and operational. The critical heat flux for ignition is one of the most important parameters used in fire safety. For example, it may be used for the fuel breaks estimation at Wildland Urban Interface. The critical heat flux for ignition of dead and live Pinus Halepensis needles (moist and dry) is investigated using a cone calorimeter. It is determined by using a recently developed method based on the phase transition theory where ignition time behaves according to a power-law trend near threshold. Compared to the usual deterministic methods, this method accounts for the probabilistic ignition behavior observed for porous fuels. The determined critical heat flux for ignition seems to be independent of the state of the fuel (live or dead) and of its moisture content within the errors. A heat transfer analysis is realized using the steady temperature which is related to the absorbed incident heat flux. From this analysis it is concluded that surface temperature at ignition does not change for fresh or dry live and dead fuels.

1. Introduction

Every year, a very large number of wildfires raged across the globe (Martin et al.2016), causing human misery and damage to properties. In the last decade, wildland fires become more intense and prolonged in time. The wildland fire safety has drawn the interest of scientists and operational in the effort to overcome fire outbreak and spread. Wildland management and Wildland Urban Interface (WUI) are among the main topics requiring fire risk reduction. This may be realized either by including fire breaks or by planting less flammable fuels. The critical heat flux for ignition is the parameter investigated for this end. Usually, the critical heat flux for ignition has been estimated by deterministic methods like ASTM 1534 standards (ASTM, 2017). However, such methods do not account for the probabilistic behavior of ignition that occurs near the critical heat flux. Recently, a new method based on phase transition theory (Stanley, 1971; Yeomans, 1992) has been proposed for the estimation of the critical heat flux for ignition applied to porous fuels (Sabi et al., 2021). The critical heat flux obtained by this method appears much smaller than those using deterministic ones. This is due to the probabilistic behavior occurring at lower heat flux intensities. Phase transitions are ubiquitous in nature, they can be observed in various fields like conductor/insulator or percolation (Stauffer and Aharony, 1992), liquid/gas (Blundell and Blundell, 2006), paramagnetic/ferromagnetic transitions (Stanley, 1971), etc.

The flame is a gas phase phenomenon (Drysdale, 2011), and emitted volatiles can be either in the flame state if ignition occurs, or remain in gaseous state if ignition does not. Ignition/non-ignition phase transition is referred to the different states of the gas phase: flame (ignitable) or gas (non-ignitable) (Sabi et al. 2021). Sabi et al. (2021) have studied analytically the ignition time behavior using a simple model based on conservation energy, where ignition temperature was the only ignition criterion. This analysis led to a logarithmic divergence of ignition time while this divergence has been found experimentally to be power-law. The power-law divergence has been recovered by considering the critical rate of flammable gas emission. The critical heat flux for ignition may depend on various fuel parameters like moisture content, porosity, and its live or dead state. Terrah et al.

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(2020) have found that there is no critical moisture for ignition; they suggested that for any moisture content there is a critical flux for ignition because of the difficulty igniting of fresh live fuel. Jervis and Rein (2015) have shown that the most flammable fuels are fresh dead and aged needles followed by dry live needles, the least flammable are the fresh live needles. Recently, it was found that the rate of spread is higher for dried live *Pinus Halepensis* needles (with maximum flame height) than for fresh live ones (with smaller flame heigh) which indicates the existence of moisture threshold for fire spread (Aizeti, 2021). According to such a flammability difference, it is expected that the more the fuel is flammable, the more its critical heat flux for ignition is smaller. For instance, it can be reasonably thought that a moist fuel has a larger critical heat flux than a dry one. In this work, the influence of the state of the fuel (dead or live) and moisture content on the critical heat flux for ignition of *Pinus Halepensis* needles is investigated using a cone calorimeter.

2. Experimental setup and sample preparation

The ignition process is realized through a cone calorimeter with an electrical resistance of a power of $3000\ W$ used as a heat source. The heat source provides to the sample an incident radiation heat flux of magnitude ranging from 5 to $25\ \mathrm{kW/m^2}$. The received heat flux is varied by changing the distance of the top surface of the sample to bottom of the cone calorimeter. The heat flux at the top surface position of the sample is calibrated by using a water-cooled heat flux sensor of type Hukseflux SBG 01 working in the range 0-200kW/m². The experimental setup and calibration are shown in Fig.1. The ignition is controlled by a pilot flame located *2 cm* above the sample top surface. Although the distance to pilot is slightly greater than the $1\ cm$ required by ASTM 1354 standards (ASTM 2017), it allows avoiding the contact of needles with the pilot. The cone calorimeter is further equipped with a K-type thermocouple measuring surface temperature (placed perpendicular to the needles at the top surface of the sample). The time evolution of temperatures provided by the K-type thermocouples is recorded via a data acquisition station Graphtec midi-LOGGER GL 840 connected to a personal computer. The steady temperature is realized by exposing the samples to a sufficiently low heat flux to avoid ignition. In this case, both surface and gas temperatures become nearly constant at a maximum value within a steady period (around 50 min). As will be shown below, the maximum steady temperatures are related to the absorbed incident heat flux.

Pinus halepensis needles are harvested from the Campus of USTO University. The fuel is in three (3) states: dead, fresh live and dried live. The live fuel is completely dried using a micro-wave oven for $3\ min$. This device allows a short drying time to maintain the fuel it is live state before ignition. The micro-wave oven provides the same drying quality as the other devices (Terrah et al, 2020). Live fuels of $10\ g$ mass are either ignited directly (moist fuels) or completely dried (moisture content of 50% in wet basis) before ignition. Dead fuels of $5.5\ g$ mass (moisture content of 10% in wet basis) are considered for ignition. The samples are placed in a cylindrical holder of $10\ cm$ diameter of a mesh shape. The mass was weighted using a Kern PCB 350 balance with $1\ mg$ resolution. The ignition test is considered as succeeded and recorded if the flame persistence time is greater than $4\ s$ (sustained ignition). It is considered as failed if smoldering combustion is observed instead of flaming, with complete oxidation of the fuel in its solid phase (Rein, 2016).

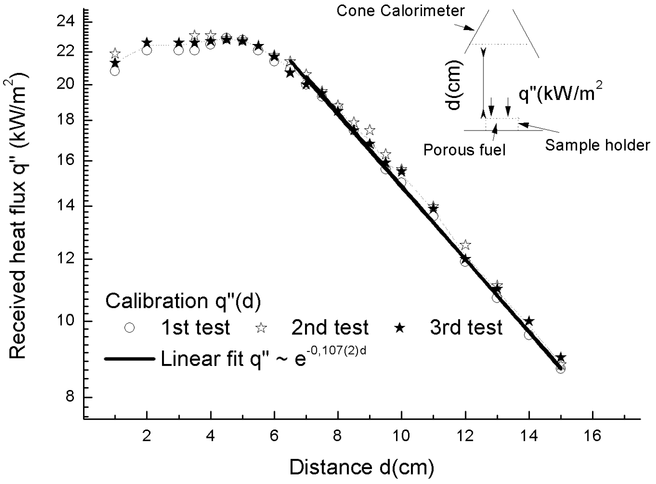

Figure 1- A schematic representation of the calibration flux and the experimental setup

3. Results and discussion

As mentioned above, recently a new method based on phase transition theory (Yeomans, 1992; Stanley, 1971) has been proposed to estimate the critical heat flux for ignition of porous fuel (Sabi et al. 2021). Compared to the usual methods, this method has been shown to account for the ignition probabilistic behavior occurring near the region of the critical heat flux for ignition. Sabi et al. (2021) have shown that ignition time t_{ign} diverges as a power-law as $q"_{inc} - q"_c$ as

$$t_{ign} \sim (q"_{inc} - q"_c)^{-\gamma} \tag{1}$$

The critical exponent γ is related to the kind of ignition. The estimation of the critical heat flux consists in varying $q"_c$ until the power-law trend appears of t_{ign} as a function of $q"_{inc} - q"_c$ (i.e. until the best linear fit of the plot in logarithmic scale is obtained).

Fig. 2 shows ignition time as a function of $q"_{inc} - q"_c$ in logarithmic scale for the 3 states of *Pinus Halepensis* needles (fresh live, dry live and dead). The critical heat flux for ignition $q"_c$ is obtained as to have the best linear fit. The uncertainty is estimated by estimating the critical flux within 5 % reduced correlation coefficient. It is found that the critical heat flux for ignition is the identical within uncertainties for the 3 states (dead fuel, fresh live fuel and dried live fuel), despite that the ignition process takes a longer time for moist live fuels than dried ones or dead fuels. The critical heat flux for ignition is independent of moisture content contrary to Terrah's suggestion (Terrah et al. 2020). The lines representing the three states of the fuel in Fig.2 (logarithmic scale) appear nearly parallel, corresponding to nearly constant a critical exponents. This suggests that ignition process is similar for the three states of the fuel.

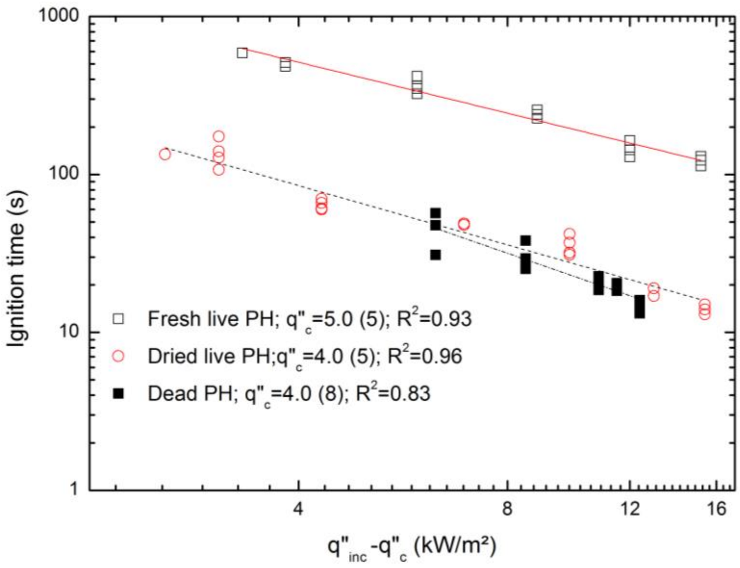

Figure 2: Ignition time vs. $q"_{inc} - q"_c$ for dead and live fresh and dried live fuls

To interpret this result let us analyze the heat transfer mechanism involved in ignition process. When the fuel bed of mass $m = \mathrm{m_{dry}} + \mathrm{m_w}$ is submitted to an incident heat flux $\mathrm{q"_{inc}}$, it is heated to a temperature T, and the net absorbed heat flux by the fuel $\mathrm{q"_{net}}$ is related to the absorbed incident heat flux $\mathrm{aq"_{inc}}$ and the lost flux. Neglecting conduction heat transfer, and vapors emission, this is described by the following equation:

$$\mathrm{q"_{net}} = \mathrm{aq"_{inc}} - \mathrm{h(T - T_0)} + \sigma\varepsilon\left(\mathrm{T^4 - {T_0}^4}\right) = \left(\mathrm{m_{dry}{c_p}^f + m_w {c_p}^w}\right)\frac{dT}{dt} \qquad (2)$$

Here h is the convection coefficient, σ is the Stefan Boltzmann constant, ε is the emissivity of the fuel, $\mathrm{T_0}$ the ambient temperature, and $\mathrm{{c_p}^f}$ ($\mathrm{{c_p}^w}$) is the specific heat of fuel (water). As surface temperature T increases with time, the lost heat flux increases, which decreases the net absorbed heat flux until it vanishes asymptotically (for a sufficiently low heat flux with no ignition), leading to a steady (maximum) temperature T_{max}. Therefore, the absorbed incident heat flux is related to the maximum temperature as:

$$\mathrm{aq"_{inc}} = \mathrm{h(T_{max}\text{-}T_0)} + \sigma\varepsilon\left(\mathrm{{T_{max}}^4\text{-}{T_0}^4}\right) \qquad (3)$$

In Fig.3 time evolution of temperature is presented for the parameters of moist and dry *Pinus Halepensis needles* used in (Sabi et al., 2021). The maximum temperatures seem to fluctuate within 10° C. Within this temperature interval, both moist and dry fuels maximum temperatures seem to collapse. At the critical heat flux for ignition, the maximum temperature coincides with ignition temperature. This means that the fuel bed surface temperature reaches ignition (T_{ign}) asymptotically at $t \to \infty$. Replacing T_{ign} in equation (3) The critical heat flux for ignition reads thus:

$$\mathrm{aq"_c} = \mathrm{h}\left(\mathrm{T_{ign}\text{-}T_0}\right) + \sigma\varepsilon\left(\mathrm{{T_{ign}}^4\text{-}{T_0}^4}\right) \qquad (4)$$

As a consequence of the results shown in Fig.2, it appears that ignition temperature does not vary with moisture content, and is identical for dead and live fuels within the uncertainty.

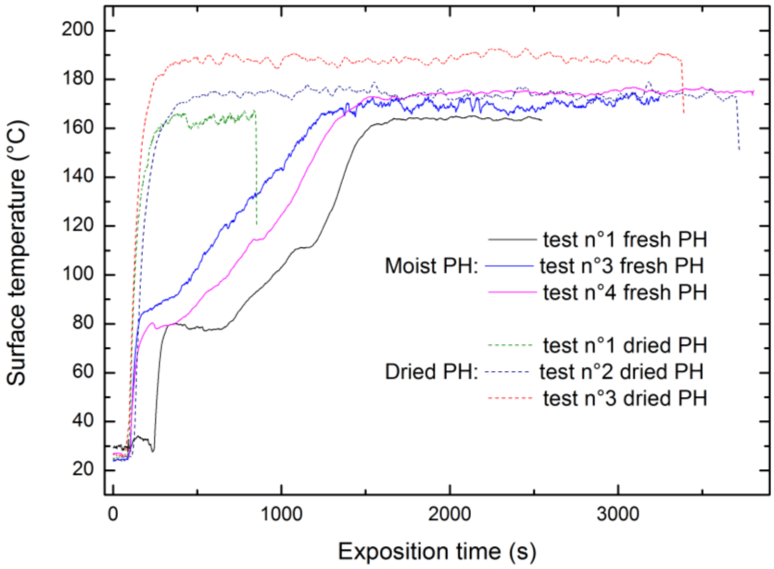

Figure 3: Steady surface temperature as a function of exposition time for moist and dried Pinus Halepensis

4. Conclusion

The estimation of the critical heat flux for ignition based on phase transition theory is used to compare the ignition for three states of *Pinus Halepensis* needles: dead, live fresh and live dried. The critical heat flux for ignition seems identical for the three states, although ignition time is very different for each state. A heat transfer analysis led us to conclude that surface temperature at ignition is identical for these states of the fuel bed within statistical errors.

5. References

Aizeti, A. (2021), Etude de l'effet de la teneur en eau sur la propagation du feu de végétation ; Détermination de la teneur en eau critique de propagation, Master in physics, Université des sciences et de la technologie d'Oran, Algeria.

ASTM (2017), International, Designation E 1354-17, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

Blundell, S.J., Blundell, K.M. (2006), Concepts in Thermal Physics, Oxford: Oxford University Press.

Drysdale, D. (2011), An Introduction to Fire Dynamics, Chichester: John Wiley & Sons, 3rd ed.

Jervis F.X., Rein G, (2015) Experimental study on the burning behavior of pinus halepensis needles using small-scale fire calorimetry of live, aged and dead samples, Fire Mater. 40, 385–395, https://doi.org/10.1002/fam.2293

Martin D., Tomida, M., Meacham, B., (2016). Environmental impact of fire, Fire Science Reviews. 5:5 DOI 10.1186/s40038-016-0014-1.

Rein, G. (2016). Smoldering combustion, in: M.J.Hurley (Ed), SFPE Handbook of fire protection engineering, chap.19. Heidelberg :Springer pp. 581-603.

Sabi, F.Z., Terrah, S.M., Mosbah, O., Dilem, A., Hamamousse, N., Sahila, A., Harrouz, O., Boutchiche, H., Chaib, F., Zekri, N., Kaiss, A., Clerc, J.P., Giroud, F., Viegas, D.X. (2021). Ignition/non-ignition phase transition: A new critical heat flux estimation method, Fire Safety Journal 119 (2021) 103257, https://doi.org/10.1016/j.firesaf.2020.103257

Stanley, H.E. (1971). Introduction to phase transitions and critical phenomena. Oxford: Clarendon Press.

Stauffer, D., Aharony, A. (1992), Introduction to Percolation Theory, London : Taylor and Francis.

Terrah, S.M., Sabi, F.Z., Mosbah, O., Dilem, A., Hamamousse, N., Sahila, A., Harrouz, O., Boutchiche, H., Chaib, F., Zekri, N., Kaiss, A., Clerc, J.P., Giroud, F., Viegas, D.X. (2020). Nonexistence of critical fuel moisture content for flammability, Fire Saf. J. 111, 102928, doi :10.1016/j.firesaf.2019.102928.

Yeomans J.M. (1992), Statistical mechanics of phase transitions. Oxford : Clarendon Press.