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Experimental investigations on accelerating forest fires thermochemical hypothesis

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Abstract
Accelerating forest fire phenomenon is studied in this paper. This phenomenon characterizes fires with a sudden increase of the rate of spread and of the energy released without any changes in the meteorological and topographic conditions. The thermochemical explanation is investigated in this study: acceleration of the rate of spread could be the consequence of the ignition of Biogenic Volatile Organic Compounds emitted by fire heated vegetation. Two experimental setups are used to perform very simple experiments in order to give validation elements to this thermochemical approach. The first experimental setup used permits to show that gases emitted by vegetation (even if they are hot) are diffused mainly in the direction of the ground. The second one shows that the gases emitted by heated *Rosmarinus officinalis* needles can be ignited with a pilot flame. *Rosmarinus officinalis* is a typical vegetal species involved in accelerating forest fires. This work does not prove neither that this hypothesis has been validated nor that this is the only explanation for accelerating forest fire accidents, it only brings arguments for future discussions and for a possible validation of the thermochemical approach.

Keywords: *α-pinene; BVOCs flame; accelerating forest fire.*

1. Introduction

The main purpose of this work is to give experimental data that would permit to take into account in a better way the combustion process in forest fires models. The aim is of course to better control and prevent wildland fires. A particular care is taken to a special type of accidents, named accelerating forest fires (AFF) and characterized by a sudden increase of the rate of spread and of the energy released. These accidents have been reported and detailed in the literature for several years (Arnold and Buck, 1954; Rothermel, 1993; Dold *et al*. 2009). Different hypothesis have been developed to explain these accidents. During the last ten years, two interesting explanations have been proposed. One suggests that these accidents are the consequence of the feedback effect of the convection induced by the fire (Viegas, 2005). Another explanation suggests that fire acceleration is caused by flow attachment in the direction of the fire propagation (Dold and Zinoviev, 2009). We suggested in previous works (Courty *et al*. 2012; Chetehouna *et al*. 2014) a possible explanation for these accidents, named thermochemical hypothesis to explain accelerating forest fires. This hypothesis is based on the fact that Biogenic Volatile Organic Compounds (BVOCs) emitted by heated vegetation could accumulate near the ground to form with air a flammable mixture. AFF would therefore be the consequence of the ignition of such gas clouds. We identified in previous works the BVOCs emitted by different vegetal species and determined combustion characteristics of these BVOCs by measuring their laminar burning speeds, Markstein lengths and flame thicknesses (Courty *et al*. 2012; Chetehouna *et al*. 2013). We worked with vegetal species typical of the Mediterranean climate, often involved in forest fires. This work aims at presenting some experimental studies that we performed in order to show that the ignition of BVOCs accumulated in a canyon can be plausible. The thermochemical approach to explain accelerating forest fires is a controversial topic in the wildland fire safety scientific community. This work does not prove neither that this hypothesis has been validated nor that this is the only explanation for AFF, it only brings arguments for future discussions and for a possible validation of the thermochemical approach.

2. Methods

2.1. BVOCs diffusion direction

The main issue we want to solve concerning accelerating forest fires thermochemical approach is to know if BVOCs can accumulate at terrain scale in sufficient concentration to form with air a flammable mixture. One of the necessary conditions to form this flammable mixture is that emitted gases diffuse in the direction of the ground and do not dissipate in the air. Indeed, if BVOCs diffuse in the direction of the ground, it is possible that in canyons the low value of lower flammability limit (1% vol. in air) of BVOCs/air mixtures is reached. We have shown in previous works (Courty, 2012; Courty *et al*. 2012; Chetehouna *et al*. 2014 among others) that the amount of gases emitted is very dependant of temperature and is increasing with the increase of temperature. It is therefore important to prove that the BVOCs diffuse in the direction of the grown, even if they are hot.

To prove it, we used an experimental setup that consisted in a cubic hermetic enclosure made of cellular concrete (Siporex). Its volume is around one cubic meter and it is equipped with a radiant panel simulating an ongoing fire front. It is also equipped with two electrodes providing the ignition energy. The radiant panel is made of sixteen black ceramic plates, each of them providing a maximal thermal power of 1200 W. The maximal power per unit area provided by the panel is around 83000 $W.m^{-2}$. Let us notice that this hermetic enclosure is the same used by Chetehouna *et al*. (2009) to study the gaseous emissions of *Rosmarinus officinalis* vegetal species at plant scale.

Different amounts of different BVOCs (99 % pure from Sigma Aldrich) initially liquid, are placed in a cup inside the enclosure, 50 cm from the radiant panel and at the centre of the enclosure. Different tests are done, the cup being placed above or below the ignition source (i.e. the electrodes). The distance cup-electrodes and the amounts of BVOCs are varied. Figure 1 presents a schematic overview of the experimental setup. Five BVOCs are studied, they correspond to the major component emitted by each of the species studied in Courty (2012): α-pinene, limonene, *p*-cymène, 3-hexen-1-ol and l-fenchone.

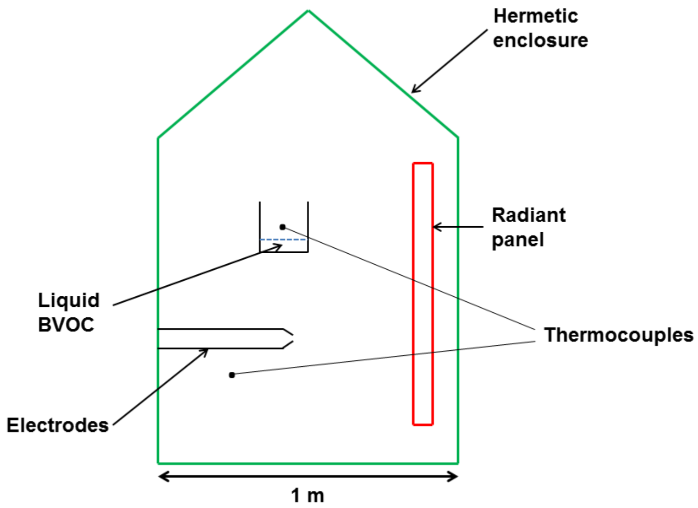


Figure 1. Schematic overview of the experimental setup showing the diffusion direction of BVOC.

2.2. BVOCs ignition

This subsection aims at proving with very simple experiments that gas mixtures emitted by vegetal species can ignite. To do so, we just used some heated needles of *Rosmarinus officinalis*. The setup consists in a necked flask of 500 mL heated with a heating mantle. Around 50 g of needles of *Rosmarinus officinalis* vegetal species are placed inside the flask and heated up to a temperature around 443 K. Temperature is measured thanks to a thermocouple placed in the needles bed. Emitted gases are collected in a beaker thanks to a transfer hose connected to the necked flask. Beaker is then placed next to a pilot flame, a candle is used. This setup is illustrated by a schematic overview in Figure 2.

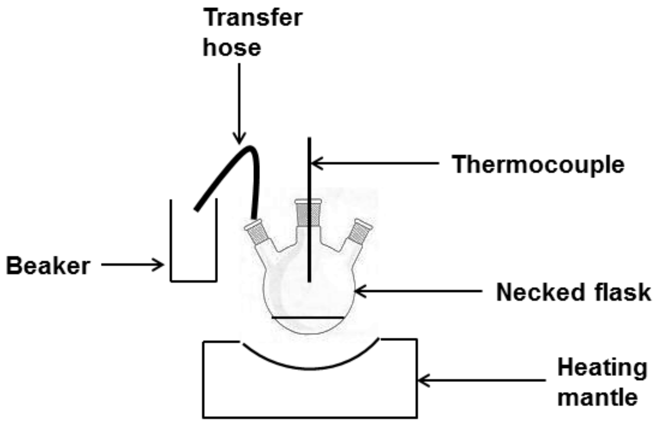


Figure 2. Schematic overview of the experimental setup used to study the ignition of BVOCs.

3. Results

3.1. BVOCs diffusion direction

Two thermocouples, one next to the electrodes and the other in the liquid, are used to study temperature as a function of time. Clearest results are obtained with 7 mL of BVOCs and results will be presented with this amount of BVOCS. Liquid samples are introduced at ambient temperature and spark is ignited at the temperature of maximal emissions. This temperature depends on the BVOCs and is around 443 K (Courty *et al*., 2014). Ignition is observed or not thanks to the window situated on right side of the enclosure.

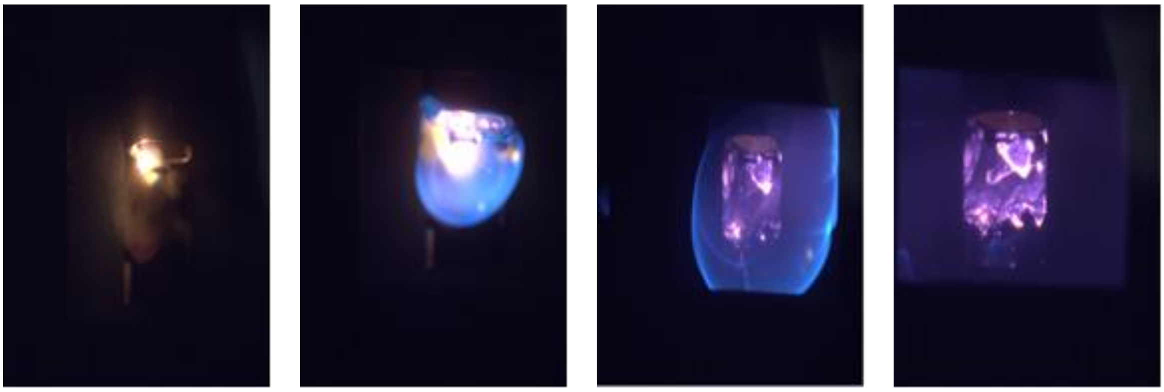
We observed that when the spark is situated below the cup, we managed to ignite up to a distance of 40 cm between the electrodes and the cup. On the contrary, when the spark is situated above the cup, no ignition occured for distances electrodes-cup higher than 14.5 cm. This clearly shows that the direction of the VOCs diffusion is downward (even if a small amount is diffusing upward). These results are valid for the 5 studied BVOCs and similar conclusions are obtained with different amounts of BVOCs placed initially in the cup.

A high speed digital camera Photron Fastcam APX RS operating at 2000 images/second has been used to illustrate this phenomenon. Figure 3 illustrates the ignition of α-pinene placed in a cup 3 cm above the electrodes. It is clear reading Figure 3 that the α-pinene vapours are diffusing downward.

t_0 $t_0 + 9{,}5$ ms $t_0 + 22$ ms $t_0 + 77$ ms

Figure 3. Ignition of α-pinene in the heated hermetic enclosure.

Other experiments have been performed in the same enclosure, with the electrodes placed in a box situated below the cup (filled with α-pinene). In this configuration, emitted gases are concentrated in a box and it is interesting to observe the differences with the previous configuration (without concentrating gases). Electrodes are placed at the center of the box. A color high speed digital camera Phantom V310 operating at 400 images per second is used to follow the flame propagation. Example of flame propagation is presented in Figure 4. This phenomenon was very rapid and not very luminous; this is the reason why we had to use a color high speed camera. Spherical propagation and blue color are characteristics of premixed flames: we actually created a premix α-pinene/air by diffusion of α-pinene in air.



t_0 $t_0 + 20$ ms $t_0 + 45$ ms $t_0 + 80$ ms

***Figure 4.** Ignition of α-pinene vapours concentrated in a box.*

We have therefore shown that BVOCs are diffusing in the direction of the ground and for this reason they can accumulate at the bottom of a canyon. We have also shown that liquid BVOCs when heated can create with air a flammable mixture. It is now interesting to see if it possible to ignite directly BVOCs mixture emitted by a vegetal species.

3.2. BVOCs ignition

One of the necks of the flask is let open at the beginning of the heating in order to let water vapor going out of the flask. From 393 K, this neck is closed and the gases are transferred in the line that leads to the beaker. An ignition occurs when the beaker is placed next to a candle. This is illustrated in Figure 5.

Emitted gases are concentrated inside a beaker and of course diffusion effects that can be observed at canyon scale are not taken into account with this very simple experiment. Nevertheless, we can see that heated needles can emit enough BVOCs to create an ignition.

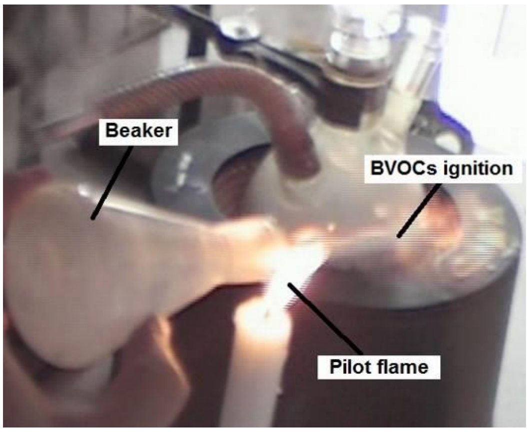


Figure 5. Picture of the ignition of BVOCs emitted by heated Rosmarinus officinalis needles.

4. Conclusion

Very simple experiments were performed in this study in order to give validation elements to the thermochemical explanation for accelerating forest fires. This hypothesis is based on the fact that almost all vegetal species involved in forest fires emit BVOCs that can form with air a flammable premix. The acceleration of the fire rate of spread could therefore be the consequence of the transition between a diffusion flame characteristic of forest fires and a premixed flame. We have shown in this work that gases emitted by vegetation are diffused mainly in the direction of the ground and that BVOCs mixture emitted by *Rosmarinus officinalis* needles can be ignited with a pilot flame. It will be of course necessary to validate the thermochemical hypothesis for accelerating forest fires to prove that BVOCs are emitted in concentration sufficient to create with air a flammable mixture, this will be investigated in a future work. Up to now, we just proved that this hypothesis can be possible.

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