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Generalized Blaze Flash, a "Flashover" Behavior for Forest Fires—Analysis from the Firefighter's Point of View

François-Joseph Chatelon[1], Sophie Sauvagnargues[2], Gilles Dusserre[2], Jacques-Henri Balbi[1]

[1]Università di Corsica, UMR CNRS 6134 SPE, Corte, France
[2]Ecole des Mines d'Alès, Institut des Sciences et des Risques, Alès, France
Email: chatelon@univ-corse.fr

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Abstract

The phenomenon called "flashover" or "eruptive fire" in forest fires is characterized by a sudden change in fire behavior: everything seems to burst into flames instantly and firefighters are overwhelmed by a sort of eruption, spreading at a speed at far several meters per second. Unfortunately it has cost several lives in the past. The reasons for such an accident always create controversy in the research field. Different theories are highlighted and especially two major axes are currently subject to discussion because they are very popular among people involved in firefighting. The one with regard to VOCs emissions is the best-known among firemen. Under great heat, during summer or with a fire approaching, plants emit VOCs and the more the temperature grows, the more the amount of VOCs emitted grows. Under specific conditions (essentially topographical, meteorological and atmospheric), the cloud of gas can accumulate in an appropriate zone. The concentration of VOCs may therefore reach the Lower Explosive Limit, triggering the burst of the cloud when in contact with the fire. The second theory depends on physical considerations. An example is based on a convective flow created by the fire itself. When a fire spreads on a slope, it creates an aspiration phenomenon in a way to supply the fire with oxygen. The more this phenomenon is important, the more the flames tilt and increase the rate of speed, needing even more oxygen and thus induced flow. This vicious circle can stabilize or have an erratic behavior to trigger off a fire eruption. This article presents these two theories, and especially the new advances on this research subject.

Keywords

Fire Behavior, Flashover, Blow up, Induced Wind, VOC

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1. Introduction

Flashovers are complex phenomena that are met in specific cases of fires in enclosed areas (house, room, shed, etc.). After the excessive accumulation of combustible gas and heat, or the sudden intake of a large quantity of oxygen (by "Backdraft"), the very fast burning of the area can be observed: it is the self-ignition of all combustible elements. The Generalized Blaze flash (GBF) phenomenon that is described in this review does not have much in common with the flashover in enclosed areas, except from a visual point of view. According to most firefighters, it consists in a practically instantaneous ignition of a forest area in the whole vegetation from surface to canopy. Instantaneousness is the main characteristic which explains the name given to the phenolmenon by firefighters, although its relevance is questionable. Actually, if a flashover in an enclosed space is well known (NFPA 921, 2011) especially in fire safety science (NFPA 555, 2000), the GBF must be compared to blowup fires, defined by Butler et al. (1998) as a rapid transition from a surface fire exhibiting relatively low intensity to a fire burning in the whole vegetation complex, from surface to canopy and demonstrating dramatically larger flame heights, higher energy release rates, and faster rates of spread. When blowups occur in single layer fuels, the definition of eruptive fires is used and characterized by Viegas (2004a) as a fire in which a sudden change of the rate of spread of the head fire occurs in a very short lapse of time with or without the influence of any changes of the fire's temporal or spatial boundary conditions.

This phenomenon is fairly rare, difficult to predict and then extremely dangerous for firefighters (or civilians). Many casualties result from several accidents identified in the last fifty years around the world. Causes of the GBF phenomenon are not precisely known but some theories about its development and onset were reviewed by Viegas and Simeoni (2010). Two mechanisms among all the ones proposed in the literature were mainly given by people present when the GBF occurred. Indeed, some witnesses describe a huge cloud of gas that ignites suddenly while others talk about an acceleration of the fire front which spreads up to several meters per second. Whatever the real cause is, it is easy to understand the inability for firefighters to get out of this dangerous situation. These suggestions are mainly linked to a gas accumulation or a self-accelerating fire.

Carbonell et al. (2004) described some accidents that occurred in the USA (e.g. the Storm King Mountain accident reported by Butler et al., 1998), as well as some eruptions that occurred in France, where the most commonly known one was the Palasca accident reported by Dold et al. (2009a). The two main avenues of research inspired by the firefighter's comments were gas explosion and canyon effect.

In this paper, a critic review of the firefighter's ideas about fire eruption is done. In the first section of the paper, the main ideas of the volatile organic compound (VOC)'s theory are recalled. In the second section, some advances in modeling and predicting fire eruptions are given.

2. Chemical Issues: VOC's Theory

2.1. General Information on VOC Emissions

In some instances, still subject to discussion, a steady-state forest fire can abruptly change its behavior. While it predictably spread, firefighters could be led to believe that they master the situation, its features suddenly change: it increases in intensity, and speed, so that in a flash, all the plants blaze. It is what some firefighters call Generalized Blaze Flash or eruptive fire according to some researchers. This phenomenon, considered as unpredictable by most of the firemen, represents a great danger to people present in the surroundings, firefighters and civilian. In GBF, the fire front velocity is about 5 to 40 $m \cdot s^{-1}$ and the temperature increases over 1500˚C. When the atmosphere is unstable, the hot gases produced by the combustion easily draw the air to ground level and thereby enhance the combustion process. This creates an extremely powerful updraft, which may cause a local depression.

In order to have a better understanding of the phenomenon, including the theory of VOCs, it is first necessary to understand a few basic elements on plants and VOC emissions, as well as the characteristics of a gas mixture, which we will detail later even the energy released by a spark may trigger the phenomenon.

In the case of a hot region, such as in Mediterranean forests, so as to protect themselves from the heat, plants draw water from the soil and this water evaporates through the leaves. It is called evapotranspiration. In case of drought, the evapotranspiration is complemented by the vaporization of biogenic volatile organic compounds (BVOC). When approaching a fire, the more the temperature rises, the more plants emit BVOC in large quantities as demonstrated experimentally by Barboni (2006). During a forest fire, these gases, together with the pyrolysis generated gases and unburned compounds allow combustion and fire spread. So regardless to the theory giving the cause of a GBF, it is important to note the essential role of the VOCs in fire forest. The following pieces of information about VOCs are valid in all circumstances, only the fact that a single cloud of VOCs causes such an accident, is specific to the theory. Rapid combustion can propagate in a gas mixture by deflagration or detonation. In the case of GBF, we are facing an explosion or deflagration.

The Palasca accident (Dold et al., 2009a) seems to be an evidence of this theory. Indeed, the event was fortunately filmed by a couple of tourists and shows a sudden inflammation of the complete vegetation in the front fire, burning many acres in a few seconds. Deflagration requires a fuel ignition content between the lower and upper flammable limit (LFL and UFL). The initiation of inflammation requires low energy (EMI, minimum ignition energy), where the possibility that even the energy released by a spark can trigger the phenomenon. The flame spreads by heat transfer and diffusion of free radicals. There is no shock wave (as in a detonation) and its speed is of a few meters per second. The overpressure depends on the speed of the flame front and can be about few millibars. When the flame spreads throughout mixture explosion, the LFL is reached. Beyond the UFL, the gas mixture does not ignite by blast mode. Indeed, oxygen content (i.e. oxidant) is too low to allow the flame to continue to grow. The values of these limits depend on initial temperature and pressure.

Mason and Wheeler (1918) demonstrate that a temperature difference between 20˚C and 100˚C brings up a LFL variation of about 1%. In forest fires, an inert diluent gas (nitrogen in air composition) is present, which implies the existence of a minimum concentration of oxidizing gas (CMO) below this value the mixture does not ignite. Clearly, a minimum amount of oxidizing gas is needed to ignite the mixture.

Two characteristics of gas mixtures are interesting in this study. The flashpoint is the minimum temperature required by the vapors, emitted by the heated substance, to ignite hot gases. The flashpoint allows a ranking of hazardous substances. Indeed, a flashpoint equal to 0˚C is defined as extremely flammable, a value of 55˚C as highly flammable and a value of 100˚C as only flammable. The second characteristic is the auto-ignition temperature (AIT). This is the minimum temperature in which a product or mixture ignites willingly with air by spontaneous combustion. AIT is measured with a pyrometer.

2.2. VOCs' Role

The density of VOCs emitted by plants is greater than air density and therefore they may accumulate near the ground under vegetation or even down a slope to the bottom of a canyon, even heated at high temperatures.

Many authors (Barboni, 2006, Peuch, 2007, Chetehouna et al., 2009) showed that it could create a flammable mixture. The conditions required for the occurring of this preflammable mixture in an open environment are quite difficult to imagine, but nevertheless possible. A key result is that pure or mixed VOCs have very low LFL (of the order of 1% by volume in air). At the field scale, VOCs diffuse toward the ground, so that it is locally possible to reach that value. The Generalized Blaze Flash (GBF) is then due to the accumulation of a carpet of gas released by the plant (caused by water stress in particular). We can see several acres ablaze instantly. So we have lights that are growing very quickly despite relatively moderate ambient wind.

According to Courty (Courty, 2012), unburned products from the plume, as well as those from unburned pyrolysis gases produced elsewhere in the fire, accumulate in front of the fire when allowed by the topographic configuration. This accumulation has an important role in accelerating the fire growth when the flammable mixture is touched by the flame front. Note that there is a limit to this assumption because a premixed flame propagates only for sufficiently high concentrations in fresh gas. It is difficult to consider that the gases can accumulate over a large area (several acres) in excess of the LFL. Indeed, Courty (Courty, 2012) shows, according to his work, that it is possible to reach this locally LFL through the field. However, he also states that experiments to quantify the VOC emissions at real scale are possible and the creation of a premixed VOC/inflammable air over a large area is possible.

2.3. Plants and VOC

Each plant species, including those found in the Mediterranean and Corsica emits VOCs in various quantities. These include the "Kermes oak" (*Quercus coccifera*) but also "thyme" (*Thymus vulgaris*) or "bay-tree" (*Laurus nobilis*) that emit aromatic, diterpenic or terpenic VOCs. The amount emitted is a function of ambient conditions (humidity, temperature, etc.).

The main results obtained by Barboni (2006) focus on the terpenic compounds which play an important role in triggering GBF. Five species were investigated: the laricio pine (*Pinus nigra* subsp. *laricio* var. *corsicana*), maritime pine (*Pinus pinaster*), *cistus* (*Cistus monspeliensis)*, heather (*Erica arborea)* and arbutus (*Arbutus unedo)*. The results are an average of all field samples near Corte made weekly between July and September (2004 and 2005). Samples are introduced into an empty tube placed in a furnace which heats the tube in order to obtain the desired temperature. The results for *Pinus nigra* subsp. *laricio* var. *Corsicana* and *Pinus pinaster* show that the number of compounds emitted is respectively 24 and 26 with α-pinene as major constituent for both. It is noted that the maximum temperature for emission of compounds is equal to 175˚C (a temperature easily reached when approaching a flame front). In addition, the LFL (0.7%) and flashpoint (33˚C) values for α-pinene are low. It is then possible to conclude that a very small amount of α-pinene in the air may allow inflammation of a gas bubble.

Consequently, the proportion of terpenes increases to a so-called critical temperature that is 175˚C. Beyond this temperature, the plant begins to blacken, the early phase of thermal degradation of the plant. In *Cistus monspeliensis* analysis, besides the α-pinene, the presence of many diterpenes themselves issued in maximum quantities is found for a critical temperature of 200˚C. The compound mainly issued by the *Cistus monspeliensis* (98.6%) is a diterpene (oxide 13-epi-manoyle) and also has a low LFL (0.4%). For *Erica arborea* and *Arbutus unedo*, traces of α-pinene and acetic acid are observed in too low quantities to cause the burning of a gas concentration at the ground level. However, these plants burn and emit fumes. Courty's thesis (Courty, 2012) permits to increase significantly the database on emissions of VOCs from heated plants but also to create one on their combustion properties.

Combustion characteristics such as fundamental flame speed, Markstein length and flame thickness have been studied on three VOCs emitted mainly by Mediterranean vegetation. It should be noted the study of α-pinene from *Rosmarinus officinalis*, limonene from *Pinus pinea* and p-cymene from *Thymus vulgaris*.

2.4. Configurations Which Raise the Accumulation of VOCs

The landscape has a complex influence on this phenomenon. A closed confined relief (dale, dry river bed) increases the heating and therefore the issue of VOCb. Other parameters such as high ambient temperature, low humidity and medium or low wind speed play a role in the onset of the phenomenon. Indeed, when the wind is low, gas accumulation is made easier when the cloud is located in a confined area. A strong wind, however, can either move the gas cloud or dilute it. However, with some identified experience feedback, it is impossible to truly predict the phenomenon with any relief because the conditions are always different. Actually, it has been observed, in the past, that the GBF is possible on steep field (e.g. Palasca, Dold et al., 2009a) as well as on flat field (e.g. Cornillon-Confoux, Carbonell et al., 2004).

Barboni (2006) and Carbonell et al. (2004) have given the main type of configurations leading to a GBF.

- The valley bottom. This takes place at a crowded river bed full of fuel. Flames go down the hill, driven by the wind, and the heat from the fire front heats the fuel to cause a GBF. The accumulation of VOCb (biogenic VOCs) can also be seen in a small valley. The gases released by plants upstream of the fire accumulate and cause a decrease of oxygen. If the VOCb concentration reaches a value greater than the LFL, the mixture ignites when touching the flame.
- The thermal bubble. It occurs in a field surrounded by a rocky area, a flat area or a slight basin. Fire usually spreads in rising and takes a natural way. One can observe a pyrolysis of the fuel gas caused by the heat and the formation of a hot zone fuel gas. Gas ratio grows, goes up by expansion, undergoes the wind direction and they don't mix with ambient air. The gas bubble, corresponding to an accumulation of VOC moves randomly into the roasting zone and is a significant infrared source, which moves at light speed.
- The carpet of fire. A thalweg forms a roasting zone and the flame front is located on an upward slope. Plants are exposed to heat and release VOCb, the gaseous mass (accumulation) is confined to the valley floor. An in-draft involving a GBF causes the ignition in the burning carpet.
- Spread from a slope to another one. It takes place in a steep dale with low vegetation (garrigue, shrub land) in which the fire comes down slowly on a slope. On the opposite side, the fuel is facing stress due to the increasing radiation generated by the flame front and releases consequently VOCb. The fire engulfs the side in an exploding phase.
- GBF due to a cold air layer. The plants combustion causes smokes, combustion gases and increases their temperature near the fire. Hot gases are confined in a large roasting zone by a colder layer of air provided by

a strong wind. There is a temperature overthrow. In this case, there is a GBF causing the total destruction of the fuel, that is to say an explosion of smoke.

3. Physical Issues: Eruptive Fires

According to some researchers (Viegas, 2004a, Butler et al., 1998), the phenomenon referred to as "GBF" by the firefighters would be an extreme behavior of a forest fire, a kind of runaway related to many factors (topography, weather, own fire properties, etc.). Viegas (2004a) describes eruptive fire behavior as an extreme case of dynamic fire behaviour, in which the fire Rate of Spread (ROS) changes suddenly in the course of time even when the other factors are constant. So the phenomenon is unpredictable and involves a sudden and very important acceleration of the fire front. It visually corresponds (and also in terms of consequences) to the GBF phenomenon.

In the literature, the phenomenon called "fire eruption" (its onset) is then only a deviation of the behavior of high intensity fire, related to time. Indeed, it would have a dynamic behavior, because of its interaction with its environment. The GBF would be triggered by the fire itself, which is opposed to the theory of accumulation of VOCs where the onset is linked to a gas cloud. It is the internal dynamics of fire that cause the acceleration. It is important to note that even if the eruption's occuring is related to many factors (ambient temperature, fuel characteristics, topography, wind speed...), eruptive fire, characterized by increasing velocity and intensity, triggers without any change in the external conditions. It is then necessary to define propagation velocity according to time. Indeed, in the case of non-steady state fires (case for fires leading to an eruption), it may increase or decrease over time. According to Viegas (2004a), it depends on many local parameters: the effects of wind and slope are particularly highlighted in his theory.

3.1. Flow Attachment

The work conducted by Dold and Zinoviev (2009b) is mainly based on Albini's one (Albini, 1982), which considers that the fire behavior at a given time depends on its past behavior. They resume the description of an eruptive fire as the result of a sudden and fast increase in the velocity and intensity of the fire, independently of the outside conditions. These researchers are interested in the concept of the flow attachment on slopes or in confined topographies. They argue that a change in the flow field around the fire causes changes in its behavior, and leads to a blowout. Thus, the attachment of floor drains, and surface vegetation at the flame front and just above it, is a key factor for the onset of an eruption. Experimental studies and field observations allow to support this theory, showing the correlation between this flow attachment and the development of an eruptive fire. The air flow, associated with the attachment of the flow has no connection with the weather (especially wind), which corresponds to the basic assumptions of a dynamic fire behavior. The only changes are generated by the fire itself, making a transition between the steady state behavior of fire (constant speed of propagation) and when it accelerates or "erupts".

In a few words, modeling performed by Dold and Zinoviev (2009b) and Dold et al. (2011) provides the following results: Byram (Byram, 1954) introduced a number bounding the ROS R ($\text{m}\cdot\text{s}^{-1}$) to the Byram's fire line intensity I_B ($\text{kW}\cdot\text{m}^{-1}$), the Byram number:

$$B = QmR/I_B. \quad (1)$$

where Q and m are respectively the energy of combustion ($\text{kJ}\cdot\text{kg}^{-1}$) and fuel load consumed in fire ($\text{kg}\cdot\text{m}^{-2}$). When this number is equal to 1, the conditions of a steady-state propagation are obtained. When the spread rate of the fire is not steady, the relationship linking ROS and Byram's fire line intensity becomes a power-law formula: $R \propto I_B^{v}$. When the power v is less than one, eruptive fire growth cannot occur. When the power v is greater than one, the ROS goes to zero if the Byram number is less than one and goes to infinity otherwise. In this last case, eruption occurs.

Sharples et al. (2010) used this hypothesis and considered the trench effect (mechanism for fire propagation on enclosed slopes) in a wildfire context as a possible trigger. This interpretation was further developed by Dold et al. (2011) in a recent article.

3.2. Convective Flow Induced by the Fire

In a pioneering interpretation, Viegas (2004b) also argued that the notion of a steady ROS is not relevant to explain a fire eruption. His theory highlights the importance of an air flow induced by the fire which leads to a significant change in the fire behavior, especially in presence of wind and/or slope. During the propagation, if the external wind cannot supply the flame with enough fresh air, the fire creates an in draft in order to provide oxygen to the combustion. This air movement induced by the fire itself may increase over time and is directly related to the ROS. This phenomenon was proved by Vie gas and Pita (2004) at the laboratory scale when simulating fires in canyon shaped topographies. They observed the dynamic behavior of the fire, which is governed by a time-dependant ROS. The presence of the fire-induced flow is put in evidence with an experiment in which this flow was inhibited by a metal plate placed across the base of the canyon. This experiment provides no eruptive fire behavior. Under the same fuel bed conditions, the large differences (fire growth, ROS) between experiments with and without the metal plate clearly show the important role of this flow in the eruption's triggering.

The convection flow phenomenon was also observed at the field scale, through the experiments conducted in Gestosa, 2001 (Viegas et al., 2002). Actually, the canyon shape of one plot covered by shrub land, allows witnessing the dynamic fire behavior. When the total duration of the experiment was 32 min, more than 30% of the area was burnt during the last 4 min of the experiments. Measures of the wind inside the canyon were much more greater than the external wind (with gusts of about 100 km·h^{-1}).

Another evidence of the importance of the convective flow was reported during the accident of Freixo de Espada-a-Cinta, Portugal (Viegas 2004a). The fire was given as extinguished but for a small extension of flames in the bottom of a large canyon. The data recovered by a meteorological station located on the top of the ridge (by coincidence) showed very clearly the fire eruption. Actually, the wind velocity went from 15 km·h^{-1} up to 65 km·h^{-1} with gusts of 96 km·h^{-1}. It can be noticed that the wind that was blowing from the northwest in the downslope direction turned suddenly to south-southwest which is approximately the direction up slope.

Based on these considerations, Viegas (2004a) proposed a mathematical model to predict the ROS of an eruptive fire. It expresses the non dimensional ROS *R'* (quotient of the ROS by the ROS under no wind and no slope conditions) as a solution to a non linear differential equation:

$$\mathrm{d}R'/\mathrm{d}t = a_1^{(1/b_1)} b_1 a_2 \left(R'-1\right)^{(1-1/b_1)} R'^{(b_2)} \tag{2}$$

where a_1, a_2, b_1 and b_2 are four model parameters.

These parameters are measured experimentally at laboratory and field scales and checked against real fire cases in various situations. Two assumptions are necessary to obtain the non linear differential equation. At first, it is assumed that there exists a unique relation between the ambient wind velocity and the ROS. Next, the ambient wind velocity is modified by the air flow induced by the fire. Changes in the velocity of the convective flow induced by the existence of the fire front lead to variations of the ROS.

The ROS mainly depends on the effect of the wind and the slope but also on the fuel bed properties and the fire's own charateristics but in an indirect way, through the four model parameters. So the role of each of these factors is not well known because they are not explicitly included in the model.

The main goal of the work conducted by Chatelon et al. (2011) is to build a simplified and closed physical model for surface fire spread, which allows to predict the accurate conditions of eruption occurrence and development. In the authors' opinion, the phenomenon involved in a fire eruption occurrence is the same than the one pointed up by Viegas, called here induced wind. Indeed, the combustion needs an in draft which provides oxygen at stoichiometric ratio with the pyrolysis gases. If the external wind cannot supply the flame with enough air, the fire creates an induced wind, which allows stoichiometric conditions. In some cases, an accelerating feedback occurs. The induced wind strongly tilts the flame and increase the flame radiation. As a consequence, the fire ROS, the flame depth and consequently the pyrolysis gas production rate increase too. This leads to an increased induced wind and fuels the feedback effect, triggering the fire eruption.

The model is based on the steady-state physical model proposed by Balbi et al. (2007, 2010). It derives from usual simplified physical balances as momentum equation, thermal balance, mass balance, energy balance etc. The computation of the ROS *R* and the flame tilt angle constitutes the two main algebraic equations of the model:

$$\tan\gamma = \tan\alpha + U/u_0 \tag{3}$$

$$R = R_b + R_f \tag{4}$$

where α is the terrain slope angle, *U* the wind speed, u_0 the upward gas velocity, R_b the radiation of the burning fuel bed and R_f the flame radiation which mainly depends on the flame tilt angle, the ROS and a radiant coefficient of which value is based on several fuel bed properties.

Chatelon et al. (2011) wrote a model for the induced wind. Its formulation derives from a simplified mass balance based on the geometrical flame characteristics between the top of the vegetal stratum and the mid-height flame. The expression of the flame's height can be found in Marcelli et al. (2011). It leads to a new formulation for the ROS, which is obtained when solving the system:

$$R = p\left(\tan\gamma - \tan\alpha\right) \tag{5}$$

$$R = R_b + R_f \tag{6}$$

where p is a coefficient depending on the flame temperature, the ambient temperature, the flame residence time and the flame height. This coefficient p expresses the effect of the induced wind on the ROS.

The proposed model is a steady state model and as reported by Dold et al. (2009) and Viegas (2004a), the eruptive phenomenon is related to a sudden change of the ROS over time. Here, the system of Equations (5)-(6) can exhibit from zero to three steady solutions whereas the physical phenomenon involves only one solution. In fact, the study of the non-steady properties of the phenomenon allows understanding this paradox. The analysis of the unsteady ROS gives a spread behavior characterized by an exponential which tends toward infinity in some cases.

But the most interesting result given by the model is a physical condition of eruption danger. Indeed, a condition depending on flame temperature, fire front width, flame length and properties of the vegetal stratum is proposed:

$$\rho_v \Big/ \left(\tau_0 \cdot B \cdot T_a \cdot T^3 \left(Y \big/ 4\left(C_p \Delta T + m\Delta h\right) - 1\big/\left(2 \cdot v \cdot \chi_0 \cdot \Delta H\right)\right)\right) < 1 \tag{7}$$

where ρ_v is the fuel density, T_a the ambient temperature, T the flame temperature, C_p the specific heat, m the fuel moisture content, ΔH the heat of combustion of the pyrolysis gases, v the absorption coefficient, Δh the heat of evaporation and Y a coefficient involving the ratio fire front width/flame length. All the other parameters are constants.

As long as Equation (7) is satisfied, fire behavior tends toward a steady ROS over time and fire cannot erupt. When Equation (7) is no longer satisfied, a fire eruption becomes possible but is not certain. In this case, fire will erupt only if the slope angle is greater than a threshold value computed in solving numerically the system (5)-(6). So the required conditions to carry out the possible eruption are: a low buoyancy vegetation, weakly ligneous, with a sufficient fuel load, bad meteorological conditions (high ambient temperature, low relative humidity) and/or a large fire front.

The proposed model has been successfully confronted to two sets of laboratory experiments and one real accident. The first set of experiments carried out by Viegas (2004b) does not provide any eruption even with steep slopes (40˚). The second set of experiments conducted by Dold et al. (2010) shows an eruption for a slope angle value bounded by 25˚ and 30˚ (the model gave a fire eruption for a 26˚ slope angle). The last test is against an accident which took place in the island of Kornat, Croatia in 2007 and caused the death of 12 fire fighters and severe burns for another one. Here again, the model gives the canyon slope angle to within about 1˚.

The Kornaty accident is the largest fire fighting accident ever recorded in Croatia. The fire ignition point was in Vrulje bay on the island of Kornat. The fire ran about 6 km/s until it arrived in a small canyon (sipnate canyon). Twelve experienced fire-fighters died and one severely injured. The location has low-height and sparse vegetation, mostly grass with a few small trees. The fire was pushed by a S-E wind (about 40 km/h at 10 m height). The canyon's main axis was directed to the north. A camera was found at the location of the accident. A large fire front was clearly seen on a photo from this camera with small flame lengths (below 1 m). According to the only fire-fighter who survived the accident, the important fact was the very strong wind. Indeed, in the canyon, the wind changed its direction to become parallel to the main canyon axis and the fire front was spreading at very high speed, maybe 6 or 7 m/s. His words were confirmed by the melted particles of a fire-fighter belt buckle found on a stone behind the place where his body was laying, which prove that the wind generated by the fire was very strong and coming from the south. The fire-induced wind, which grew to be stronger than the S-E wind and changed its direction, clearly has a key role in the occurrence of the eruption. Note that these few trees have not been burnt, that means that flames were very slanted (in agreement with the flame attachment assumption).

4. Discussion

4.1. VOCs' Theory

According to the theory of the accumulation of VOCs, a phenomenon referred to as "flashover" by the firefighters occurs when the vegetal stratum is under conditions of severe water stress. This is the case in summer, especially when a fire front approaches. Indeed, as plants did not find sufficient water in the soil, they release more VOCs in order to cool down themselves.

The compounds responsible for a potential ignition of a gas bubble are issued for a maximum temperature of 175˚C or 200˚C depending on the fuel studied by Barboni (2006). This temperature is easily reached during the progression of a fire front. These compounds with relatively low LIFL (between 0.5% and 1% in air) and a low flash point, can simply burn and therefore cause a GBF. This explanation is very popular among firefighters. Indeed, their empirical knowledge associates the strong odour of VOCs in vegetation to the very fast transition in the fire propagation, especially when the terrain configuration is confined (e.g. canyon or basin). Some survivors to a GBF have been thrown down by a blow which evokes an explosion. Moreover, firefighters near the place where a GBF occurred relate a feeling of suffocation, oppression, suggesting a presence of a heavy gas cloud. On the other hand, the video of the Palasca accident shows the characteristics of an hydrocarbon fire, which supports the opinion of the role of VOCs in a GBF. Indeed, if two young fire-fighters were killed and six others suffered burns, survivors reported being surrounded by a lake of fire that rapidly developed and began to die away over a period of about one minute. But the reason for this accelerated fire is still in question (Dold et al., 2009a).

The study of the VOCb issue introduces some remarks. First, a GBF occurrence requires a rugged topography, a fire front spreading sufficiently slowly to preheat the fuel without damaging it. Then the amount of gas has to reach a concentration value between the two flammability values (LFL and UFL). But many questions remain unanswered. For example, the amount of VOCb released by the *Pinus nigra* subsp. *laricio* var. *Corsicana* at 50˚C (which is an easily reached temperature in summer) is sufficient to reach the LFL, but this is not the case for *Pinus pinaster* or *Cistus monspeliensis*; so is the solar radiation alone sufficient to obtain an explosive layer? Another question concerns the terpenes. Are terpenes the only compounds of the gas mixture responsible for a GBF or do the degradation products of the fuel (pyrolysis gases, unburned products, etc.) also take part in a GBF?

Albini (1976) shows that when the fire spreads upslope, the tilted flame practically lies down and heat the fuel ahead of the fire front in a short distance and is only supplied for a short period. The gravity forces and the wind effects become negligible, involving an upright position of the flame above the fuel bed and a decreasing heat transfer rate of unburned fuel. This unusual fire behavior is often related to small explosions.

But if Butler et al. (1998) presented the fire behavior in some cases as an explosive event, it is only from a visual point of view. They state that the occurrence of a GBF in the forest is simply a fast transition from a low intensity fire with a slow ROS to a high intensity fire with a very fast ROS. They also stipulate that the volatile compounds emitted by radiation and convection due to the fire front burn and provide a usual fire spread; gases do not concentrate enough to cause an explosion.

The theory involving the VOCb as a triggering factor of a GBF remains difficult to prove. In fact, although the amount of measured VOCb are likely sufficient for the formation of an explosive gas pocket and then confirm the hypothesis about the possible existence of such a phenomenon, it seems strange that a gas pocket could be concentrated on several acres while the flame front has not yet reached this level. Indeed, it will be a long job for the fuel (when a fire approaches) to emit an amount of VOCb large enough for ignition. In concrete terms, a gas pocket could be formed near the fire front, but the impact of the fire front on the fuel decreases dramatically with the distance. Moreover, no concentration studies were conducted to check if any flammable mixture could be encountered in the field. In the same way, the "fire ball" description sometimes given by the firefighters was discarded by Butler et al. (1998) in the report of the Storm King mountain accident. So, in our opinion, the emission of VOCs is not likely to explain alone a fire eruption but may be considered as an aggravating factor.

4.2. Fire Properties' Theory

The flow attachment theory developed by Dold and Zinoviev (2009) is recent and considers that the fire behavior at a given time depends on the fire behavior in the past of the fire. In their last work (Dold et al., 2011), a model for eruptive fire behavior is presented. Nevertheless, at the moment, this model is purely theoretical and presents three major disadvantages. Indeed, the core of the model is an assumed relationship between the non-steady ROS and fire line intensity of type $R \propto I_B$. The expression of R reduces to Byram's relationship (Byram, 1959) for $n = 1$ but other values, including $n > 1$ that creates eruptive behavior, are not based on any sort of physical considerations. Moreover, conditions of occurrence and behavior are not provided and the model has not been confronted to experiments.

The pioneering interpretation given by Viegas (2004a) in order to explain the occurrence of a fire eruption consists in the feedback effect caused by the convective flow induced by the existence of the fire under the effect of the wind or a positive slope. This effect has been proved in laboratory experiments with canyon shaped topographies and has been observed in a field experiment. Moreover, the accident of Freixo de Espada-a-Cinta (Viegas, 2004a) constitutes a real proof of the existence of the flow induced by the fire. Indeed, the records of a meteorological station that was in the way of the fire clearly show the changes in wind direction and velocity. The important thing is that no other atmospheric phenomenon could be invoked to explain the onset of eruption. This convective flow whose velocity becomes very important in the positive feedback has been also observed by the only firefighter who survived (with severe injuries) the accident of Kornati, in Croatia (Stipanicev and Viegas, 2009). He testifies to that the important fact in this fire was the very strong wind and in the canyon where the accident took place, the wind changed its direction from southeast to become parallel to the main canyon axis and the fire front was spreading at very high speed (several meters per second). The mathematical equation developed by Viegas (2004a) in order to find a modeling to the ROS with the convective induced flow is a non-linear differential equation. This model correctly reproduces the sudden increase of the ROS and has been successfully confronted to real fires. The four parameters of the model are measured experimentally at laboratory and field scales. But the formula has two major shortcomings. First, it is empirical and the model is not a predictive one. In the second place, if the model parameters are measured in various configurations in order to match most real cases, fuel bed properties, slope angle and wind velocity only appear in an indirect way in the model and then it is not possible to simulate a case without measuring first the model parameters.

Chatelon et al. (2011) also stated that the blow up phenomenon is intrinsically linked to fuel bed properties, to terrain or wind. They have given a physical modeling for the convective flow induced by the fire defined by Viegas (2004a), called here "induced wind" and added this modeling to the existing physical propagation model for surface fires defined at the University of Corsica (Balbi et al. 2007, 2010). Then a fire eruption is the borderline case of the steady-state model obtained. When the system defined by Equations (5)-(6) diverges, fire erupts. As previously mentioned, fire eruptions are not steady-state phenomena and the expression of the unsteady ROS is needed to reproduce the fire behavior during the eruption. This unsteady ROS is described in the model with an exponential that converges to a constant value in some cases, or diverges. In the latter case, the divergence is very fast and the exponential gives a better understanding of the feeling of firefighters with the phenomenon: fire speed will increase very quickly (doubling the speed within a range of 10 seconds), described as a 'wave of flame'. But the object of the work conducted by Chatelon et al. is essentially based on the prevention aspect. To our knowledge, no other existing model exibits a condition of eruption danger and predicts the eruption's triggering. One major advantage of the model lies in its physical constitution and all the parameters of the triangle of fire (fuel bed properties, wind, slope) are explicitly expressed. Then on one hand, a sensitivity analysis can be used to assess how the results of the model are affected by parameter uncertainty. On the other hand, due to the very fast calculus time (much faster than real time) it becomes easy to map hazardous areas, taking topography and vegetation into account. In fact, the model allows identifying the value of one parameter of the triangle of fire which causes a fire eruption. For example, if fuel bed characteristics (height, fuel load, density, specific heat etc.), wind speed and fire front width are perfectly known, it is possible to find the critical slope angle for which fire erupts.

It should be noted that this explanation seems to reject any involvement of VOC emissions in the onset of the phenomenon. According to Chatelon et al., the amount of VOCs released is too low to explain Ignite Generalized Flash over a long distance (several hundred meters in general) which joined the conclusions expressed by Viegas and Simeoni (2010) about gas accumulation. In fact the VOC cloud ignition phenomenon is not totally rejected. VOCs would be very marginal and would not be the cause of a starting GBF, but only a contributing factor among others. On the other hand, it would be more or less reflected in the eruption danger formula identified in this theory. Indeed, VOCs are gases igniting at a temperature lower than the conventional ignition temperature, which has an impact on the condition given by Equation (7) with a lower ignition temperature. This is taken into account in Equation (7), through a lower ΔT (difference between the ignition temperature and the ambient temperature). And the lower ΔT, the higher the risk of occurrence of an eruptive fire. There is thereby a link between the release of VOCs and GBF's triggering, as it exists with the specific heat or ambient temperature for example. Actually, in laboratory tests that have often been carried out with straw as fuel which does not release VOCs, eruption occurs. So the emission of a cloud of VOCs would not be the main cause of GBF.

Chatelon et al. have identified three high danger zones for fire eruptions: canyon shaped topographies, vegetation with two layers of different heights and trenches or corridors. But It was noted by Colonel Landrieau from the SDIS 66 (France) that some GBF (two he was able to experience) ignite when the fire goes downhill, pushed by the wind. This does not necessarily correspond to the basic model, which focuses on a fire spreading upslope, but the model can simulate this case with a negative slope angle. Eruption remains possible even if its occurrence is more difficult to obtain.

The model developed by Chatelon et al. seems relevant and has been confronted to laboratory experiments and a real case (the Kornati accident). However, it presents some limitations essentially due to the propagation model used. First, as the model is based on a surface fire propagation model, it cannot take into account crown fires which are commonly observed in the USA. Moreover, the propagation model only considers radiation as heat transfer mechanism. Even if convective effects due to the wind should be much lower that the convective flow induced by the fire, they are not taken into account in the propagation model. Another question lies in the flame height formula used in the expression of the induced wind. Actually, this formula is obtained thanks to physical considerations (Marcelli et al., 2011) and has been confronted to sets of experiments only carried out at the laboratory scale. It would be necessary to check its validity when confronted to field experiments. Finally, it would be interesting to test the model on several real accidents. But descriptions of several fire accidents can be found in the literature, sets of data describing the conditions of an eruptive behavior are very rare. So it is a tricky task to test the model, but if all the model inputs are known, it is possible to predict a dangerous situation for firefighters.

5. Conclusion

A Generalized Blaze Flash consists in a practically instantaneous ignition of a forest area in the whole vegetation and several explanations of its triggering are considered in the literature. Two kinds of considerations (chemical and physical) are provided by firefighters' experience feedbacks but specific cases can be found where each theory shows its limits. This is particularly the case with a strong wind for the VOCs' explanation or with a flat terrain for other explanations. In order to better understand the event, it is necessary to take into account all the investigated causes. Indeed, each one must have more or less importance in a GBF occurrence, and to maximize the chance of forecasting it; a single track cannot be neglected.

After discussions with people involved in fire-fighting, it seems reasonable to think that there can not be a single phenomenon, and in this case all the theories outlined in this paper could be relevant and explain each type of GBF. This could explain not only the validity of each model, but also the differences related in feedback from firefighters. Actually, they are sometimes in agreement with the hypothesis of a very fast increase in ROS, but they also relate the typical appearance of an oil fire, leaning so for the theory of accumulation of VOCs, which corresponds to the visual combustion observed.

It has been noted that aspects of prevention of such a phenomenon, which is the main concern for firefighters, have been little discussed in the literature. Indeed, only the model proposed by Chatelon et al. (2011) is able to predict the fire eruption occurrence, depending on many parameters (fuel, slope, wind, dynamic parameters of the fire). As its computational time is very fast, an application for a smart phone or tablet could be developed but it needs to be coupled with a fuel characteristics database. For the moment, the only thing in which the firefighters are interested is how to detect a fire eruption situation on the field. With low wind speeds, the real danger is when the flames are very tilted up to be practically laid down on the vegetal stratum.

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