Modelling the propagation of one-end-burning cylindrical firebrand based on the measured regression rates

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1 Abstract

Spotting phenomenon of a burning firebrand lofted in the flow field is the key mechanism of fire spread in a large-scale wildfire such as Forest Fire. Although many models have been developed to determine the maximum spotting distance of the burning firebrands under various conditions, few focused on the effects of volume regression rate. The combustion on a firebrand can be enhanced by its inclined surface, which further increases its regression rate. This effect is discussed even less. In this paper, experiments determining the volume regression rates of one-end-burning cylinders at different incident angles have been conducted. From the initial results, it is found that the angle of incidence can either weaken or strengthen the regression rate of burning cylinders, especially for the cylinders of large diameters. The effects of the incident angle on the flame spread is also enhanced by increasing diameters. Furthermore, basing on the measured volume regression rates, numerical models have been developed to estimate the maximum spotting distances of the burning cylindrical firebrands lofted in a constant flow field. The results demonstrate that both the improvement and the suppression of spotting distances due to volume regression are significant. It highlights the important role of the volume regression rate in the propagation of burning firebrands, and suggest that the effects of incident angle on volume regression and mass loss should be included in the models in order to estimate more accurately the spotting distances.

2 Introduction

Spotting ignition is one of the main features which greatly contributes to the fire spread in large-scale-fires happened in the history, such as the 1871 Chicago Fire and the 1923 Tokyo Fire. Even until today, the tragedies are hard to avoid, as are demonstrated by the California Fire in 2018. Since Tarifa's research in 1960s [5], the propagation of firebrands has been considered as one of the most difficult, yet important problems in the study of fire spread. In the past century, a significant amount of experimental research has been devoted to investigate the spotting distances of firebrands (see, e.g., a recent review by Koo, 2010 [3]). Nevertheless, little research has focused on the effects of incident angles of firebrands on the regression

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rates, which can further influence the propagations of burning particles. The effects of incident angle on volume regression rate, as an important factor affecting the propagations of burning particle, has not been considered in the modelling of firebrands' trajectories.

Meanwhile, the effects of inclined surface on the charring rate of a burning particle is one of the important topics in combustion field. An example can be found from Moodie's research in 1992, where it is found that the wooden escalator at 30° of inclination strongly contribute to the 1987 King's Cross Fire in London [4]. Many studies have been devoted to investigating the effects of inclined surface on the flame spread, but not many have studied such effect on the relatively large particles in a flow field, such as firebrands.

In this paper, experiments have been conducted to determine the volume regression rates of burning cylindrical firebrands at different incident angles. The effects of incident angle on volume loss are investigated. The comparisons with published experimental research and models are provided as well. Based on the determined volume regression rate, simplified numerical models are developed to estimate the maximum spotting distances of cylindrical firebrands under various conditions, including wind speed, density, dimensions and incident angle. The influence by volume regression on the propagation of the burning cylinder is obtained.

3 Conceptualization of model and experimental set-up

On the modelling side, mathematical models are developed to determine the trajectories and maximum potential spotting distances of the cylindrical firebrands in the transporting phase. For a firebrand already exits the main fire zone and keeps gliding in a flow field, shown in the Figure 1, the effects of the plume can be ignored. The aerodynamic drag and lift exerted on the particle are included as the main forces supporting its propagation. Considering the axisymmetric aerodynamic behaviours of the cylindrical firebrands, the coordinate system is simplified into two-dimensional. From the Newton's second law of motion, the governing equations of a firebrand can be expressed as:

$$m_f \frac{dV_{f,x}}{dt} = \frac{1}{2} C_D \rho_a A \left|\vec{\boldsymbol{V}}_R\right| \left|\vec{\boldsymbol{V}}_{R,x}\right| + \frac{1}{2} C_L \rho_a A \vec{\boldsymbol{V}}_R^{\,2} \left|\vec{\boldsymbol{n}}_x\right| \tag{1}$$

$$m_f \frac{dV_{f,y}}{dt} = \frac{1}{2} C_D \rho_a A \left|\vec{\boldsymbol{V}}_R\right| \left|\vec{\boldsymbol{V}}_{R,y}\right| + \frac{1}{2} C_L \rho_a A \vec{\boldsymbol{V}}_R^{\,2} \left|\vec{\boldsymbol{n}}_y\right| - A\tau \left(\rho_f - \rho_a\right) g \tag{2}$$

where m, ρ, A, τ, g and , $\vec{\boldsymbol{V}}_R$ respectively indicate mass, density, projected area, thickness, gravitational acceleration and relative velocity of the firebrand with respect to ambient flow. The subscript x and y indicate the x- and y-axial directions. The direction vector of lift force, $\vec{\boldsymbol{n}}$, can be calculated as:

$$\vec{\boldsymbol{n}} = \underbrace{(V_{R,x}\, cos\varphi + V_{R,y}\, sin\varphi)(V_{R,y}\, cos\varphi - V_{R,x}\, sin\varphi)}_{sign} \cdot \underbrace{\frac{(-V_{R,y}\,\vec{\boldsymbol{\imath}} + -V_{R,x}\,\vec{\boldsymbol{\jmath}})}{\sqrt{{V_{R,x}}^2 + {V_{R,y}}^2}}}_{magnitude} \tag{3}$$

where φ is the incident angle between the particle and the horizontal direction. The first part on the right hand side of the equation indicates the sign of the vector $\vec{\boldsymbol{n}}$ and the second part indicates the magnitude. According to the studies by Zastawny [6], the coefficients of drag and lift for a cylinder can be calculated as:

$$C_D = \left(\frac{20.35}{Re^{0.98}} + \frac{2.77}{Re^{0.396}}\right) + \left(\frac{20.35}{Re^{0.98}} + \frac{2.77}{Re^{0.396}} - \frac{29.14}{Re^{0.97}} - \frac{3.66}{Re^{0.16}}\right) sin^{2.12}(\varphi) \tag{4}$$

$$C_L = \left(\frac{8.652}{Re^{0.898}} + \frac{0.704}{Re^{-0.028}}\right) sin^{0.978+0.036Re^{0.451}}(\varphi)\, cos^{1.359-0.43Re^{0.007}}(\varphi) \tag{5}$$

Meanwhile, the regression rates of cylindrical firebrands derived by Anthenien [1] and Koo [2] are utilized to compare with the determined volume regression rate from the experiments conducted in this paper. Due to the limited space, more details will be discussed in the full paper.

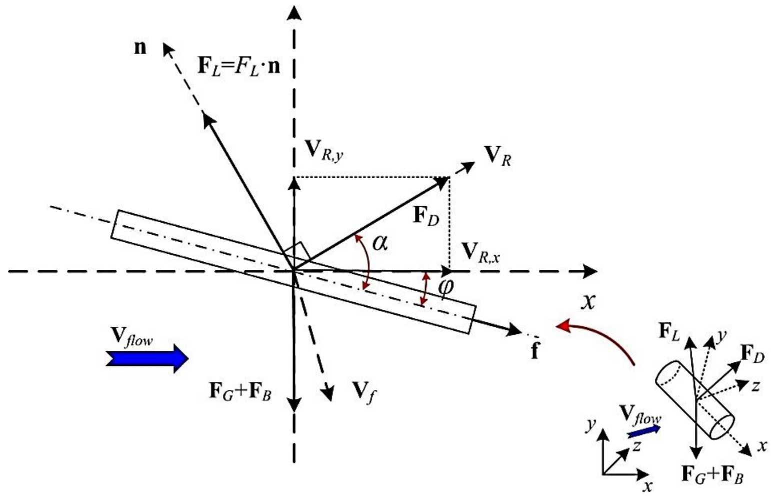

Figure 1. Schematic representations of the transporting model of a cylindrical firebrand lofted in a flow field.

Aiming at more accurate simulations of the partial burning on firebrands, the dimensional regression has been included in the transport model. The length of the firebrand is changing, as natural burning, while the gliding of firebrand. The radial change is neglected based on the experimental observation which is in good agreement with Koo's results [2]. The firebrand is assumed to be released at 100 m in height and glide in a constant flow field. Note the assumptions is made that particle hold the shape while transporting. The orientation of the cylinder is assumed to be neglected while gliding as a simplified model. The rotations and vibrations, such as tumbling and wobbling, are neglected. The effects of combustion on the aerodynamic coefficients are beyond the topic of this paper. Meanwhile, the combustion on the surface of cylinders are assume not to be extinguished during propagations.

On the experimental side, a high-speed colour imaging system is utilized to determine the volume regression rate of burning cylindrical firebrands. In order to visualise the ambient flow of burning particle, a 'z-type' Schlieren system is used as well. For the tested cylindrical firebrands, a broad range of diameters have been covered, including 6, 7, 8, 9, 12, 15 and 18 mm. In order to provide enough data, the cylinders tested are 400 mm in length. The cylinders are fixed at different incident angles by using a holder and ignited by pre-mixed fuel flow (methane and air) at one end of the particles. Note that the ash after burning is brittle and can be easily broken off the cylinder, which is neglected while calculating the volume of cylinders. Note that as another part of this series of firebrand ignition experiments, the firebrands ignitions at the downstream end from the ambient flow field will be conducted as a future work but not discussed in this work.

4 Key results and discussions

In order to determine the effects of incident angle on volume regression rates of burning cylindrical firebrands, a broad range of the incident angle has been covered from -60° to 60°. At each angle of incidence, the cylinders of seven different diameters have been tested. Given the limited space in this abstract, the results of the burning cylinders with 9 mm in diameters, at 30° and -30° of incident angles, are presented in Figure 2 as examples. More details of the results will be provided in the full paper.

Figure 2. The volume regression rates of the burning cylinders of different diameters.

It can be seen that the combustion of the cylinders at the negative incident angle were stronger than those at the positive angle. By using the high-speed Schlieren imaging system, it can be observed that the heated flow above burning particle was much wider when the cylinder was at negative incident angles (the ignited end pointing at the downward direction), and the flow was more turbulent. Part of the calculated regression rates of burning cylinders are presented in Figure 3, which shows the absolute values of the volume regression rates of the burning cylinders at 30°, 0° and -30° of incident angles. The comparisons with published models developed by Anthenien [1] and Koo [2] are provided.

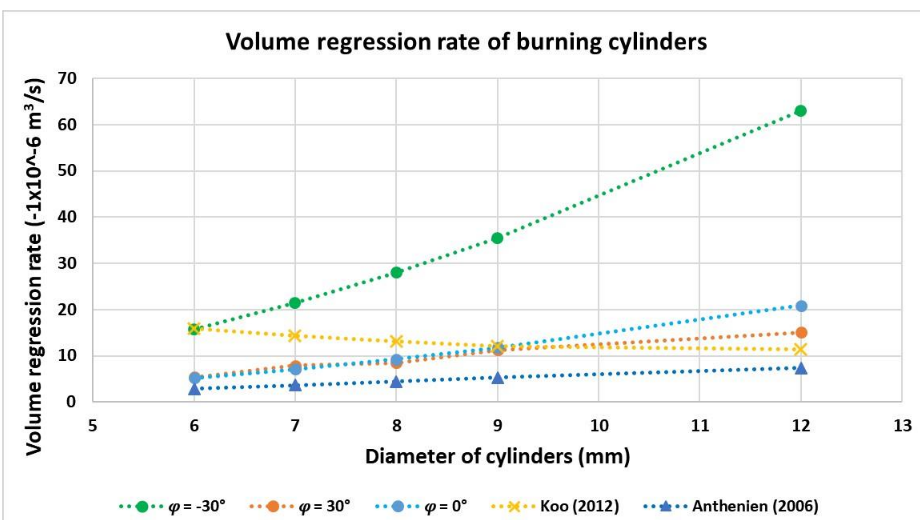

Figure 3. The volume regression rates of the burning cylinders of different diameters.

It is found that the volume loss of cylindrical firebrands due to burning can be significantly strengthened or weakened by the incident angle. The maximum increase of volume regression rate can be as high as 320% at -30° of incident angle with respect to the results at 0°. Meanwhile, the regression rate can be decreased by up to 39% when the angle of incidence is increased to 30°. The results at 0° and 30° of incident angles are in fairly good agreement with published models. However, for the results at -30°, the measured volume regression rates are significantly larger than the values estimated from burning models. This finding strongly highlights the importance of the incident angle on the transporting model of firebrands.

Furthermore, based on the determined volume regression rate of burning cylinders, numerical models are used to estimate the maximum spotting distances of burning cylindrical firebrands. The comparisons between burning and non-burning firebrands are presented in Figure 4. The density of firebrand is 250 kg/m^3 and the diameter of the cylinders is 12 mm. The length of the cylinders is 20 mm to ensure the burning lifetime is long enough. The velocity of the ambient flow is from 5 to 10 m/s. It is assumed that the firebrand is released at still. Meanwhile, the combustion on the surface of the cylinders are assumed not to be extinguished during the propagations.

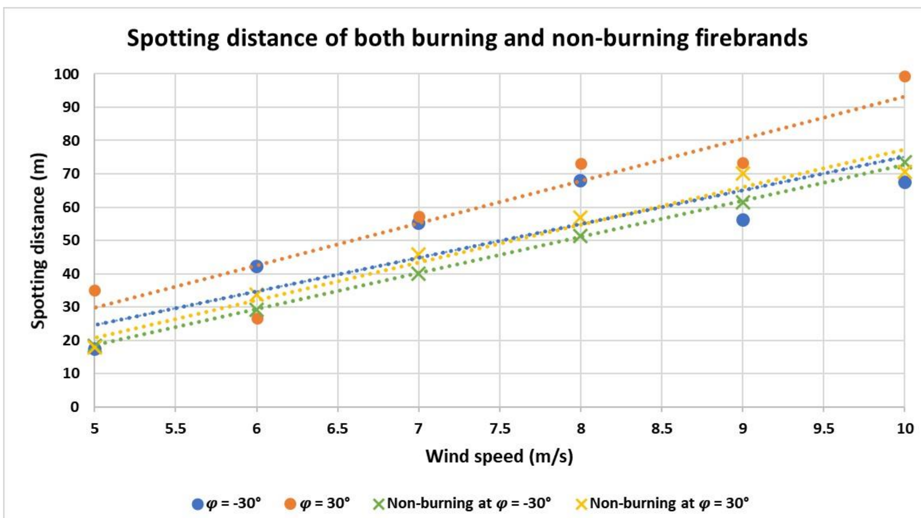

Figure 4. The volume regression rates of the burning cylinders of different diameters.

It can be obtained that, when the incident angle is at -30° (in the range from -30° to 30°) and the ambient flow velocity is 10 m/s (in the range from 5 to 10 m/s), the spotting distance of both burning and non-burning firebrands achieve the maximum values, up to 100 m for the burning cylinder and up to 80 m for non-burning cases. The results indicate that both the burning and non-burning firebrands will travel further with increasing flow velocity and decreasing incident angle. By comparing with the propagations of the non-burning particle, it can be seen that the effect of volume regression due to burning on spotting distance is significant for both the cases at positive and negative incident angles. Although it can be observed that the volume regression trends to increase the spotting distance, some exceptions can be obtained when the firebrand is at -30° of inclination. For example, when wind speed is at 9 m/s, the non-burning particle horizontally travels 61 m, which is 9% longer than the burning firebrand (56 m). Both the horizontal and the vertical accelerations are increased by the volume regression at the same time, which results in shorter flying time of burning particle. From the results, it is found that, due to the volume regression, the spotting distance can be either improved up to 37%, or supressed up to -13%. For experimental validations of the simulations presented in this paper, since it is difficult to estimate spotting distance of the firebrands from literatures which matches similar geometries, density, wood type, aspect ratios, wind speed and incident angle. Thus, as the validations which is relatively close to this study, both the aerodynamic drag and lift coefficients calculated from simulations are compared with Anthenien [1] and Zastawny [6], less than 10% of difference can be determined. Furthermore, the estimate glide ratio of cylindrical firebrand (10 mm in diameter, 13 m/s of wind speed, steady falling without orientation and oscillation) from Anthenien [1] presents good validations, that estimated result was 0.92 which is similar with the results determined from burning cylinders at 30° of incidence.

5 Conclusions

Experiments for determining the volume regression rates of burning cylindrical particles have been conducted. It is found that the maximum volume loss can be up to 63×10^{-6} m^3/s, at -30° of incident angle. The comparisons with published data are provided. Significant effects of the incident angle on the volume regression rate are obtained. Both the strengthening and weakening effects by incident angle are obtained, up to 320% at -30° and -39% at 30°. The effects can be further enhanced by increasing the diameter of the cylinder. Simplified numerical models for estimating the propagation of firebrands are developed. Based on the measured volume regression rate, the maximum spotting distance of each case is obtained. The results indicate that the propagations of burning cylinders are increased with increasing flow velocity and decreasing incident angle. By comparing the trajectories with non-burning particles, it is obtained that the volume regression due to combustion can either enhance or suppress the spotting of cylindrical firebrands, up to 20% of enhancement and -8% of suppression. From the comparisons with published models, it highlights the importance of incident angle in modelling the propagations of burning firebrands. Overall, the results in this paper strongly suggest that the incident angle should be considered to determine more accurate volume regression rate of burning particles. Meanwhile, the effects of incident angle on the size regression and mass loss should be included into the transporting model of firebrands in order to estimate extreme spotting distance.

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