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Air permeability of the litter layer in temperate forests of south-east Australia

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Abstract

Fuel on the ground, such as leaves, twigs and decomposing matter, accumulate over time and account for a large percentage of the total fuel load in forests. In fire events, material on the ground is often referred to as a fuel bed. The air permeability of a fuel bed is a critical factor that influences fire behaviour because it controls the amount of air (oxygen) available for combustion within the fuel bed. The aim of this study is to provide a better understanding of the air permeability of the fuel beds in forests. The air permeability for different fuel beds were determined using experimental and theoretical methods. The pressure drop across the fuel bed samples were experimentally measured using a verified permeability testing rig. The air permeability was then calculated using Darcy's Law (Darcian flow) or the Forchheimer equation (non-Darcian flow) from the pressure drop measurements. The particles in the fuel beds were characterised in terms of particle size and shape. Based on the particle characterisation, the air permeability of the fuel beds was also calculated using the Kozeny-Carman equation. The results show that the experimental method is preferred when determining the air permeability for natural forest fuel beds due to the variability in the size and shape of the particles. The results also show that both particle size and particle type are influential on the air permeability of the fuel bed. The significance of this study is that it increases the ability to predict the air permeability of fuel beds in forests, which is essential for modelling the combustion behaviour within the fuel beds.

Introduction

Wildfires are a recurring issue throughout summer and the drier months in many parts of the world. In addition to potential loss of life, wildfires cause tremendous economic loss. For example, the cost of the 2009 Victorian Black Saturday disaster in Australia is conservatively estimated at A$4.4 billion [14]. Climate change is increasing the risk and impact of wildfires [13], hence greater economic impact can be expected without improved methods of wildfire mitigation. Amongst the multiple measures to mitigate the risks of wildfires, hazard reduction burning (HRB) is one of the most effective and economical methods. As with any other technique, HRB has some drawbacks. For instance, the control of HRB is still challenging, especially in large-scale burning, where uncontrolled fire spread can occur. There is still room for improvement in the management and predictability of HRB; however, to do so, a more comprehensive understanding of hazard reduction burning is needed. Hence, the overall aim of this study is to develop a better understanding of HRB.

Ideally, the purpose of HRB is to apply controlled fires to a predetermined area in order to reduce the fuel load in that area. However, to achieve that, many specific conditions have to be met, such as weather conditions and the conditions of the fuel bed. Therefore, the success of HRB is influenced by many factors, such as the characteristics of the fuel, the weather and the topography [2]. These factors are so diverse that it is challenging to understand and effectively control HRB. At the moment, many decisions about HRB are made based on experience, and that is why trained personnel are essential for conducting HRB. Furthermore, there is a lack of detailed understanding of the effects of these factors on HRB. To better control and understand HRB, modelling is a critical approach. It is necessary to develop robust models which can provide a comprehensive understanding of HRB. Furthermore, these models can later be used as tools to predict and manage the HRB activities. However, to develop accurate models, reliably measured data such as air permeability of fuel beds are required as model inputs.

Fuel beds account for a large percentage of fuel in forests [2] and are especially important for HRB, as most of the fuel reduction is from them [7]. Modelling of their combustion needs to consider two different combustion regimes: smouldering and flaming. The combustion regime of a fuel bed can be controlled by oxygen availability [6, 11, 15, 16], which is affected by the fuel bed's air permeability. The air permeability of a fuel bed, which can be considered a porous medium, characterises the ease with which air can pass through it. It is critical to have a better understanding of the air permeability of the forest fuel bed, but there have been few studies on this aspect [5, 11]. Determining the air permeability of a fuel bed is challenging because of the diversity of the material in fuel beds. In the literature, fuel beds are often characterised based on particle size [1, 4]. However, from the point view of the air permeability, it is likely that for the same particle size, a fuel bed made of different fuel particles will have different air permeability. Therefore, it is necessary to identify a robust way of characterising the fuel bed and its impact on the air permeability.

The overall aim of this study is to provide a better understanding of the air permeability of fuel beds, in the context of HRB; since the air permeability has significant effects on the combustion of fuel beds. First of all, it is important to find a robust method of determining the air permeability of fuel beds. It is also necessary to examine whether the fuel bed material can be characterised in a way that is suitable for providing input data into models. The experiments described in this study were designed to investigate the air permeability of natural forest litter layer, and the effects of particle size and particle type on the air permeability. Due to the lack of data in the literature, the air permeability of natural forest fuel beds will be reported. A function can be developed to determine the air permeability from the easily defined characteristics of the fuel bed material.

Methodology

The experimental testing rig was designed to determine the air permeability of a fuel bed by measuring the pressure drop across the fuel bed. The experimental testing rig consisted of three parts: a permeability testing rig, an air supply system and a manometer (Model 9565, TSI Inc., Shoreview, United States). The air permeability testing rig shown in Figure 1 has top and bottom sections. There are a dual air inlet and a bed of ceramic beads in the bottom section to obtain uniform flow through the fuel bed. Fuel bed samples were loaded in the top section of the air permeability testing rig. The input air flow in this study was supplied by an air compressor, and the moisture in the input air flow was removed by a dehumidifier before introducing into the air permeability testing rig. By removing the moisture in the air, the accuracy of the input flowrate and the pressure drop measurements can be improved, and the uncertainties caused by the moisture in the ambient air can be minimised.

Three categories of fuel bed samples are used in this study: glass beads, milled biomass particles and natural forest fuel particles. For the milled biomass particles, pulverised and dried pine chips, gum bark and gum leaves were used to represent the three common fuel types in forests. The pine chips samples are from Pinus radiata, and the bark and twig samples are from Eucalyptus *camaldulensis*. To reduce variability between samples, the pine chips, gum bark and gum leaves were milled and sieved into three size ranges (1–2 mm; 2–3 mm; 3–4 mm). All the forest fuel bed samples used in this study were collected from a forest in East Gippsland, Victoria (for more details about the collecting site, refer to[10]). This forest is located in one of the wildfire-prone areas of Victoria, Australia.

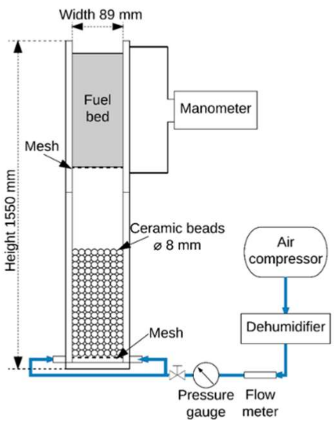

Figure 1. Schematic diagram of the experimental testing apparatus for the air permeability experiments.

The input air flow rate was varied from 50.5 to 404 $g{\cdot}m^{-2}{\cdot}s^{-1}$ (42 to 337 $mm{\cdot}s^{-1}$), with a 50.5 $g{\cdot}m^{-2}{\cdot}s^{-1}$ increment. Below the lower limit (50.5 $g{\cdot}m^{-2}{\cdot}s^{-1}$), the error in the pressure drop measurement significantly increases due to the range of the manometer. Above the upper limit (404 $g{\cdot}m^{-2}{\cdot}s^{-1}$), the bed becomes fluidised. The pressure before and after the fuel bed (Figure 1) was measured using the manometer through holes in the rig. Prior to each experiment, fuel material was weighed and loaded into the rig. The fuel material was carefully loaded to create an unconsolidated fuel bed; this is to ensure the consistency throughout the fuel bed. The pressure drop across the fuel bed was based on a 60-second averaging period, with a 1 Hz sampling frequency.

The permeability of a porous medium can be determined using either Darcy's Law, or the Forchheimer equation, depending on the flow regime (Figure 2). The fundamental principle in determining the air permeability is based on the pressure gradient, for a particular flow velocity [12]. The air permeability in fuel beds can also be calculated using the Kozeny-Carman equation, based on the physical properties of the porous medium. The Kozeny-Carman equation has been widely applied to flow through soils, sands, and synthetic materials [3, 8, 9]. However, the validity of the Kozeny-Carman equation has not been demonstrated for particles in natural forest fuel beds. The natural forest fuel beds are highly variable, which means that rather than relying on simple correlations, experimental methods are needed to determine characteristics of fuel beds. The results may subsequently be used as an input data for models.

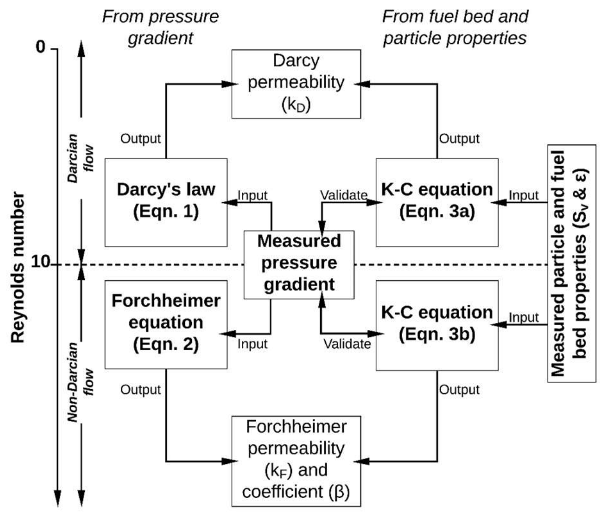

Figure 2. Schematic diagram for determining the air permeability of a fuel bed.

Results

Due to the diversity and complexity of natural forest particles, benchmarking experiments using well-controlled particles are first presented. These not only verify the reliability of the experimental testing apparatus, but can also be used as a reference for the natural forest samples. Hence, a set of experiments were conducted using the experimental testing apparatus for regularly-shaped spherical glass beads.

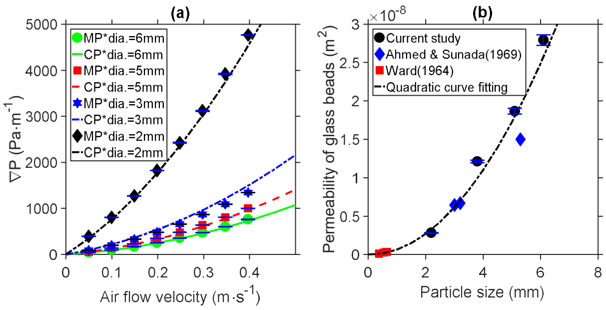

Figure 3. Spherical glass bead particle results. (a) Pressure gradient as a function of air flow velocity for various sized particles. MP* is the measured pressure gradient and CP* is the calculated pressure gradient calculated using the Kozeny-Carman equation. (b) Air permeability measurement compared with previous studies. Repeatability of measurements represented by ± 1 standard deviation error bars.

Figure 3(a) shows that, for spherical glass bead particles, the pressure gradient calculated using the Kozeny-Carman equation shows good agreement with the measured pressure drop. The results in Figure 3(a) demonstrate that the experimental testing apparatus is reliable and gives an approximate value for the pressure gradient that may be expected for forest fuels of a similar size. Figure 3(b) includes a quadratic curve fitting which shows a good agreement with the experimental results. Hence, this confirms that a quadratic relationship between the air permeability and particle size may be used for subsequent analysis.

After verifying the reliability of the experimental testing apparatus using regular-shaped particles, a set of similar experiments were conducted for milled and sieved pine chips. Compared with glass beads, the milled biomass particles are more irregular in shape, and the behaviour of a porous medium made from them is expected to be more complex than that of the glass beads. In the case of spherical particles, it is accepted that the pressure gradient is independent of the bed depth. In the case of the irregular biomass fuel particles, this independence has not yet been confirmed in the literature. Hence, Figure 4 assesses the linearity of the pressure drop measurements, as a function of bed depth, for a range of different particle size milled pine chips.

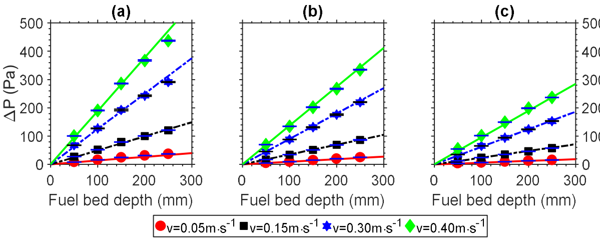

Figure 4. Measured pressure drop as a function of the fuel bed depth for (a) 1–2 mm (b) 2–3 mm (c) 3–4 mm milled pine chip particles across a range of air flow velocities. Repeatability of measurements represented by ± 1 standard deviation error bars.

Overlaid on the experimental data points in Figure 4 are lines of best fit. It is apparent that the pressure drop across fuel bed is indeed linear with the fuel bed depth, which means that the pressure gradient of fuel bed is constant with a specific superficial velocity. In other words, the pressure gradient of fuel bed is dependent of fuel type, particle size and superficial air velocity. Hence, the pressure drop only needs to be measured at a single fuel bed depth and can be inferred for other depths. For the remainder of the tests, only the deepest fuel bed was used, so as to maximise the pressure drop and thus minimise the uncertainty in the pressure gradient.

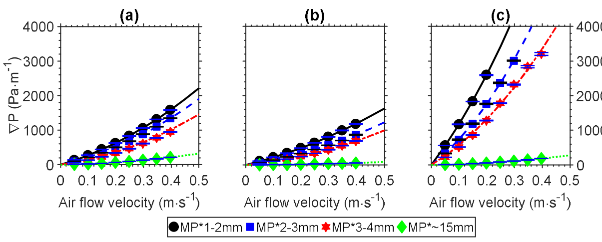

Figure 5. Pressure gradient as a function of air flow velocity for particles: (a) pine chips (b) gum bark (c) gum leaves (Marker: measured pressure gradient; Line: calculated pressure gradient based on deduced measured specific area). Repeatability of measurements represented by ± 1 standard deviation error bars.

Figure 5 presents the measured pressure gradient (markers) and the calculated pressure gradient (lines) against the superficial velocity. The calculated pressure gradient was calculated using the Kozeny-Carman equation based on the deduced specific area. The consistency between the measured and calculated pressure gradients show that the relationship between the pressure gradient and the superficial velocity is quadratic for the milled biomass fuel beds, as the pressure gradient in the Kozeny-Carman equation is a function of the square of the superficial velocity. The results in Figure 5 also show that for the same particle size and superficial air velocity, milled gum leaf particles have the highest pressure gradient; the milled gum bark has the lowest pressure gradient. The difference in pressure gradient implies that fuel type has significant effects on the pressure gradient of a fuel bed, as different fuel type results in different shapes of milled particles.

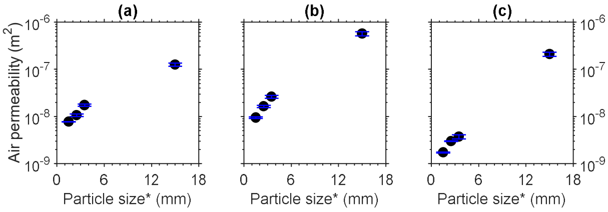

Figure 6. Permeability (k) as a function of particle size for the milled particles (*Average sieve opening size) (a) pine chips, (b) gum bark, (c) gum leaves. Repeatability of measurements represented by ± 1 standard deviation error bars.

The results in Figure 6 show that the air permeability of the fuel bed with small particles (<4 mm) is much less than that of the fuel bed with large particles (~15 mm). Furthermore, small particles contribute much more mass in natural forest fuel beds. Hence, small particles are expected to dominate the permeability. The relationship between the air permeability and particle size is quadratic according to the Kozeny-Carman equation. The results shown in Figure 5 imply that the Kozeny-Carman equation is applicable for the milled biomass particles. Hence, theoretically the air permeability of the milled biomass fuel beds can be presented in a function of the square of particle size. The air permeability can be calculated from either pressure gradient or the particle/fuel bed properties. However, the pressure gradient needs to be obtained by conducting the experiments because the measured specific area of particles is not robust enough for the Kozeny-Carman equation. Hence, the air permeability of the milled biomass fuel beds can be alternatively estimated based on the average particle size, as it is much easier to measure the particle size.

The results of the three milled biomass particles are presented and discussed, where the fuel particles were broken down into small sizes using a mill. However, the fuel particles in the real world are broken down through the natural decomposition process. Hence, the shape of the particles in forests may be quite different from the milled fuel particles. As discussed previously, the particle shape has a significant effect on the air permeability. Hence, it is also important to determine the air permeability of the natural forest fuel particles.

Figure 7 shows the measured pressure gradients (makers) and the calculated pressure gradients (lines) against the superficial velocity for the natural forest fuel particles. The calculated pressure gradient was calculated using the Kozeny-Carman equation based on the deduced measured specific area. The results in Figure 7 show that the measured and calculated pressure gradients are in good agreement, and this implies that the fuel bed made of the natural forest fuel material can be represented using the Forchheimer equation and the Kozeny-Carman equation. In comparison with the milled biomass, for the same particle size, the pressure gradient versus the superficial velocity curves of the decomposing matter beds are similar to those of the pine chips beds.

Based on the quadratic function of the pressure gradient and the superficial air velocity, the pressure gradient for each natural forest fuel bed particle size at a given superficial air velocity can be calculated. Similarly, the Forchheimer permeability was calculated based on the Forchheimer equation and the function of the pressure gradient versus the superficial velocity. However, similar to the milled biomass fuel particles, it is also difficult to measure the specific area of the natural forest fuel particles.

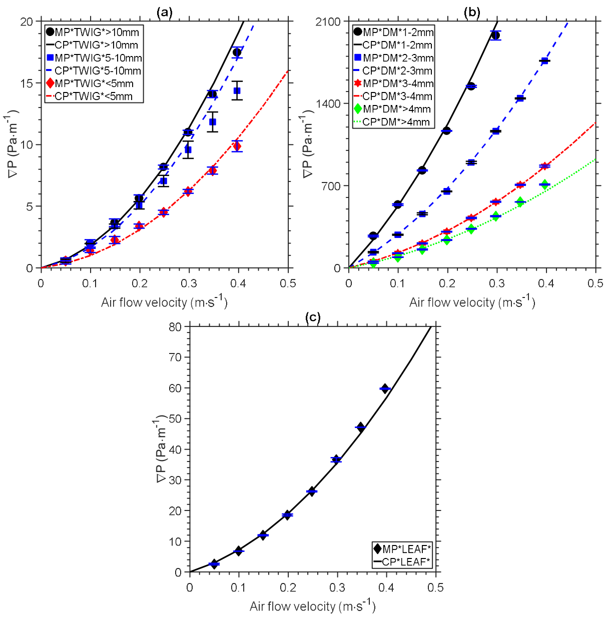

Figure 7. Pressure gradient as a function of air flow velocity for particles: (a) twig (b) decomposing matter (DM) (c) leaf. (MP*: measured pressure gradient; CP*: calculated pressure gradient based on the deduced measured specific area). Repeatability of measurements represented by ± 1 standard deviation error bars.

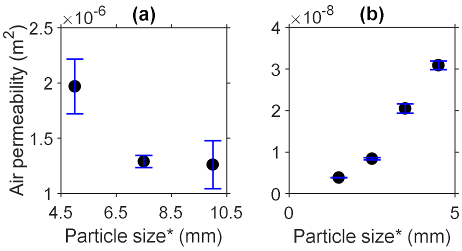

Figure 8. Permeability (k) as a function of particle size (*Average sieve opening size) (a) twig (b) decomposing matter (DM). Repeatability of measurements represented by ± 1 standard deviation error bars.

Figure 8(a) shows that the particle size does not have a significant effect on the air permeability for the twig particles in the range of particle sizes investigated in the current study. Figure 8(b) shows that decomposing matter shows a similar trend to the milled particles, i.e. a decrease in particle size decreases the air permeability. As shown in Figure 7(b), the Kozeny-Carman equation is validated for the decomposing matter. Hence, the relationship between the air permeability of the decomposing matter beds and particle size is quadratic.

Conclusions

This paper investigated the air permeability of fuel beds in forests, from the perspective of its effect on the combustion of fuel beds. An experimental testing apparatus was designed and developed to investigate the effects of particle size and type on the air permeability. The efficacy of the experimental testing apparatus was verified using spherical particles in different sizes. The air permeability of the porous medium made of glass beads were determined by experiment and calculation. The results show that the calculated pressure drop showed excellent agreement with the measured pressure drop, which implies that it is capable of calculating the air permeability for spherical particles. It was also found that the relationship between the air permeability and particle size is quadratic for spherical particles. More research is needed to better understand the relationship between the air permeability and the combustion of the forest fuel beds.

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References

[1] Anderson, H.E., Aids to determining fuel models for estimating fire behavior. The Bark Beetles, Fuels, and Fire Bibliography, 1982: p. 143.

[2] Biswell, H.H., Prescribed burning in California wildlands vegetation management. 1989: Univ of California Press.

[3] Chapuis, R.P. and M. Aubertin, Predicting the coefficient of permeability of soils using the Kozeny-Carman equation. 2003: École polytechnique de Montréal.

[4] El-Sayed, S. and T. Khass, Smoldering combustion of rice husk dusts on a hot surface. Combustion, Explosion, and Shock Waves, 2013. 49(2): p. 159-166.

[5] Erić, A., et al., Experimental method for determining Forchheimer equation coefficients related to flow of air through the bales of soy straw. International Journal of heat and mass transfer, 2011. 54(19): p. 4300-4306.

[6] Huang, X. and G. Rein, Interactions of Earth's atmospheric oxygen and fuel moisture in smouldering wildfires. Science of The Total Environment, 2016. 572: p. 1440-1446.

[7] Knapp, E.E., et al., Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. Forest Ecology and Management, 2005. 208(1): p. 383-397.

[8] Kyan, C.P., D. Wasan, and R. Kintner, Flow of single-phase fluids through fibrous beds. Industrial & Engineering Chemistry Fundamentals, 1970. 9(4): p. 596-603.

[9] Mavis, F. and E. Wilsey, Filter sand permeability studies. Eng. News Rec, 1937. 118: p. 299-300.

[10] Possell, M., et al., Emissions from prescribed fire in temperate forest in south-east Australia: implications for carbon accounting. Biogeosciences Discussions, 2014. 11(9).

[11] Santoni, P., et al., Bulk and particle properties of pine needle fuel beds–influence on combustion. International Journal of Wildland Fire, 2014. 23(8): p. 1076-1086.

[12] Sobieski, W. and A. Trykozko, Darcy's and Forchheimer's laws in practice. Part 1. The experiment. Technical Sciences/University of Warmia and Mazury in Olsztyn, 2014(17 (4)): p. 321--335.

[13] Steffen, W. and L. Hughes, The critical decade 2013. Climate Change Science, Risks and Responses. Climate Commission, Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, Commonwealth of Australia, 2013.

[14] Teague, B., R. McLeod, and S. Pascoe, Final report, 2009 Victorian bushfires royal commission. Parliament of Victoria, Melbourne Victoria, Australia, 2010.

[15] Wang, H., et al., Identification and Quantitative Analysis of Smoldering and Flaming Combustion of Radiata Pine. Energy & Fuels, 2016. 30(9): p. 7666-7677.

[16] Wang, H., et al., Effects of Oxygen Concentration on Radiation-Aided and Self-sustained Smoldering Combustion of Radiata Pine. Energy & Fuels, 2017.