PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

STUDY ON RADIATA PINE FOREST LITTER SAMPLING AND ITS INCIDENCE ON COMBUSTION

SEBASTIÁN IGNACIO FEHRMANN SOTO

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:

JUAN DE DIOS RIVERA AGUERO

Santiago de Chile, August 2015

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To my niece Olivia Ardiles Fehrmann and in the memory of my grandfather Augusto Fehrmann Schulz.

ACKNOWLEDGEMENTS

I would like to start recognizing all those involved somehow in my learning process through my entire life as this thesis summarizes a lot of years of effort and life stages. Thanks to all my teachers and masters having in mind only a few of them thought me in a classroom. Thanks to my family, friends and girlfriend Andrea for all the patience and support.

As this research has an important experimental component, I would like to thanks the Mella family, Ramón Mella Mella and his son Ariel, who allowed me to go sampling in several occasions to their forests. I am also thankful to the Santamaría family as in the early stages of this project they offered me their forest, but the research brought me to different places.

My time in the Mechanical Engineering Department would have been a lot more difficult if it was not for all the support given by Marcelo Gutiérrez, Luis Valdés, Nacho, Roberto, Fabián, Parra, Enrique, Miguel Ángel, Gloria, Anita, Patricio Pérez and Manuel Galvez.

Thanks to my friends who went sampling with me early in the morning in summer weekends: Erwin Etcheberry, Juan Guillermo Ávila and Nicolás Reyes. Thanks also to Jorge Gómez, from Universidad de los Andes, whose help with electronic components was invaluable.

Finally I want to specially thank professor Juan de Dios Rivera for his goodwill and for being always available as well as professor Wolfram Jahn for his help and contributions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Forest litter flammability metrics have long been studied under laboratory conditions, but little research has been made in quantifying how different artificially reconstructed litters are to natural litters. To test if fuel bed structure matters in fire spread we present a sampling method to obtain almost un-perturbed radiata pine litters and procedures to experimentally study their permeability in the two principal directions of interest (vertical and horizontal directions).

A comparison was made between the two kinds of litters, founding that permeability of reconstructed litters is more similar to vertical permeability on natural litters than to horizontal permeability, the latter being one order of magnitude smaller than the others.

In combustion tests under different moisture content and different bulk densities, fire spread velocity of natural litters was found to be one order of magnitude slower than in reconstructed litters.

A mathematical model linking permeability, fuel properties and fire spread velocity is presented, showing more quantitative differences between natural and artificially reconstructed litters.

We also inform about surface to volume ratio of both kinds of litters and the respective densities, porosities and a qualitative comparison. Surface to volume ratio as well as densities and porosities were notably different between both kinds of litters.

Keywords: litter flammability, litter sampling, permeability, fuel bed, forest fire, fire spread velocity, radiata pine, pinus radiata.

RESUMEN

La flamabilidad de lechos de bosques ha sido ampliamente estudiada bajo condiciones de laboratorio, pero hay poca investigación que cuantifique cuán distinta es la situación de laboratorio comparada con la situación natural. Para estudiar si efectivamente la estructura del combustible importa proponemos un método de muestreo para obtener muestras de lechos de pino radiata prácticamente sin perturbar y presentamos procedimientos para determinar experimentalmente la permeabilidad del lecho en las dos principales direcciones de interés.

Se hizo una comparación de lechos naturales con lechos artificialmente reconstruidos, encontrando que la permeabilidad de estos últimos es similar a la permeabilidad en la dirección vertical del lecho natural y que la permeabilidad en la dirección horizontal del lecho natural es un orden de magnitud más pequeña que en la dirección vertical y que en lechos reconstruidos.

En ensayos de combustión realizados bajo diferentes contenidos de humedad y densidad aparente de los combustibles, se encontró que la velocidad de propagación del fuego es un orden de magnitud más pequeño en lechos naturales que en lechos reconstruidos.

Se presenta un modelo matemático que relaciona permeabilidad, propiedades del combustible y velocidad de propagación del fuego, evidenciando más diferencias cuantitativas entre lechos naturales y artificialmente reconstruidos.

Se informa también de la relación de superficie a volumen de ambos tipos de lecho, sus densidades y porosidades, además de una comparación cualitativa. Tanto la relación superficie a volumen como densidad y la porosidad son notoriamente diferentes.

Palabras Claves: flamabilidad de lechos, muestreo de lecho, permeabilidad, camas de combustible, incendio forestal, velocidad de propagación del fuego, pino radiata, pinus radiata.

1. ARTICLE BACKGROUND

Forest fires are a threat in many places, not only to people but also to ecosystems. Forestry is an industry which led to plant big surfaces with quick grown species and in Chile the most planted species and the one representing the most burnt area is radiata pine. Better understanding of its burning dynamics and improvements in experimental set-ups are needed.

In particular there is a need to know how different the experimental set-ups are compared with the natural occurring forest situation, in order to know whether the data gathered until now is useful, or how to better gather it.

In the Introduction we present a review of the national and international situation on forest fires, a qualitative description of natural litters and artificially reconstructed litters, and how--until now--litter flammability research has handled litters under laboratory conditions. In the second chapter we present results of quantitative and qualitative comparison between natural and artificial litters. In the annex there is additional and detailed information on some of the procedures we performed.

It is important to notice that chapter 2 was sent to Fire Technology Journal to be published as an article with Juan de Dios Rivera and Wolfram Jahn as co-authors.

1.1 Introduction

1.1.1 Forest Fires in Chile and Other Countries

Forest fires have been a constant problem in Chile in its history, having a mean augmentation in its frequency (number of fires per year), in damage per fire, and consequently in total damage per year in the last decades. Looking at official statistics

(CONAF, 2014b), in average between 1984 and 2014, 52 814 hectares of forest were burnt per year with a standard deviation of almost 27 000. In the same period, 99.3 % of these fires occurred between October and April, being January the month with most fires in average and presenting the most damage in average along with February.

Of all species affected by forest fires, radiata pines and eucalyptus sp are the most vulnerables, representing an average of 15.2 % and 5.5 % of the total burnt surface respectively. It is also important to take into account that the most planted forest species in Chile are radiata pine (52.7 % or 839 412 hectares) and eucalyptus globulus (26.2% or 417695 hectares) for the period 1998-2012 (CONAF, 2014a).

In Figure 1, we can appreciate how forest fires concentrate in the center of the country between the fifth and the ninth regions. Of special interest is the sixth region because of its high affected surface-to-number of fires ratio, and because this region represents 6% (CONAF, 2014a) of the planted and reforested surface of the country (between 1998 and 2012).

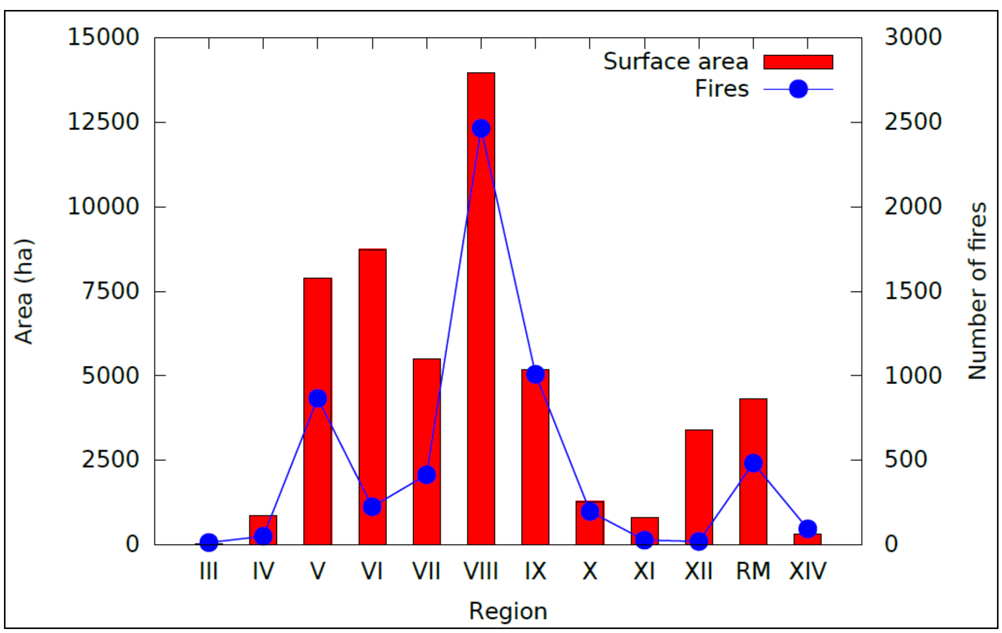

Figure 1: Occurrence and area damaged by region in Chile, period 2003-2012 (CONAF, 2014b).

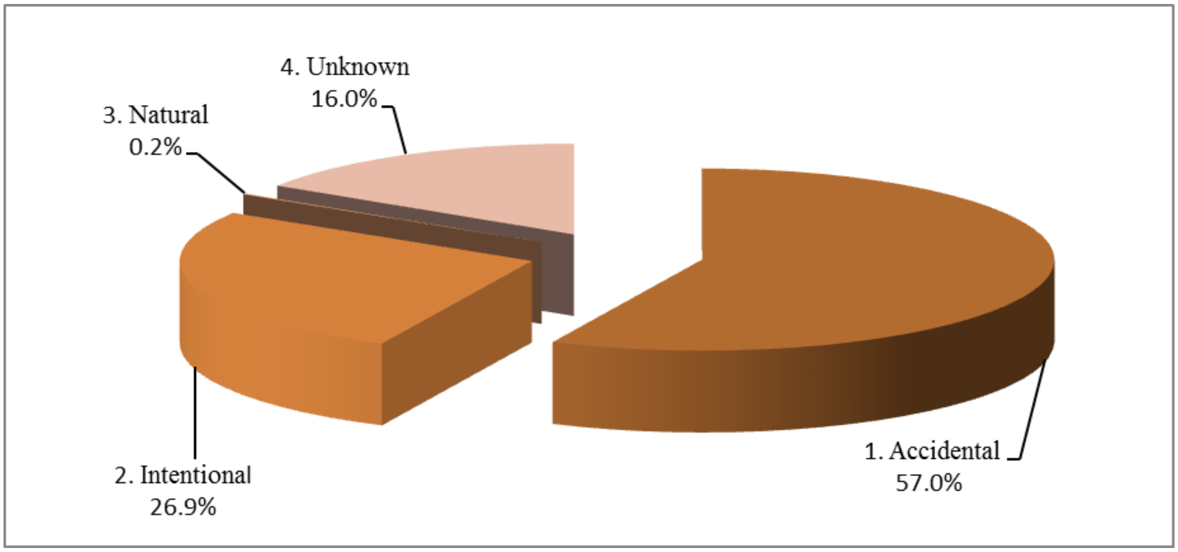

Figure 2: Forest fire causality in Chile, period 2003-2014 (CONAF, 2014b).

Taking into account the causality of forest fires (information provided by CONAF, Corporación Nacional Forestal), 83.9 % of them have proven human related causes, and 26.9 % are intentional, meaning that a person started a fire because he wanted that fire to happen (mostly for agricultural land management and some arson cases).

According to NFPA statistics (Ahrens, 2013), in the USA 20% of reported brush, grass, or forest fires were intentionally caused, and human related causes explain directly more than 96% of all brush, grass or forest fires.

In Europe, forest fires are also caused mainly by human factors, and only an average of 4,2% of all fires of known cause are explained by natural causes (Ganteaume et al., 2013). In European Mediterranean countries 71% of all fires had an identified cause in the period 2006-2010, of which 95,4% were caused by human related activities, mostly by deliberate action (55,8% of the total) (Ganteaume et al., 2013). In Portugal for example, human activities are practically the only explanation of fire ignition (Perestrello De Vasconcelos et al., 2001) and in Canada they explained an average of 62% of them in the period 1976-1999 (Wotton et al., 2003).

Among natural occurring forest fires around the world, lightning explain the majority of them (Gugliettaet al., 2015; Wotton et al., 2003) but the strike-to-ignition ratio changes significantly from place to place, and seasonally (Outcalt, 2008). In Finland, for example, lightning explains about 13% of all forest fires annually (Larjavaara et al., 2004) and is practically the only possible cause of fire ignition when there is no influence of human activity, whereas in the USA a 4% of all brush, grass and forest fires are caused by lightning.

Looking at 2013 data of 17 countries around the world, forest fires represent in average 3% of their total declared fires (Brushlinsky et al., 2015), being an important issue worldwide.

Climate has an influence over forest fires and wild fires in general (Ganteaume et al., 2013; Gill & Zylstra, 2005; Guglietta et al., 2015; Larjavaara et al., 2004; Wotton et al., 2003) mostly because its incidence in fuel moisture content (Williams et al., 2015) and wind velocity (Babak et al., 2009; Morandini et al., 2006), but also wind temperature (Westerling et al., 2006), being all of them important factors when assessing forest fire hazard (Castro, 1998).

1.1.2 Forest Litter

In the ignition study of forest fires it is common to assume that the fire starts in the forest litter rather than the trees themselves (Bessie & Johnson, 1995; Scott & Reinhardt, 2001; Van Wagner, 1977), as independent crown fires (a self-sustainable fire burning canopy fuels (Scott & Reinhardt, 2001)) are rare and short lived (Van Wagner, 1992).

Despite the particular forest litter being studied, the ignition mechanism being occupied or the purpose of the research where litters are used in laboratory experimentation, results can be extrapolated to other cases. Little research has been done in this area, and there are only few studies that occupy natural forest litters (Ganteaume et al., 2014; Varner et al., 2015).

Several studies on pine litters (Catchpole et al., 1998; Fernandez-Pello et al., 2014; Hepp, 2009; Jervis & Rein, 2015; P. A. Santoni et al., 2014; Schemel et al., 2008; Valdivieso & Rivera, 2013; Valdivieso, 2010; Varner et al., 2015; Viegas et al., 2012; Yin et al., 2012), fuel beds in general (Àgueda et al., 2011; Fernandez-Pello et al., 2014; Manzello et al., 2006) and pine needle fuels (Liodakis et al., 2002; Liodakis et al., 2006) related to combustion were reviewed and only three used natural forest litters (Curt et al., 2011; Ganteaume et al., 2014; Ganteaume et al., 2011), and in fact one of them was a study to determine differences in laboratory results when natural and artificially reconstructed litters were used. One of their main conclusions was that some of the flammability metrics they measured were significantly different when using natural litters and artificial litters. Other studies centered on wildland fires used data from recreated forest fires, but did not include laboratory litter experimentation (Carvalho et al., 2002; P. a. Santoni et al., 2006; Silvani & Morandini, 2009).

When reconstructed or artificial litters are used in laboratory experiments, some properties change. In Figure 3 an artificial litter can be appreciated. It was reconstructed for this study with radiata pine needles by letting them fall freely into a specially constructed holder. As can be observed, spatial distribution over the whole volume is relatively homogeneous.

Figure 3: Artificial forest litter.

In fact, when looking at the litter from two perpendicular directions, especially the horizontal and vertical directions, no particular difference is found. The situation can be represented as shown in Figure 4.

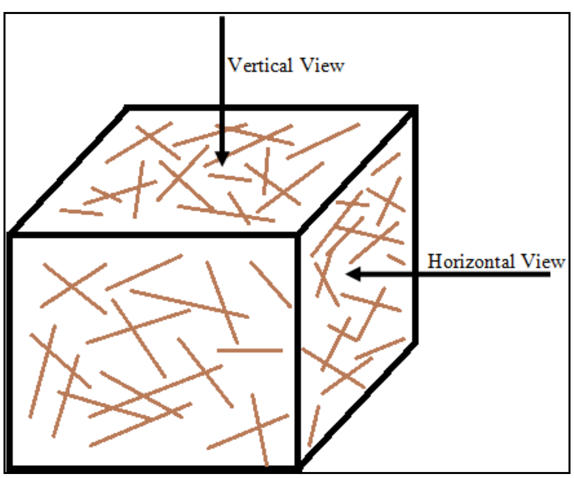

Figure 4: Representation of a reconstructed pine needle litter or artificial litter. Figure based on the work of Jaganathan et al. (2008a)**.**

Figure 5 shows a photograph of a mature radiata pine forest litter, when it is looked at vertically. Three things are immediately observed: The first observation is that pine needles are not the only fuel as there can be seen leafs from other species, branches and wooden sticks. The second observation is that although it does not seem to be an ordered fuel bed, it looks quite homogeneous despite being differences from one site to another. The third observation is that there is no particular direction in which needles are oriented.

Figure 5: Vertical view of a natural forest litter.

In Figure 6, a photograph of the same radiata pine litter but seen horizontally, it can be observed three particularities as well. First, one can observe that again pine needles are not the only fuel available (observation made in other studies too (Varner et al., 2015)). In particular, seeds are seen in this picture. Second, while an approximately homogenous distribution of the components is seen in its depth, it’s a different kind of distribution than the one seen in Figure 4 and Figure 5. And third, the angle the needles form with the horizontal plane is small.

Figure 6: Horizontal view of a natural forest litter.

Taking only into account pine needles of the forest litter, Figure 7 is a good representation of the needle's spatial distribution, layered horizontally in the horizontal direction and in a fairly perpendicular plane to the vertical direction, but not pointing to any particular direction.

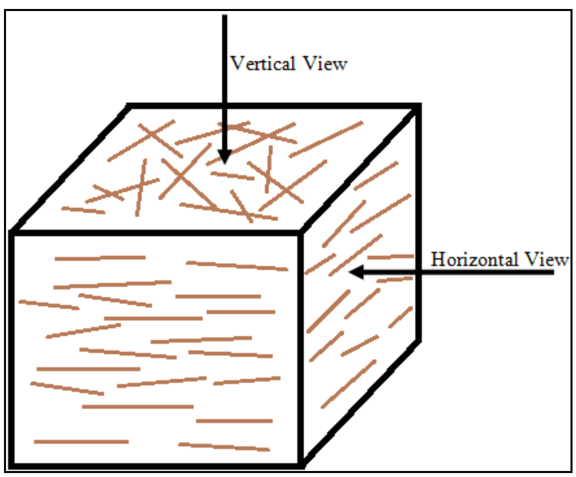

Figure 7: Natural pine forest litter representation. Figure based on the work of Jaganathan et al. (2008a)**.**

Moreover when litter thickness is being studied, two horizons are identified (Sato et al., 2004; Vorobeichik, 1995), leaf horizon (LH) and fermentation or fragmented horizon (FH). LH may be defined as an upper and un-decomposed layer containing mainly dead leaves, whereas FH may be defined as a layer with decomposed organic material. Ganteaume et al. (2014) introduced in their work another layer, the humus layer or humus horizon (HH) defined as the “upper part of the humus layer”. In all reviewed works in which forest litter is reconstructed in a laboratory, except for the latter one and few others (Curt et al., 2011; Ganteaume et al., 2011; Varner et al., 2015), only a selected LH is present. Going even further it is unknown how soil moisture dynamics affect the heat transfer of a fire propagating over it in the litter layers, how other species like fungus affect combustion, and how all the fuel layers interact with each other, with soil and with other commonly present components. It is clear though that at least qualitatively natural radiata pine litters are different from reconstructed litters and there is evidence (Ganteaume et al., 2014) of quantitative difference between them for other similar forest species.

To better represent the forest reality and to have better laboratory test results concerning litter combustion we propose a new sampling method and an experimental comparison between the classic reconstructed pine needle litter and the new proposed one, all with mature radiata pine forest litters from the central zone of Chile (sixth region).

1.1.3 Fuel Bed Experimentation

Combustion tests have been practiced for long time on forest litters in order to better understand how wildfires propagate and how to prevent and extinguish them with lesser losses of all kind. To get better laboratory results we focused the research on two topics: litter sampling and litter comparison between natural litters (proposed by us) and artificial litters (the commonly used). To be able to get better samples it is mandatory to know what parameters are important in forest litter combustion.

Santoni et al. (2014) studied the influence of pine needle litter characteristics on combustion. They found permeability to be a key parameter influencing the rate of heat release when forced flow was imposed, and surface to volume ratio (SVR) to be essential in driving the time to ignition. They observed that pine needle litters have different combustion behavior than solid fuels as litters have higher porosity. Higher porosity increases the rate of oxygenation of the combustion front, but found permeability to be the principal property governing combustion dynamics in a porous fuel bed. Rostami et al. (2003) also found permeability to be an important parameter to smoldering behavior since it has direct effect on mass transfer, which agrees with other studies on porous fuels (He & Behrendt, 2011).

Varner et al. (2015) found in their research that bulk density of the fuel bed along with geometrical characteristics of the fuel itself, are drivers of flammability. Ganteaume et al. (2014) found differences when using natural litters versus artificially constructer litters and that it could be explained by the different compactions (bulk densities) between them.

Bartoli et al. (2011) also found that flow conditions, as well as fuel species, within the fuel bed appears to be important when analyzing combustion dynamics of porous fuels, such as pine needle litters. Flow conditions play roles in both heat and mass transfer (Schemel et al., 2008) and it is recognized that geometrical characteristics of fuel induced changes in flow conditions. Fuel geometry is also recognized as a possible source of difference between artificial fuel beds and natural litters by Fernandez-Pello et al. (2014).

Catchpole et al. (1998) performed 357 experimental forest fires in a large scale wind tunnel and found that packing ratio, diffusivity and fuel arrangement may have played an important role influencing spread rate.

As permeability is a measure of the ability of a medium to allow a flux through it and is dependent only on the geometry of the medium, it is in accordance with the reviewed literature that permeability is a key parameter influencing flammability metrics.

In mathematical terms permeability is a constant (for a material, no matter the fluid going through it) that relates pressure drop along the material whit fluid velocity. Darcy's expression is the simplest form, and can be stated as showed in Equation (1) (Jaganathan et al., 2008b; Spielman & Goren, 1968).

$$-\frac{dP}{dX}=\frac{\mu}{k}v \tag{1}$$

where P is pressure, X is the direction in which pressure is being measured, μ is fluid dynamic viscosity, v is fluid velocity and k is permeability.

Equation (1) is valid only for Darcy flow (or creeping flow), where low velocities are predominant making inertial terms negligible. Forchheimer introduced a power law term (Papathanasiou et al., 2001), usually used as a second order term to represent the macroscopic inertial effect, resulting in Equation (2) in its one dimensional form (Miguel et al., 1997; Molina-Aiz et al., 2006; Teitel et al., 2009; Valera et al., 2006).

$$-\frac{dP}{dX}=\frac{\mu}{k}v+\rho\left(\frac{Y}{\sqrt{k}}\right)v^2 \tag{2}$$

In Equation (2), ρ is fluid density and Y is the inertial factor.

Criteria are presented by Z. Zeng and R. Grigg (2006) to decide which of the two previous equations is better to use according to flow conditions based on a modified Reynolds number and a Forchheimer number. In their study they recommend to use a revised Forchheimer number (see Equation (3)) to determine what kind of flow is present in a porous media.

$$F_o=\frac{k\beta\rho v}{\mu} \tag{3}$$

In Equation (3) the term β is calculated as shown in Equation (4).

$$\beta=\frac{Y}{\sqrt{k}} \tag{4}$$

They concluded that a good reference for a critical Forchheimer number is 0.11, meaning that under this value inertial terms are negligible, hence being under Darcy flow conditions.

According to the work presented by Jaganathan et al. (2008a) and by the work presented by J.R. Fanchi (2008) and Z. Huang et al (2011), permeability of porous media is better represented by a tensor than by a single number because depending on the directional characteristics of the medium its anisotropy may affect flow conditions. As seen before, radiata pine needle litters are qualitatively anisotropic, so *a priori* a permeability tensor would be a better way of characterizing this measure.

An original experimental procedure was established in order to measure radiata pine litters permeability, for both artificial and natural cases.

Along with measuring the principal permeability tensor components to better see practical differences between natural and artificially reconstructed radiata pine forest litters, combustion tests were performed with both kinds of fuel beds.

In general, litter combustion has three main stages, ignition, propagation and extinction. Two kinds of ignition exists: piloted ignition and non-piloted or spontaneous ignition (Mindykowski et al., 2011). Since human related activities causes the majority of wildfires, and a big portion of said wildfires are intentional, piloted ignition would be a better way to study wildfire behavior. Two kinds of combustion are also recognized: flaming combustion and glowing combustion or smoldering. It is common in fuel beds with high moisture content to present smoldering and having flaming combustion when its moisture content is lower. It is also common to have intermittent changes between one state and the other (Hepp, 2009; Valdivieso & Rivera, 2013; Valdivieso, 2010).

Ignition probability as well as fire propagation are highly affected by fuel moisture content (Varner et al., 2015; Viegas et al., 2012; Yin et al., 2012) and wind velocity (Catchpole et al., 1998; Valdivieso & Rivera, 2013). Fuel moisture content as well as pyrolysis are influenced by wind temperature, as it affects heat transfer.

Combustion tests were carried out following procedures made by Hepp (2009) and Valdivieso (2010), slightly modifying the apparatus and fuel beds used. Main measured parameters were related to ignition conditions and fire spread velocity while having similar wind velocity, wind temperature and fuel moisture content.

1.2 Main Objectives

As stated previously, studying wildfire behavior is important, and improving its experimental set-ups is necessary as they serve directly as input in mathematical models and computational simulations. Considering the importance of pine litters in wildfires and in particular radiata pine litters in the Chilean context, we present a method for sampling pine needle litters and a quantitative comparison between them and litters as used traditionally.

The new proposed method of litter sampling was designed to be able to test natural undisturbed forest litters with LH, FH and a layer of soil, in order to be able to replicate the complexity of wildfires more accurately under laboratory conditions.

The quantitative comparison is meant to establish differences in combustion related metrics that have influence over their behavior and see if fuel bed structure matters in fire spread velocity. The comparison was made by measuring the permeability and by making combustion tests to both natural litters, sampled by our proposed method, and artificial litters, constructed as usual.

2. PERMEABILITY AND FIRE SPREAD IN NATURAL AND ARTIFICIAL PINUS RADIATA FOREST LITTERS

2.1 Introduction

In wildfire research, it is common to use artificially reconstructed forest litters to measure flammability related metrics under laboratory controlled conditions (Bartoli et al., 2011; Catchpole et al., 1998; Fernandez-Pello et al., 2014; Hepp, 2009; Jervis & Rein, 2015; Manzello et al., 2006; Mindykowski et al., 2011; P. A. Santoni et al., 2014; Schemel et al., 2008; Valdivieso & Rivera, 2013; Valdivieso, 2010; Viegas et al., 2012; Yin et al., 2012).In the forest, leaves or needles from the litter are collected, stored in bags or boxes, and transported to the laboratory, where they are conditioned. Then, they are arranged by hand in a sample holder before testing. It is important to notice that only leaves, dead or fresh are used (Jervis & Rein, 2015) and not any other litter component commonly present in actual forest litters.

In artificially reconstructed litters it is seen that needles laying on any plane, for instance, horizontal or vertical, are randomly oriented (see Figure 8).

Figure 8: Artificial litter have randomly oriented needles in any plane, for instance a vertical plane (left) or a horizontal plane (right).

Figure 9: A natural litter has other components besides needles, and their orientation depends on the plane in which they are seen. Needles seen vertically (above) are randomly oriented, but those seen horizontally (below) have a preferential horizontal orientation.

Natural forest litters have a different composition and structure. Indeed, besides needles there are seeds, branches, twigs, roots, fungus and decomposing fuel, as shown by Figure 9 and Figure 11; this agrees with observations made by Varner et al. (2015). It is also seen that in natural litters needles seen vertically are randomly oriented, but those seen horizontally have a predominantly horizontal orientation (see Figure 10). This particular arrangement is produced because, when needles fall from the tree, most of them rest almost flat on the ground surface. It is worth noting that for sloping grounds, the “horizontal” plane actually is the ground surface plane.

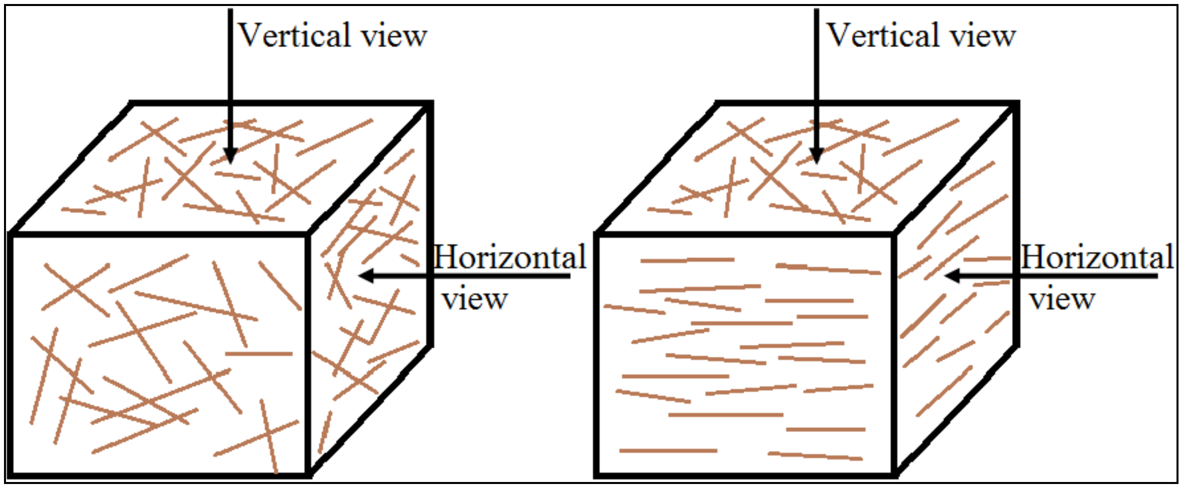

Figure 10: A representation of an artificially reconstructed litter (left) and a natural litter composed both only by needles.

Figure 11: Some of the principal litter components: live pine needles (a), dead pine needles (b), seeds (c), litter in decomposition process (d) with fungus (c), branches (f), twigs (g) and roots (h).

There is only one research that studied the differences between natural and artificially reconstructed litters (Ganteaume et al., 2014; Varner et al., 2015). That study found big discrepancies in some flammability metrics, principally in combustibility and consumability. The authors state that this might be explained because of different compaction or bulk density. Only few studies are available with natural forest litters in combustion research under laboratory conditions (Curt et al., 2011; Ganteaume et al., 2014, 2011; Varner et al., 2015).

Permeability, a property of porous materials that relates pressure drop with the velocity of the fluid flowing through them, has been found to be a key parameter influencing the rate of heat release (P. A. Santoni et al., 2014) when a flow is imposed through the fuel bed, as it increases the oxygen flow to the combustion front. Moreover permeability is an important parameter for smoldering behavior (Rostami et al., 2003) because of its effect on heat and mass transport, which agrees with other studies on porous fuels (He & Behrendt, 2011).

Other studies show that geometry related parameters of fuel itself or of the fuel bed are important to some flammability metrics (Fernandez-Pello et al., 2014; Varner et al., 2015). Bulk density, diffusivity and fuel arrangement are listed among the possibly most important aspects guiding spread rate by Catchpole et al. (1998). Flow conditions within the fuel bed, as well as vegetal species in it, might be important in combustion dynamics analysis of porous fuels (Bartoli et al., 2011), as they influence both heat and mass transfer (Schemel et al., 2008).

It is important to notice that despite of permeability being a known parameter affecting burning behavior in flow forced experiments; it is unknown yet the degree of influence of permeability in fire spread with surface winds.

There are no extensive investigations on how much soil moisture changes forest litter combustion dynamics, or on the interaction between the different naturally occurring layers within the fuel bed. We developed a sampling method that allows collecting almost undisturbed natural forest litter samples, and safely transporting them, different from the one described in other works (Curt et al., 2011; Ganteaume et al., 2014, 2011). The samples include the leaf layer or leaf horizon (LH), the layer of partially decomposed leaves or fragmented horizon (FH) and a layer of soil. Thus, when experimenting, all these unknown relations between different litter components will be already incorporated in the results. It is important to notice that Ganteaume et al. (2014) included a humus layer, defined as the “upper part of the humus layer”, but in our case that layer was commonly thin and in most cases was included entirely between FH and the called soil layer.

We also present a quantitative comparison between artificially reconstructed litters sampled as stated in most of previous works and natural litters sampled with our method. To make the comparison and to see if the litter structure affects the fire behavior, we measured the permeability of those litters, carried out combustion tests following procedures from Hepp (2009) and Valdivieso (2010) and related metrics from both experimental set ups with a mathematical model.

2.2 The Forest and its Litter

The sampling sites were located in the central zone of Chile, close to the sea shore (34°36’10.63’’S 71°52’18.67’’O). This region has a temperate Mediterranean climate with a prolonged dry season, and the last five years have been drier than average. The samples were all taken within the same forest, consisting of about 5 hectares growing 25 years old commercially planted radiata pine trees. The age of the forest was chosen because according to Forrest and Ovington (1970), radiata pine litters are expected to reach a stable depth after the trees are 12 years old. But as Forrest’s study is valid for forests located in the Tamut region in Australia, we opted to choose a more mature forest to be sure the litter would not change its depth between two successive sampling campaigns. The measured average depth of LF and FH together was 20 mm. Another advantage of a mature forest is that the last thinning was practiced at least 10 years ago, so the litter has remained untouched for years. No other species of trees were observed within the forest and almost no undergrowth was seen. There were other species growing in the forest limits and their leaves were observed in the forest litter. The only other species observed in abundance were fungus in the FH. It is important to mention that fungus was present in almost all samples, having a notable effect of consolidating the litter components (like some sort of glue).

2.3 Sampling Method

The sampling method is a nine-steps process and each sampling site must fulfill four basic requirements. The requirements are to be at least one meter away from the more external part of the trunk of any species that may be present, to be at least 20 meters away from the nearest road, path or forest limit, not to disturb the sampling site and in case of sampling in a site that has any special particularity (being in a forest clearing for example) it is mandatory to clearly identify the specimen and the particularity noticed.

The process consist basically in placing a wooden tablet on top of the selected sample site (so it does not get disturbed when working on it) and remove a sample containing the LH, FH and soil layer with a knife and a panel like knife to then store it safely in a container. We opted to store the samples in cardboard pizza boxes for convenience.

A detailed guide on how to obtain almost undisturbed radiata pine forest litter samples is available in Appendix A.

2.4 Permeability Specimens

To better characterize litter permeability, two different kinds of specimens were prepared for natural forest litters and one kind for artificially reconstructed litters. The two natural litter specimens are for measuring permeability in the vertical direction (vertical permeability specimens, VPS) and in the horizontal direction (horizontal permeability specimens, HPS). Three identical specimens were prepared for statistical significance.

To prepare the natural litter specimens, we assumed only LH and FH were relevant for permeability measurement, as soil is expected to be orders of magnitude less permeable. Since soil is also deeper than the fuels, mass transport phenomena through it should not be as relevant for fire propagation as through the fuel bed.

The specimen preparation is a slow, time consuming process that requires effort, patience and practice. A lot of samples were not finally used because during preparation they were disturbed. It is also important to notice that there is no clear limit between the layers or horizons described within the fuel bed, with the exception the fungus layer, when present, being clear the boundary between this layer and the inorganic soil. In those cases, as fungus is composed of organic materials, it was completely considered as fuel and as part of the FH.

To obtain vertical permeability specimens (VPS) and horizontal permeability specimens (HPS), the first step is to remove the soil layer from the samples with aid of a knife and a wire mesh, resulting in “clean samples”. For VPSs, the clean sample is then put in a wooden frame filled with resin, and in the case of HPSs, several clean samples are piled up and then put in a wooden frame filled with resin.

To obtain artificially reconstructed litter permeability specimens (APS) a wooden frame is constructed and filled with pine needles by letting them freely fall into it. Then the frame is filled with resin.

In all permeability specimens the function of resin is to hold litters in position in the frame and for all of them there is an area of free flow through the litters of 200x200 mm.

Detailed indications on how to obtain and construct vertical permeability specimens (VPS), horizontal permeability specimens (HPS) and artificially reconstructed litter permeability specimens (APS) are available in Appendix B, Appendix C and Appendix D, respectively.

Figure 12: Pictures of finalized VPS (a), HPS (b), APS (c).

2.5 Permeability Tests

Permeability is a property of porous materials that relates pressure drop with the velocity of the fluid flowing through them. To measure permeability we used a small-scale wind tunnel, equipped with an S-type Pitot tube and a differential pressure gauge, to measure pressure difference across the specimens. The S-type Pitot tube is connected to a pressure sensor (OMRON, USA) model D6F-PH25AD1 capable to measure from 0 to 250 Pa with 3% error. The pressure drop sensor, model D6F-PH0505AD3 (OMRON, USA), has a range of -50 to 50 Pa, also with 3% error. They are both connected to a computer that records the measurements through an Arduino UNO (Arduino, Italy) interface. Wind velocity is controlled with an inverter (ABB, Swiss) model ACS150. There is also a water column differential pressure meter (Dwyer, USA), used to randomly verify the differential pressure gauges, and a hot wire anemometer (Testo, Germany), used to double check in almost every test the wind velocity. A diagram of the experimental set up can be seen in Figure 13.

The test section of the wind tunnel is 400x400 mm, but once the specimen is in the sample holder, the flow area is only 200x200 mm.

Each specimen was tested with at least 8 different velocities, repeated three times each, and recorded more than one data of velocity and one data of pressure per second, for no less than five minutes. Between any changes in wind velocity no less than 90 seconds were waited in order to have a stable flow.

After the three repetitions were carried out with a specimen, all forest litter contained in the 200x200mm projected area was removed, weighted and the tests were repeated to measure the frame-sample holder system permeability and pressure loss at the same wind velocities used before.

To know the wind tunnel's velocity profile, an imaginary rectangular mesh of 48 points was imposed for one VPS frame and one HPS frame. In each point velocity was measured three times at four different velocities and related to a velocity measured where the wind velocity sensors were in the official tests. With the measured velocity profiles a Lagrange interpolation was performed to have finer results, and flow variables were thus calculated. As every specimen has a known projected area, average velocity through them was calculated as

$$\bar{v} = QA_p \tag{5}$$

Where $\bar{v}$ is average velocity, Q is flow and A_p is that particular specimen projected area.

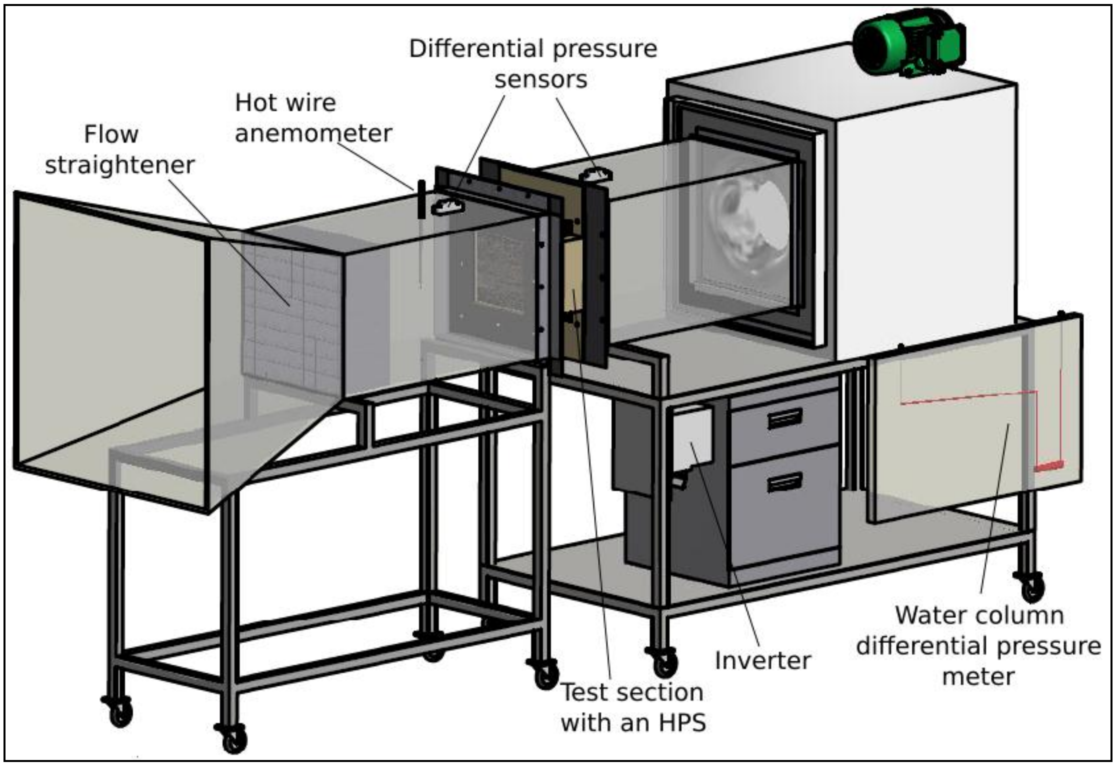

Figure 13: Permeability test set up.

2.6 Combustion Specimens

Two kinds of combustion specimens were made, one made with moisturized samples taken with a 320x150 mm wooden tablet (see Appendix A) , or natural litter combustion specimens (NLCS) and one made as traditionally described in most literature, where only a selected LH with added moisture is organized by hand in the sample holder, called artificially reconstructed litter combustion specimen (ARCS).

Fuel moisture content is widely recognized as a main factor in ignition probability and other flammability related metrics (Manzello et al., 2006; Varner et al., 2015; Viegas et al., 2012; Yin et al., 2012), hence a controlled moisture content is needed to perform the tests.

For NLCS the entire carboard box that contained the original samples was weighed, then about 200 grams of water were added evenly on top of LH with a sprinkler and finally it was sealed and stored in a plastic bag for no less than 30 days as the absorption of water by radiata pine needles is slow (Hepp, 2009; Valdivieso, 2010). In the case of ARCS 50 grams of radiata pine needles were put in plastic bags, then 100 grams of water were added with a sprinkler and the plastic bag was sealed and stored for no less than 30 days. In both cases the samples came with almost no moisture content before adding water to them. This was determined by oven drying some specimen for 24 hours at 80°C and comparing their weights before and after, concluding that if a change in mass occurred it was smaller than the scale resolution, or within its error bounds.

To have a specific level of moisture and to recreate a realistic scenario NLCS were put in the combustion wind tunnel's sample holder and dried with moderate velocity (around 3,5 m/s) and around 38°C in temperature until a wanted and previously determined moisture content was reached in order to see its effects. In the case of ARCS they were dried in an oven that allows a flux of air, at 80°C until a wanted moisture content was reached.

A gravimetric analysis was performed to know the moisture content with precision, by oven drying at 80°C for 24 hours a small part of each specimen, taken moments before the test started. To check before the combustion test, a quick analysis was carried out comparing the dried mass of the samples and the weight measured in a given instant.

As the combustion wind tunnel's sample holder measures 600x150x40 mm, two forest samples of 320x150 were put inside and the portion that did not fit into it was cut and used to determine the moisture content more accurately.

To have the ARCS ready for the test, a previously determined and moisturized amount of needles (100 or 150 grams in dry weight) were evenly distributed in the entire sample holder.

The ignition was attempted with a wooden stick with dimensions 2x2x15 mm impregnated with alcohol and put at the beginning of the specimen with dried pine needles around it.

2.7 Combustion Tests

Combustion Test were performed in a combustion wind tunnel designed and constructed by Hepp (2009), but two modifications were made. The S-type Pitot tube was replaced with a hot wire anemometer (TESTO, Germany) and the eight thermocouples were replaced by others with a fire resistant protection and instead of being inserted from under the sample holder they were inserted from the upper face of the wind tunnel because of the soil layer of NLCSs. In Figure 14 a view of thermocouple's positions is shown. The wind temperature is modified by 16 quartz heaters of 500 W each, 15 of which are individually controlled with switches. The other one is connected to the voltage drive that controls the fan velocity. Data gathered with the thermocouples was registered in a computer through an OPTO22 data acquisition system. Every test was video recorded from the same position. The set up can be appreciated in Figure 15.

For every test a wind velocity around 2,88 m/s and a wind temperature of around 28°C was previously set. Seven tests with NLCS were made and six with ARCS.

Once the specimens were ready in the wind tunnel's test section, thermocouples were set in a way such that their tips were 35 mm above the bottom of the sample holder.

Ignition of the 2x2x15 mm stick was attempted with an oven gas lighter and this marked the start of the test.

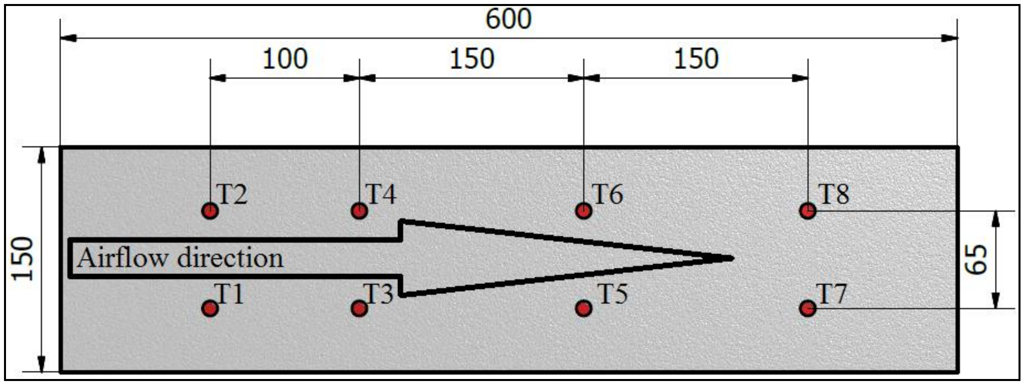

Figure 14: Diagram of thermocouple's position in the specimen holder view from above, measures in millimeters.

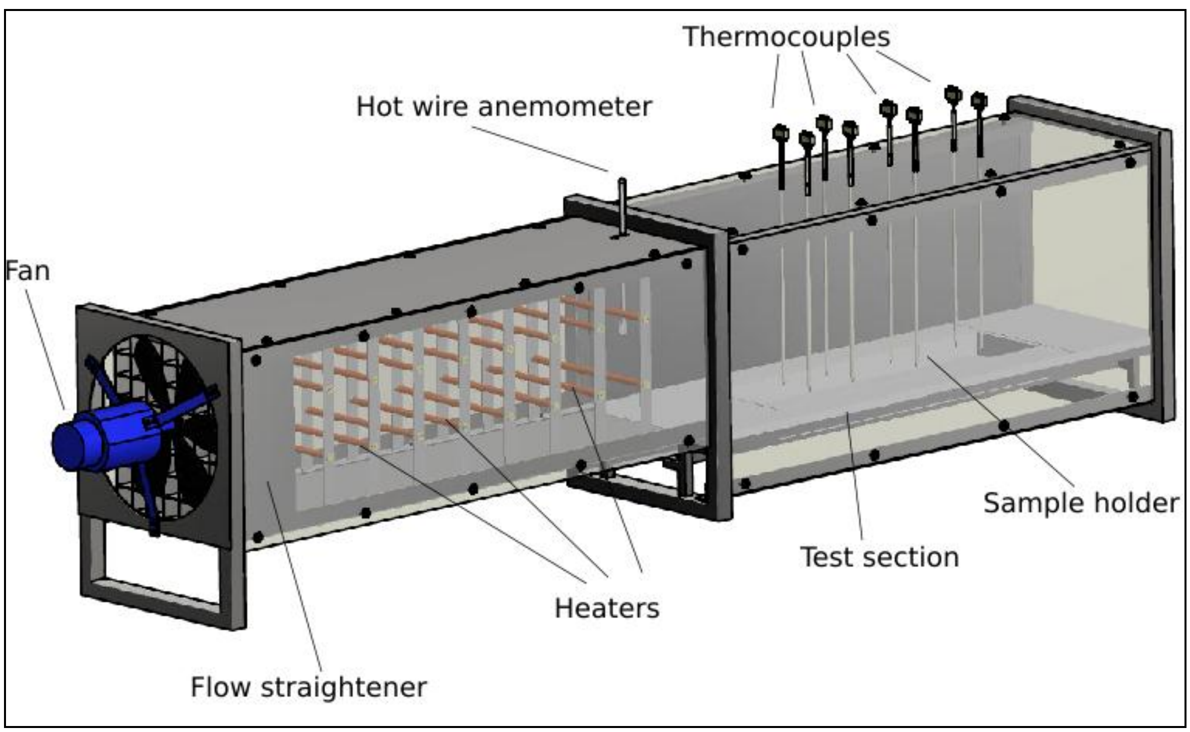

Figure 15: Combustion tunnel set up.

2.8 Results and discussion

In this section's graphics and tables we will denote VPSi, HPSi, APSi for the vertical, horizontal and artificially reconstructed permeability specimen number "i" respectively and NLCSi and ARCSi for natural litter combustion specimen and artificially reconstructed litter combustion specimen number "i" respectively.

2.8.1 Permeability results

After tests were performed, all measured variables were filtered by two conditions: in two consecutive measurements, the second one must be contained in a 15% radius from the value of the first one and only the first 500 data were taken into account for each variable at each velocity. Data gathered with differential pressure gauges with a value far out of their measure range was eliminated as an additional condition.

We worked with average values for each specimen at each different velocity, because no substantial difference was observed in any of the three repetitions made for each point in all cases.

In mathematical terms permeability is a constant (for a material, no matter the fluid going through it) that relates pressure drop along the material with fluid velocity. Darcy's expression is the simplest form, and can be stated as showed in Equation (6) (Jaganathan et al., 2008b; Spielman & Goren, 1968).

$$-\frac{dP}{dX} = \frac{\mu}{k} v \tag{6}$$

where P is pressure, X is the direction in which pressure is being measured, μ is fluid dynamic viscosity, v is fluid velocity and k is permeability.

But Equation (6) is valid only for Darcy flow (or creeping flow), where low velocities are predominant making inertial terms negligible. Forchheimer introduced a power law term (Papathanasiou et al., 2001), usually used as a second order term to represent the macroscopic inertial effect, resulting in Equation (7) in its one dimensional form (Miguel et al., 1997; Molina-Aiz et al., 2006; Teitel et al., 2009; Valera et al., 2006).

$$-\frac{dP}{dX} = \frac{\mu}{k}v + \rho\left(\frac{Y}{\sqrt{k}}\right)v^2 \tag{7}$$

In Equation (7), ρ is fluid density and Y is the inertial factor.

To see which of the two previous equations apply, depending on flow conditions, criterions are presented by Z. Zeng and R. Grigg (2006) based on a modified Reynolds number and Forchheimer number. In their study they recommend to use a revised Forchheimer number (see Equation (8)) to determine what kind of flow is present in a porous media.

$$F_o = \frac{k\beta\rho v}{\mu} \tag{8}$$

In Equation (8) the term β is calculated as shown in Equation (9).

$$\beta = \frac{Y}{\sqrt{k}} \tag{9}$$

They concluded that for a Forchheimer number under 0.11, inertial terms are negligible and, hence, the flow is in Darcy regime.

When plotting velocity against pressure drop (Figure 16), it is clear that a lineal approximation does not correlate well these two variables. This excludes using Darcy law in our entire data spectrum.

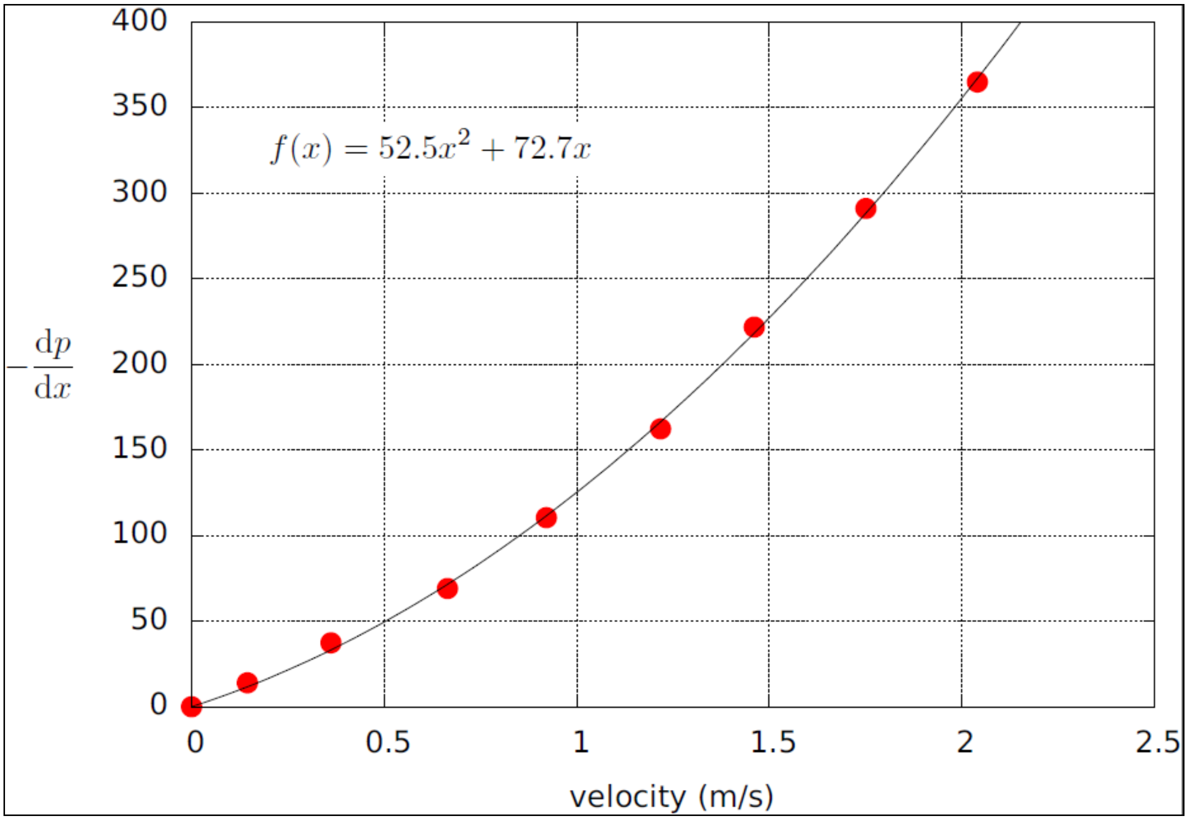

Figure 16: Pressure drop across a specimen with various velocities. Using a modified Forchheimer equation we obtained values of $R^2 = 0.9995$ for this specimen.

When using a modified Forchheimer equation (Equation (10)) a good fit was found.

$$-\frac{(\Delta P_p - \Delta P_f)}{\Delta X} = \frac{\mu \bar{v}}{k} + \beta \rho \bar{v}^2 \tag{10}$$

Where ΔP_p is differential static pressure before and after a specimen, ΔP_f is differential static pressure before and after the respective frame without litter in its inside and $\bar{v}$ is the average air velocity within the litter.

The fluid's dynamic viscosity was interpolated as function of temperature, and its density was calculated from the ideal gas law.

In Table 1 principal measured and calculated permeability related variables are presented. Both values of permeability and associated constants were obtained by adjusting a polynomial to measured data.

Table 1: Principal measured and calculated parameters.

Specimen name	Bulk density	β	$\boldsymbol{k}$	$\boldsymbol{k_{Darcy}}$	$\boldsymbol{Y}$	Critical velocity
	$kg \cdot m^{-3}$	m^{-1}	m^2	m^2	$-$	$m \cdot s^{-1}$
APS1	27,4	44,5	2,52E-7	1,91E-7	0,022	0,15
APS2	44,2	101,2	8,23E-8	5,91E-8	0,029	0,19
APS3	21,4	40,3	4,53E-7	-	0,027	0,09
HPS1	53,8	119,7	9,15E-8	7,73E-8	0,036	0,14
HPS2	64,5	113,1	9,71E-8	7,03E-8	0,035	0,15
HPS3	74,4	92,5	6,36E-8	5,73E-8	0,023	0,28
VPS1	34,9	2,1	1,53E-7	1,43E-7	0,001	5,28
VPS2	40,0	142,9	1,03E-7	-	0,046	0,11
VPS3	38,8	53,2	9,44E-8	2,59E-7	0,016	0,33

Note: Bulk density was calculated by dividing the sample's mass contained in the test zone over test zone volume, k is the permeability calculated with Equation (10), k_{Darcy} is the permeability calculated with Equation (6), taking into account only velocities below their critical velocity when available, and Critical velocity is the maximum velocity at which Darcy flow conditions are presents according to criterions presented by Z. Zeng and R. Grigg (2006).

Air density and viscosity were very similar between tests. Also inertial factors are of the same order of magnitude between different specimens, with the exception of VPS1 as can be seen on Table 1. When comparing permeability measured with Darcy equation and modified Forchheimer equation, with exception of VPS3, both values are in the same order of magnitude and are similar when looking at any particular specimen. As can be seen in Figure 17, although only few specimens were tested, artificially reconstructed litters are the only ones that show a clear relation between permeability and bulk density. This proves that the process of reconstructing a litter is very likely to change litter permeability, hence it changes the experimental conditions and affects repeatability.

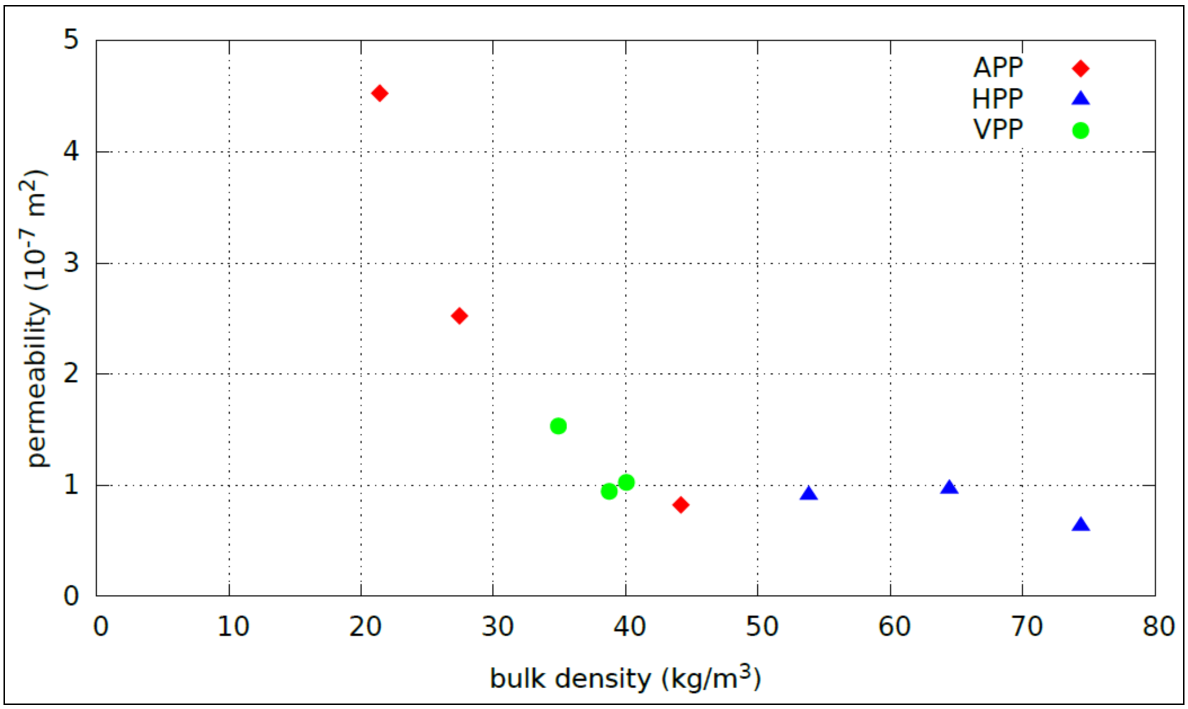

Figure 17: Permeability and bulk density.

In general it is seen that permeability in the horizontal direction is slightly lower than in the vertical direction.

Permeability results in average can be seen in Table 2. It seems that for radiata pine forest litters, permeability in the horizontal direction and in vertical direction differs in one order of magnitude, being more permeable in the vertical direction. It also seems that permeability from artificially reconstructed litters resembles more to vertical permeability than to horizontal permeability. It is important to notice that in natural forest fires the common situation is wind blowing in directions with low angles with a horizontal plane, so that the horizontal component of permeability is expected to play a more relevant role than vertical component.

Bulk density of HPSs might be higher because those specimens require 10 forest litter samples to be built, increasing the possibility to include higher density components that were not necessarily present in VPSs and APSs, as VPSs uses only one forest litter sample in its construction and APSs uses only pine needles.

Lower permeability values for HPSs can be explained because blockage of flux is more probable in the horizontal direction as in natural litters is not rare the presence of twigs or branches and their diameters are similar to the litter thickness. In VPSs if a branche, for example, is present it is easier for the flow to find another path.

Table 2: Average quantities of principal measured and calculated permeability related variables.

Specimen name	**Bulk density**	**β**	$\boldsymbol{k}$	$\boldsymbol{k_{Darcy}}$	$\boldsymbol{Y}$	**Critical velocity**
	$kg \cdot m^{-3}$	m^{-1}	m^2	m^2	$-$	$m \cdot s^{-1}$
APS	31,0	62,0	2,63E-7	1,25E-7	0,026	0,15
HPS	64,2	108,4	8,41E-8	6,83E-8	0,032	0,19
VPS	37,9	66,1	1,17E-7	2,01E-7	0,021	1,91

Santoni et al. (2014) experimentally calculated permeability for artificially reconstructed pine litters of three different species (none of them were radiata). Their results are also similar to our VPSs and APSs results and all of them are the same order of magnitude. They propose a model (see Equation (11)) to calculate permeability with geometrical information of the porous network based on the Carman-Kozeny model.

$$k_{ck} = \frac{\varepsilon^3}{20 \cdot (d/T)^4 (1-\varepsilon)^2 \sigma_p^2} \qquad (11)$$

In Equation (11) k_{ck} stands for permeability, ε for medium porosity, d for pine needle diameter, T for pine needle thickness and σ_p for surface to volume ratio. The term $20 \cdot (d/T)^4$ replaces the Kozeny constant.

In order to use Equation (11), we experimentally measured density, surface to volume ratio and porosity for both artificially reconstructed litters and for natural ones. Density was calculated by volume displacement and weighing samples, porosity was calculated with density and information from permeability specimens and surface to volume ratio (SVR) was determined following the procedure described by Fernandes and Rego (1998), using their same constant.

Equation (11) was applied with the values shown in Table 3, but resulted in a poor fit to experimental results. Kozeny's constant appears to be a major source of error in this case, but more data is needed in order to adjust its value.

Table 3: Measured and calculated parameters to use Equation (12).

Litter type	$\boldsymbol{d}$	$\boldsymbol{t}$	$\boldsymbol{\varepsilon}$	$\boldsymbol{\rho}$	**SVR**	$\boldsymbol{k_{ck}}$
	mm	mm	%	$kg \cdot m^{-3}$	m^{-1}	m^2
Natural	1,13	0,65	80,6	303,5	10696	9,18E-09
Artificially reconstructed	1,13	0,65	93,5	474,2	6461	1,80E-09

2.8.2 Combustion results

As thermocouples positions were known, fire spread velocity was calculated from temperature over time information (see Figure 18) and from video recordings. Videos were a very important source of information to determine which data point was valid, to confirm gathered data, to see how the combustion front reached each sensor and to see what peak temperature to take into account when more than one was observed.

The only specimen that did not ignite was NLCS2a, so it was exposed for a longer time to hot wind and the test was repeated and named NLCS2b in which only information from the farthest thermocouples were taken into account.

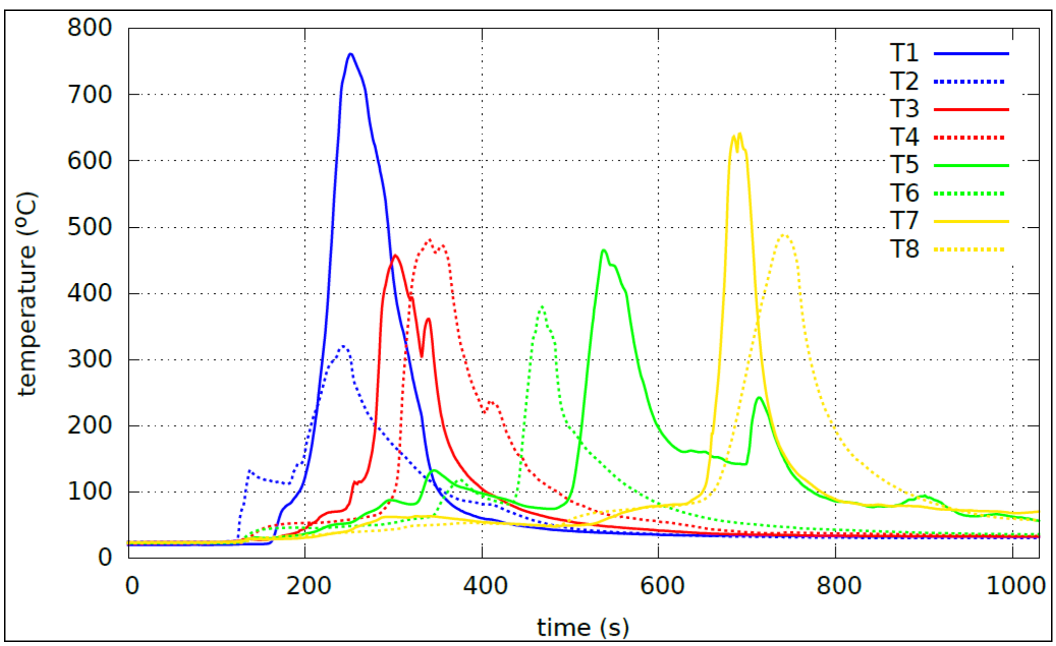

Figure 18: Example of temperature over time graphic to determine fire spread velocity of NLCS4.

Table 4: Combustion test results information.

Specimen name	Moisture content	Sample mass (dry weight)	Wind velocity	Fire spread velocity	Valid measure-ments
	%	kg	$m \cdot s^{-1}$	$m \cdot s^{-1}$	-
NLCS1	23,2	0,738	2,9	7,13E-4	4
NLCS2a	27,5	1,157	2,9		
NLCS2b	11,5	1,157	2,9	1,52E-3	1
NLCS3	25	0,924	2,8	4,92E-4	1
NLCS4	24,2	0,789	2,9	8,87E-4	8
NLCS5	9,3	2,686	2,9	6,13E-4	3
NLCS6	13,1	1,219	2,9	4,42E-4	2
NLCS7	16,4	0,650	2,9	9,33E-4	3
ARCS1	25	1,165	3,1	2,81E-3	3
ARCS2	25	0,100	2,8	2,94E-3	5
ARCS3	20	0,150	2,8	3,85E-3	8
ARCS4	20	0,100	2,8	2,26E-3	8
ARCS5	15	0,150	2,8	2,26E-3	8
ARCS6	15	0,100	2,9	2,26E-3	8

Results are presented in Table 4. It is important to notice that wind velocity is the value measured in the center of the tunnel and not the velocity within the litter. Valid measurements refer to how many pairs of thermocouples were used to determine fire-spread velocity in a particular test based on video recordings and temperature over time information, and moisture content for RLPCs includes the whole sample and not only the needles.

It can be appreciated that fire spread velocity in all ARCSs is one order of magnitude higher than in NLCSs, with the exception of NLCS2b. It was observed that ARCSs had a more stable combustion front, which translates in a higher quantity of valid measurements.

As NLCS2a was the only one that did not ignite when it got 27,5% moisture content, it might indicate that in natural litters the moisture content limit for ignition may be lower than in artificial litters (Hepp, 2009; Valdivieso & Rivera, 2013; Valdivieso, 2010). This has to be corroborated in a future study.

It can be seen in Figure 19 that moisture content and fire spread velocity have very different behavior in NLCS and ARCS. ARCSs were more stable, with the exception of ARCS3 and ARCS4, which were the only ones that showed different behavior when changing mass specimen at same moisture content.

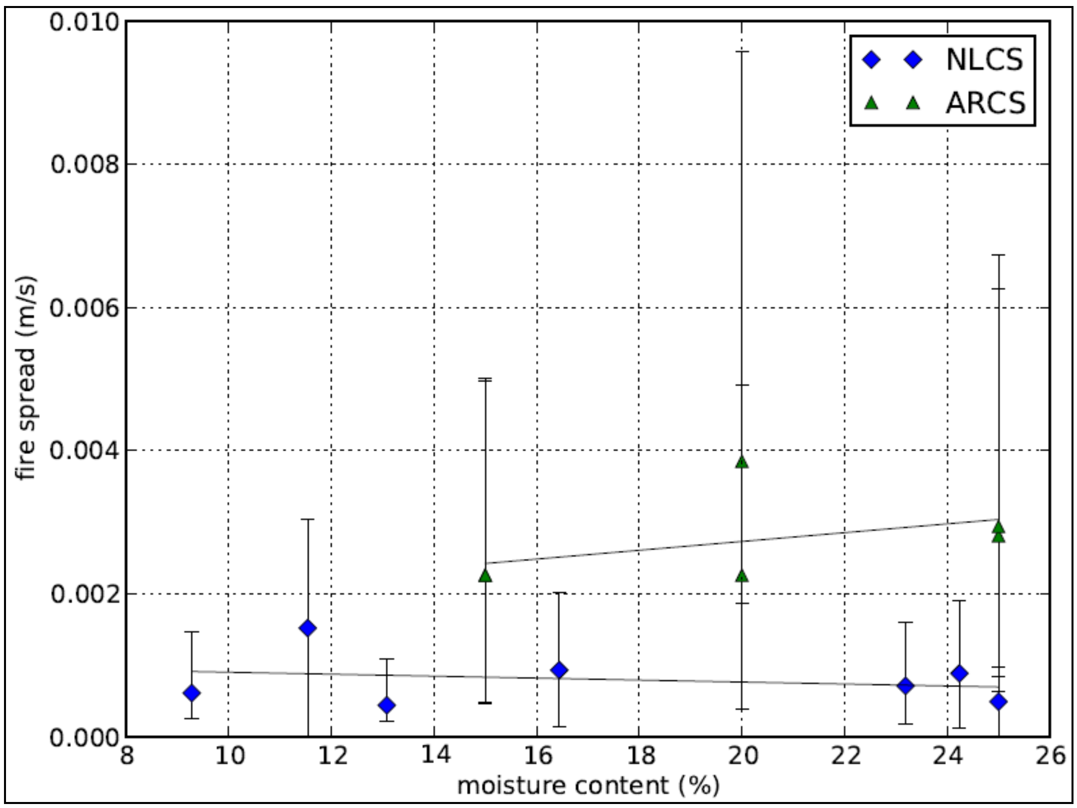

Figure 19: Fire spread velocity over total moisture content. Error bars show 95% confidence intervals.

Bulk density was not calculated in any specimen as there was going to be arbitrary when determining specimens height. Assuming that at least in all ARCS the change in height was proportional to change in mass, observations of Catchpole et al.

(1998) seems to be aligned with ours in the sense that height does not seem to be an important parameter influencing litter fire dynamics, or at least fire spread velocity.

It is important to point out the fact that not only permeability is different in ARCS and NLCS, but also composition, geometry, components, mass and density.

In Figure 20 it is shown a graphic comparison of some of the metrics presented in Table 3. In this figure, artificial litter values have been taken as the general case, as this kind of litter is the traditionally used in research. Traditionally it has been assumed that porosity and moisture content are some of the most important parameters influencing fire dynamics in forest litters, but as can be seen, despite of having similar porosities and moisture content, natural and artificial litters differ in one order of magnitude their fire spread velocity. In the other hand they present very different values for SVR, permeability and density.

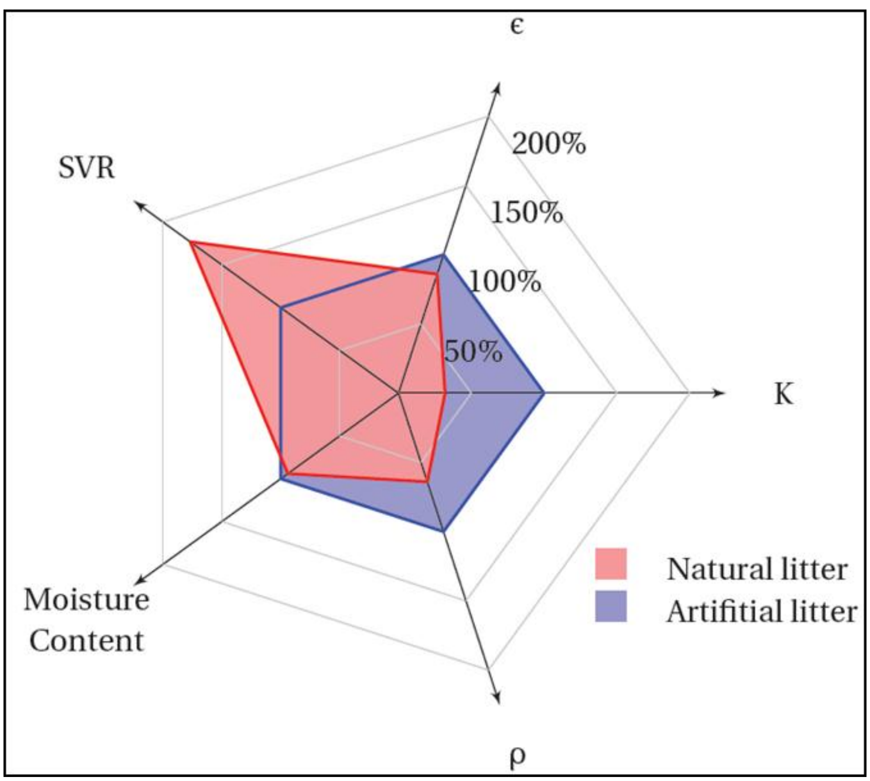

Figure 20: Graphic comparison of some of the metrics presented in Table 3

2.9 Relation between permeability and fire spread velocity

In order to have a better understanding of fire behavior, a mathematical model was used to establish a clearer relation between permeability and fire spread velocity. A simplified version of a model based on the work of Dosanjh et al. (1987) was presented by Rein (2005, 2009) and can be seen in Equation 12. The original equation was proposed for an opposed configuration, but it has been used for forward fire propagation as well.

$$u = \frac{\dot{m}''_{O_2} Q - \dot{q}''_{loss} \, {A_L}/{A_C}}{\rho_s c_{ps} (1-\varepsilon)(T_{sml} - T_0)} \tag{12}$$

In Equation 12 u is the propagation velocity, $\dot{m}''_{O_2}$ is the flow rate of oxygen per unit of area to the combustion front, Q is the energy released per unit of oxygen mass, $\dot{q}''_{loss}$ are the energy loses per unit area, ${A_L}/{A_C}$ is the heat loss coefficient, ρ_s is the density of the solid phase, c_{ps} is the specific heat of the solid phase, T_{sml} is the temperature of the smoldering front and T_0 is the temperature away from the combustion front.

If we assume flow conditions are similar to Darcy flow and that the pressure difference upstream and downstream the combustion front are due only to dynamic pressure, then the mean wind velocity within the combustion front might be stated as in Equation 13.

$$\overline{V}_{CF} = \frac{\rho_{air} v_0^2 K}{2\mu \Delta x_{CF}} \tag{13}$$

where ρ_{air} is the air density, v_0 is the wind velocity upstream and in front of the combustion front and Δx_{CF} is the width of the combustion front.

Assuming that the permeability of the combustion front is the same permeability of the litter itself and that the flow is parallel to the ground (i.e. using the horizontal permeability for natural litters), the flow rate of oxygen per unit of area can be stated as in Equation 14.

$$\dot{m}''_{O_2} = \frac{\rho_{O_2}\overline{V}_{CF}}{A_{CF}} = \frac{\rho_{air}^2 v_0^2 K X_{O_2}}{2\mu \Delta x A_{CF}} \tag{14}$$

where X_{O_2} is the mass fraction of oxygen in air and A_{CF} is the frontal area of the combustion front.

In order to have a more representative expression, we modified Equation 12 resulting in Equation 15.

$$u = \frac{\dot{m}''_{O_2} HC - L}{\rho_s c_{ps}(1-\varepsilon)(T_{sml} - T_0)} \tag{15}$$

where HC is the Huggett's constant and L is the term representing the energy losses, which was obtained by adjusting it to our experimental data.

The values used in Equations 13 to 15 are presented in Table 5. Air density was obtained using the ideal gas law at 28°C and the oxygen mass fraction in air was calculated assuming air is a mix with 21% oxygen and 79% nitrogen in volume. The combustion front width was estimated from video records and combustion front frontal areas where estimated from the litters depth and sample holder dimensions. To estimate the wind velocity in front and upstream the combustion front we measured velocity with the hot wire anemometer in the middle of the combustion tunnel's sample holder at different velocities, founding that velocity was 0.1 m/s slower than in the tunnel's measuring point. For specific heat a general value for soft wood was used (ASHRAE, 1977) and the combustion front temperature was calculated as an average of the thermocouples maximum readings, considering only those thermocouple's readings used to experimentally assess fire spread velocity.

Table 5: Values used in Equations 13 to 15.

Coefficients, variables and constants	Units	Numerical values	Coefficients, variables and constants	Units	Numerical values
ρ_{air}	$kg \cdot m^{-3}$	1.173	$A_{CF\_natural}$	m^2	3.00E-3
X_{O_2}	-	0.233	$A_{CF\_artificial}$	m^2	4.50E-3
μ	$Pa \cdot s$	1.84E-5	$v_{0\_natural}$	$m \cdot s^{-1}$	2.79
c_{ps}	$J \cdot kg^{-1} K^{-1}$	1380	$v_{0\_artificial}$	$m \cdot s^{-1}$	2.77
T_0	K	301	$T_{sml\_natural}$	K	615.7
HC	$J \cdot kg^{-1}$	1.31E+7	$T_{sml\_artificial}$	K	767.2
Δx_{CF}	m	0.02			

As can be seen in Table 6, Equation 15 presented good results when working with average values.

Apart from fire spread velocity, only the oxygen flow rate has an order of magnitude of difference between litters, but all the other equation components are very different between litters.

This model, despite of being simple, emphasizes the fact that both kinds of litters have quantitative differences. It also shows that permeability and fire spread velocity are related.

Further research in this topic is needed to assess how artificial litter experimentation can be improved or how to implement our sampling method in the commonly used apparatus.

Table 6: Results obtained with Equation 15.

Litter type	$\dot{m}''_{O_2}$	$\dot{m}''_{O_2} \cdot HC$	L	$\rho_s c_{ps}(1-\varepsilon)(T_{sml} - T_0)$	u	Experimental fire spread velocity
	$kg \cdot s^{-1} m^{-2}$	$J \cdot s^{-1} m^{-2}$	$J \cdot s^{-1} m^{-2}$	$J \cdot m^{-3}$	$m \cdot s^{-1}$	$m \cdot s^{-1}$
Natural	94.56	1.23879E+9	1.23877E+9	2.55670E+7	8.42E-4	8.00E-4
Artificial	194.74	2.55113E+9	2.55107E+9	1.98290E+7	2.70E-3	2.73E-3

2.10 Further work and study limitations

There is a need of having bigger sample space in all involved measurements in order to get empirical correlations between the metrics of interest.

It is important to notice that the sampling area was small, hence results must be taken as a comparison between the natural and the artificially reconstructed litter samples, and not necessarily representing the characteristic litter of the forest. Moreover we insist in the fact that these results apply only to the particular forest being studied, as it is unknown how litters from other locations will perform.

Despite efforts to explain this phenomenon it is unknown how in detail the sudden area reduction in the permeability measurements experimental set up affected the results, as it could have caused vortexes near the measurement points.

In the combustion experiments it is also unknown how the specimen moisture changed in time once the experiment started, as not every test had the same duration and this could be a potential error source. For NLCSs it is not clear how moisture content is distributed within the different layers and further research is needed to determine critical moisture content that allows combustion in natural litters.

Despite of permeability being a known parameter influencing burning behavior in flow forced experiments; it is unknown yet the degree of influence of permeability in fire spread with real surface winds.

It is not clear how invasive our sampling method is, despite of being designed to get undisturbed litters. The effectiveness highly depends on the sampling ability of the people recollecting them.

2.11 Conclusions

In consideration of available gathered data, APSs are similar to VPSs in terms of permeability, and HPSs are less permeable than both. APSs showed a clear dependence on bulk density over permeability, relation not seen in our sample space over VPSs and HPSs. VPSs seems to have a similar behavior with APSs in terms of permeability and bulk density.

HPSs showed out of trend bulk density compared with VPSs and APSs. This might be explained because ten times more forest litter samples are needed to construct HPSs than to construct VPSs, hence the probability of including higher density litter components is also higher.

The procedures to construct and handle natural litter specimens here presented are detailed and easy enough to be replicated in almost any species, although they were thought to be used in pine needle litters and could be simplified when used in other kind of vegetation. In our case, proposed sampling method and specimen construction proved to be an effective way to get almost undisturbed radiata pine litters to a laboratory and work with them. Once in laboratory, no qualitative differences were observed between our samples and natural forest litters.

In combustion tests ARCSs presents a faster (one order of magnitude higher) and a more stable combustion front than NLCSs. NLCSs fire dynamics seem to be affected by different factors than ARCSs, which seems to be mainly fuel moisture content. These other factors might be the presence of other vegetal species and other litter elements, as well as the soil playing a more important role when it has certain moisture content.

Permeability was not the only quantitative difference between natural and artificially reconstructed litters, important differences were also observed in litter density, porosity and surface to volume ratio, being natural litters less porous, less dense and with a higher surface to volume ratio than artificially reconstructed ones. These differences might explain differences seen in fire spread velocity.

It is necessary to perform more tests to better understand the different behavior of artificially reconstructed and natural litters, and to validate our results. Additionally, it is necessary to measure more variables in combustion tests for better statistical analysis.

As seen in Section 2.9, a mathematical model linking permeability and fire spread velocity was used showing more differences between both kinds of litter. The model also showed that permeability and fire spread velocity are connected through the oxygenation rate, an important parameter when studying fire behavior (Bartoli et al., 2011; He & Behrendt, 2011; Rostami et al., 2003; P. A. Santoni et al., 2014; Schemel et al., 2008).

Further research in general in this topic is needed to assess how artificial litter experimentation can be improved or how to implement our sampling method in the commonly used apparatus.

2.12 Acknowledgements

We want to thank to Ramón Mella Mella and his son Ariel for giving all needed help every time we needed to go sampling into their forests. We also want to acknowledge the contribution of Andes Iron SpA that permitted the construction of the wind tunnel used to measure the permeability of the fuel beds.

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APPENDIX

APPENDX A: SAMPLING METHOD

Before sampling, one must be sure to fulfill four basic requirements about the sampling sites or sampling spots. The requirements are to be at least one meter away from the more external part of the trunk of any species that may be present, to be at least 20 meters away from the nearest road, path or forest limit, not to disturb the sampling site and in case of sampling in a site that has any special particularity (being in a forest clearing for example) it is mandatory to clearly identify the specimen and the particularity noticed.

The materials needed for the extraction of the samples are:

- One wooden tablet for each required sample size, with the same dimensions as a perpendicular projection of the required specimen. In particular we used two different dimensions for our tests: 320x150 mm and 320x320mm.
- One sharpened knife. A knife sharpener will be useful.
- A panel like knife (see Figure 21) to finally remove the sample from its location. It was specially designed and constructed to this purpose using AISI 1045 commercial steel. The width (100 mm in this case) may change according to soil and container characteristics.
- Transport and storing container. In spite of our sample sizes we found that rigid pizza boxes were convenient for their availability, price and required samples dimensions.

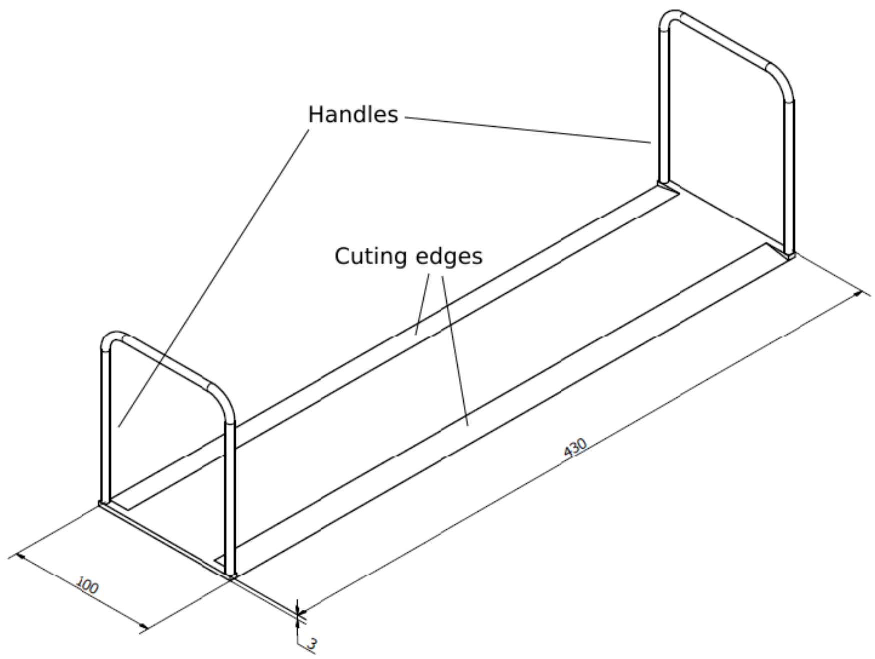

Figure 21: Panel like knife and principal dimensions in millimeters.

The sampling has the following nine-steps process. (i) Locate the sampling spot verifying that it fulfills the requirements. (ii) Without stepping onto the sampling spot, carefully place the wooden tablet on top of it. (iii) Put a big weight on top of the wooden tablet. Depending on the sample size, the person sampling can step on top of the wooden tablet and use his own corporal weight as he cuts out the sample. (iv) With the knife, cut as deep and as near the tablet edges as possible, following the tablet perimeter. (v) While still applying pressure on the wooden tablet, remove a portion of litter and soil around it. (vi) Remove the weight from the tablet and carefully take it away. (vii) With the panel like knife remove the sample from soil by cutting horizontally in a parallel plane to the plane containing the LH. It is important to control how deep the cut is made in order to have a good sample and making it possible to fit in the container. We cut at an approximate depth of 30 millimeters. (viii) Put the sample into the container without perturbing it. When using pizza boxes, the best way to do it was softly lifting a sample's edge while sliding the unfolded pizza box cover under it. Sliding was also the better way found to position the sample in place inside the container. (ix) Close the container and safely transport it, being careful in not putting too much weight on top of it so it would not be deformed in any way.

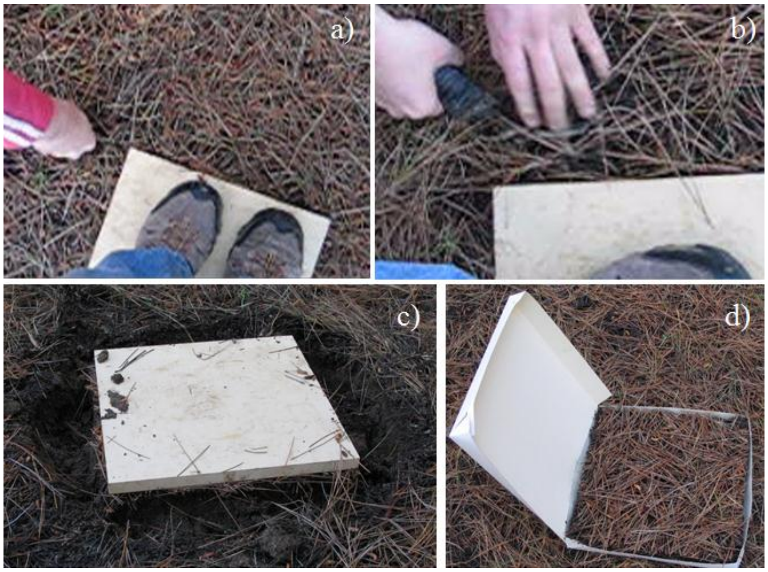

Figure 22: A quick review of the sampling process: cutting following the tablet edges (a), removing the soil around it (b and c) and finally removing the sample and storing it (d).

APPENDIX B: VERTICAL PERMEABILITY SPECIMENS (VPS)

To make these specimens we used the 320x320 mm samples in order to get an effective 200x200 mm undisturbed projected area to test.

Once in the laboratory, and checking that there is no noticeable disturbance in the sample to be used, the procedure was as follows. (i) The container was opened and a wire mesh (Figure 23a), with at least the same dimensions as the sample, was put on top the LH. (ii) With the container closed and applying pressure on the cover and on the bottom, the container was turned upside down and opened. (iii) With a sharp knife, as much soil as possible was removed making special care in not to touch or remove anything except soil. (iv) Another wire mesh with the same dimensions as the one on top of the LH was put, but this time on the bottom of the sample, that at this time was facing upwards. (v) Both meshes were sewed on all the edges with a thin metal wire, so LH and FH got held in between them without freely moving. The resultant sample at this point is called "wired sample". The chosen mesh must be rigid enough not to be deformed by its own and added weight but flexible and light enough not to compress the LH and LF excessively. (vi) The wired sample was then put with LH facing up, so that any rests of soil would fall down through the mesh. (vii) One edge of the wired sample was put inside a specially constructed holder as the one shown in Figure 23b and filled with resin up to the top. (viii) The rest of the frame was glued and every side filled with resin, being careful to fill it as much as possible. (ix) The corresponding changes were made in the frame so it could be put in a specimen holder. The specimen at this point looked like the shown in Figure 23c. Moments before putting the sample in the tunnel, the wire meshes must be removed by cutting them as near the frame as possible.

The 200x200 mm free area to test for permeability was chosen because it is big enough to be representative but small enough to ensure it would not fall apart when an air flux is imposed through it, mainly because of needles average length (124.1 mm).

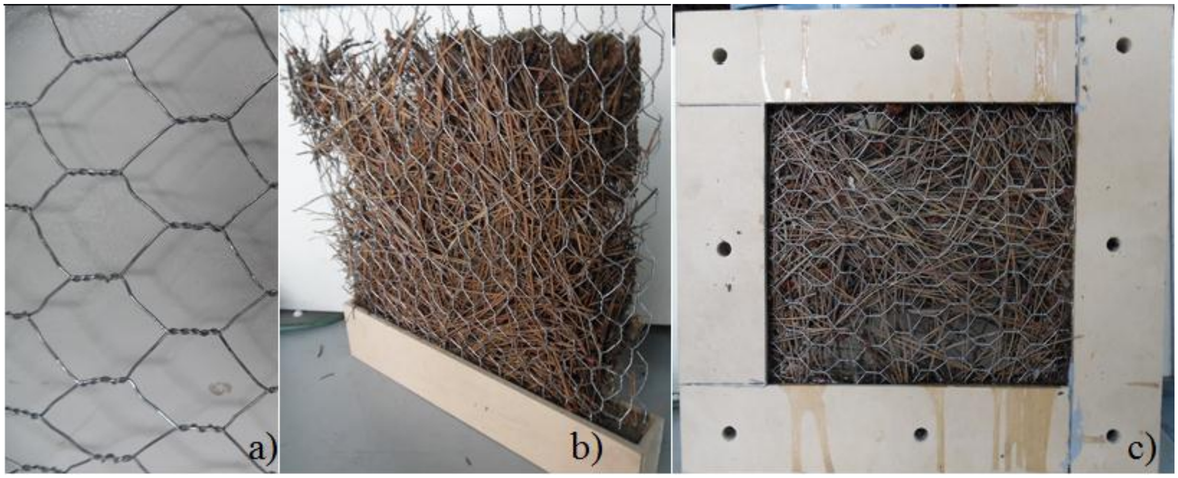

Figure 23: a) Photograph of the mesh used, b) the processed litter with the two meshes sewed, on the specially constructed holder and c) a view of the finished VPS.

APPENDIX C: HORIZONTAL PERMEABILITY SPECIMENS (HPS)

For these specimens we used the 320x150 mm samples to get 200x200 mm of projected area to test for permeability. To make this specimens the same process as with VPS was repeated until we completed the fourth step, then we continued as follows. (v) With the meshes on both faces of the sample and applying enough pressure, the sample was turned so the LH faces up, allowing the rests of soil to fall down. (vi) With care the mesh touching the FH was removed as the sample was deposited on a smooth surface (a polished wooden tablet). (vii) It was put in a meshed holder, like seen in Figure 24a, by carefully sliding it. (viii) Process was repeated until step seven was finished and then the resultant sample was piled up on top of the previously deposited processed sample inside the meshed holder. This was repeated until a height of at least 210 mm was reached. (ix) Once the meshed holder was closed (Figure 24b), it was put inside the specially constructed holder (Figure 24c) and filled to the top with resin. (x) The rest of the frame was glued and each side was filled with resin to the top. (xi) Needed changes in the frame were made so it could be put in a specimen holder. The specimen at this point looked like the shown in Figure 24d. A close up to the test section of the specimen can be seen in Figure 25.

Moments before putting the sample in the tunnel, the wire meshes must be removed by cutting them as near the frame as possible.

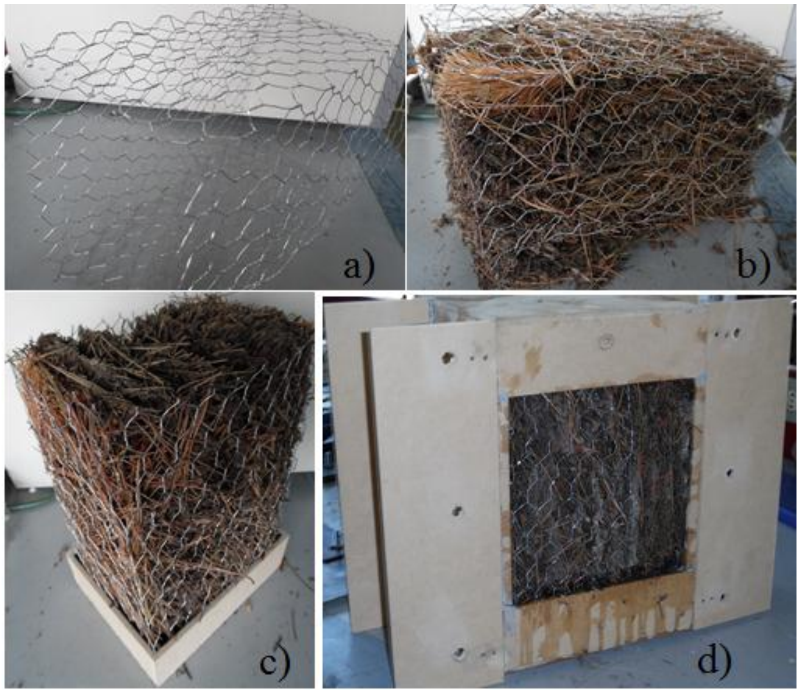

Figure 24: a) Meshed holder, b) meshed holder closed filled with processed litter samples, c) meshed holder in the specially constructed holder and d) HPS finalized.

Figure 25: Close up to the test section of a HPS specimen.

APPENDIX D: ARTIFICIALLY RECONSTRUCTED LITTER PERMEABILITY SPECIMENS (APS)

Three specimens of this kind were constructed, with three different bulk densities. The only litter layer component used was dead radiata pine needles from the same forest we took the unperturbed litter samples. The construction process was as follows. (i) The same mesh holder used for HPS was put inside an equal frame as used in that case, with a free side to allow filling it with needles. (ii) Pine needles were allowed to freely fall inside the holder until it was full to the top. To change bulk density, pressure was applied at constant intervals with the hand, so the litter got compressed. (iii) The rest of the frame was glued and each side filled with resin to the top. (iv) Needed changes in the frame were made so it could be put in a specimen holder.

These specimens also have 200x200 mm free projected area to test for permeability, because the same frame design was used as in the case of HPS.

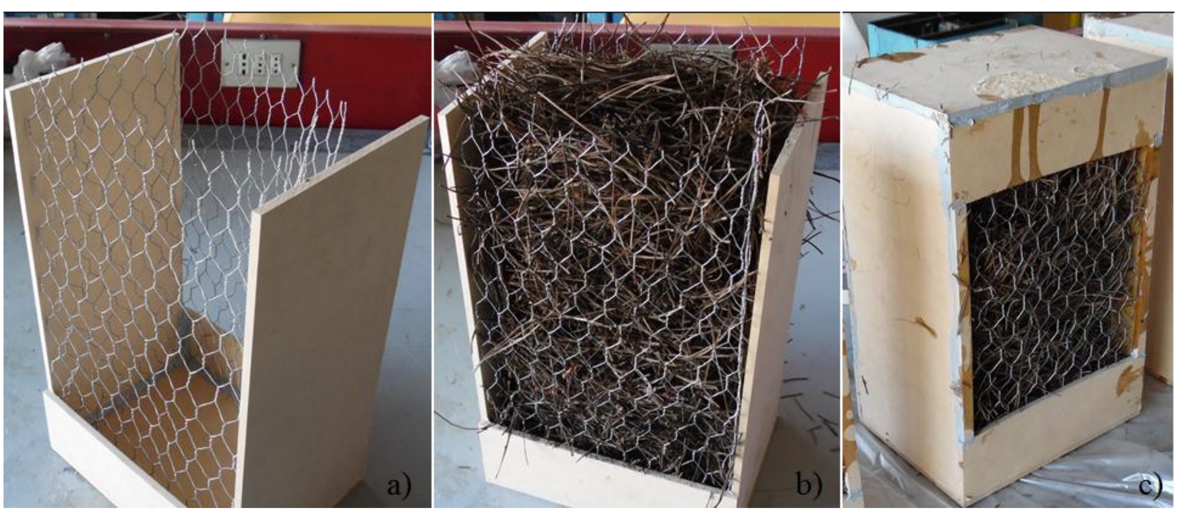

Figure 26: a) Meshed holder inside the partially closed frame, b) the same but filled with radiata pine needles and c) specimen with all the frame glued and each side filled with resin.

APPENDIX E: S-TYPE PITOT TUBE CALIBRATION

S-type Pitot tube used in the wind tunnel to measure velocity was calibrated with a Testo hot wire anemometer. Almost every permeability test (8 out of 9 specimens) was repeated twice, once with the hot wire anemometer and once with the S-type Pitot tube, both located in the same position in the wind tunnel.

Calibration given by the differential pressure sensor (OMRON, model D6F-PH0025AD1) manufacturer, is

$$DP = \frac{OP - 1024}{60000} 250 \tag{16}$$

Where DP is differential pressure in Pa and OP is the sensor's dimensionless reading.

As the sensor is connected to a S-type Pitot tube, to know velocity, Equation (13) should be used.

$$V = C\sqrt{\frac{2DP}{\rho}} \tag{17}$$

where V is velocity, C is a constant for that particular S-type Pitot tube and ρ is air density.

When using Equations (16) and (17), a poor fit is obtained, and C has low values (between 0.21 and 0.73, being usually around 0.84 or higher in commercially available models).

We found a better fit when directly relating OP with wind velocity with a linear relation, and even better for all cases except for HPS when separating data according if they were from VPS, APS or HPS. HPS was found to be the case with the most dispersed data.

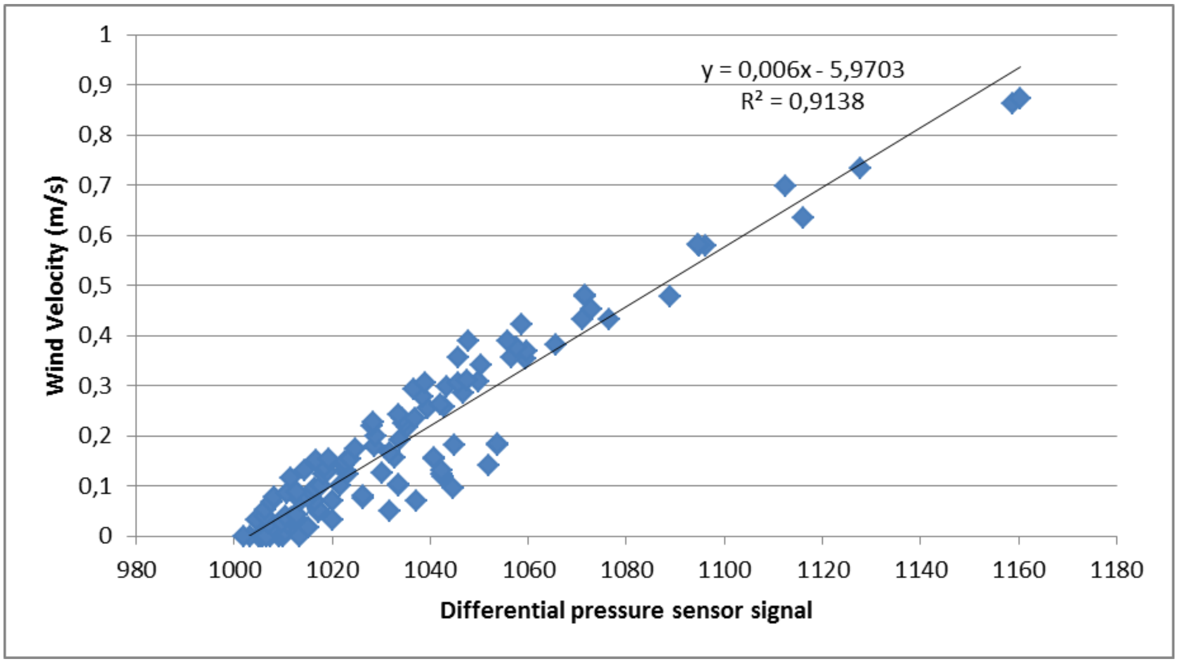

Figure 27: All measured data with both anemometer and S-type Pitot tube.

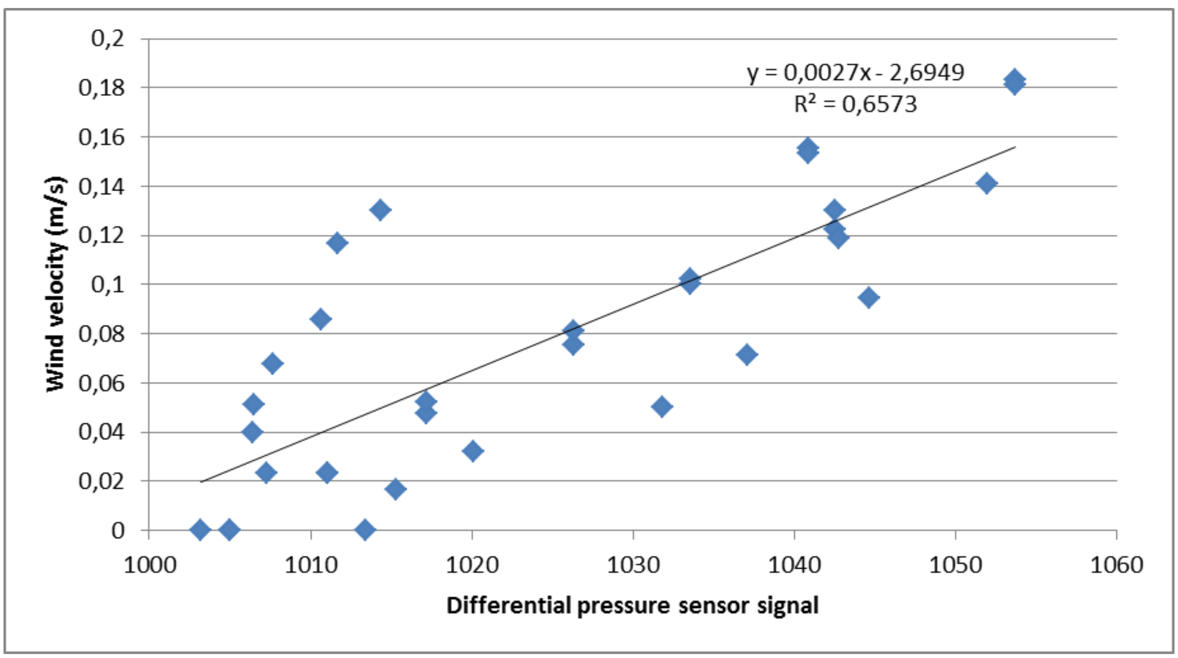

Figure 28: Data measured with both anemometer and S-type Pitot tube on HPSs.

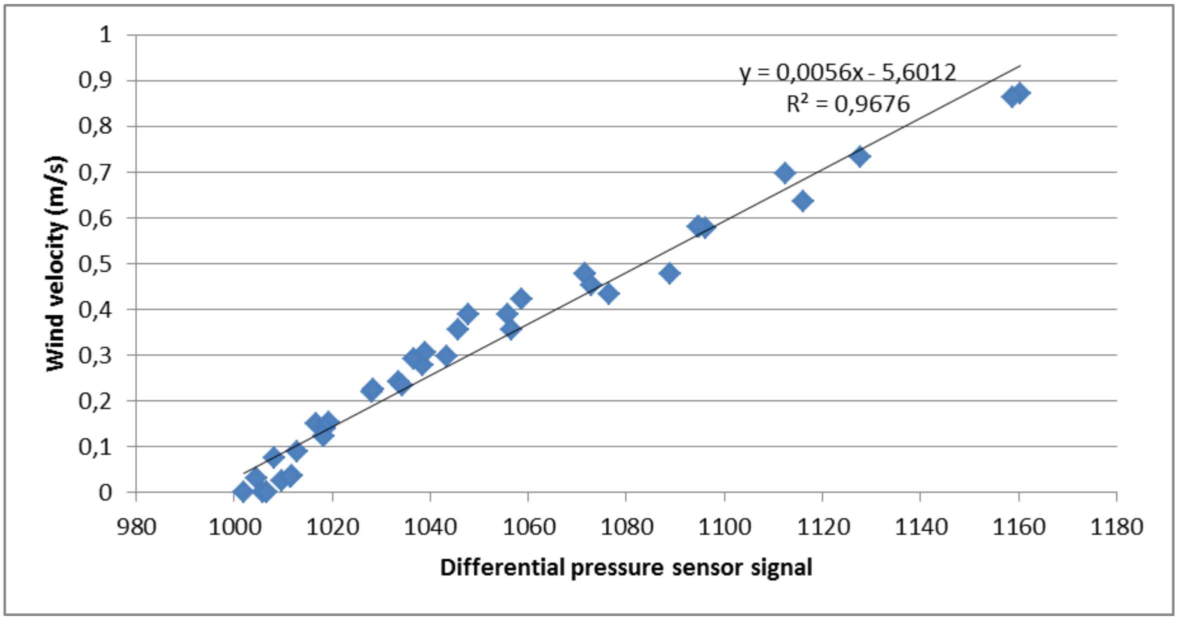

Figure 29: Data measured with both anemometer and S-type Pitot tube on VPSs.

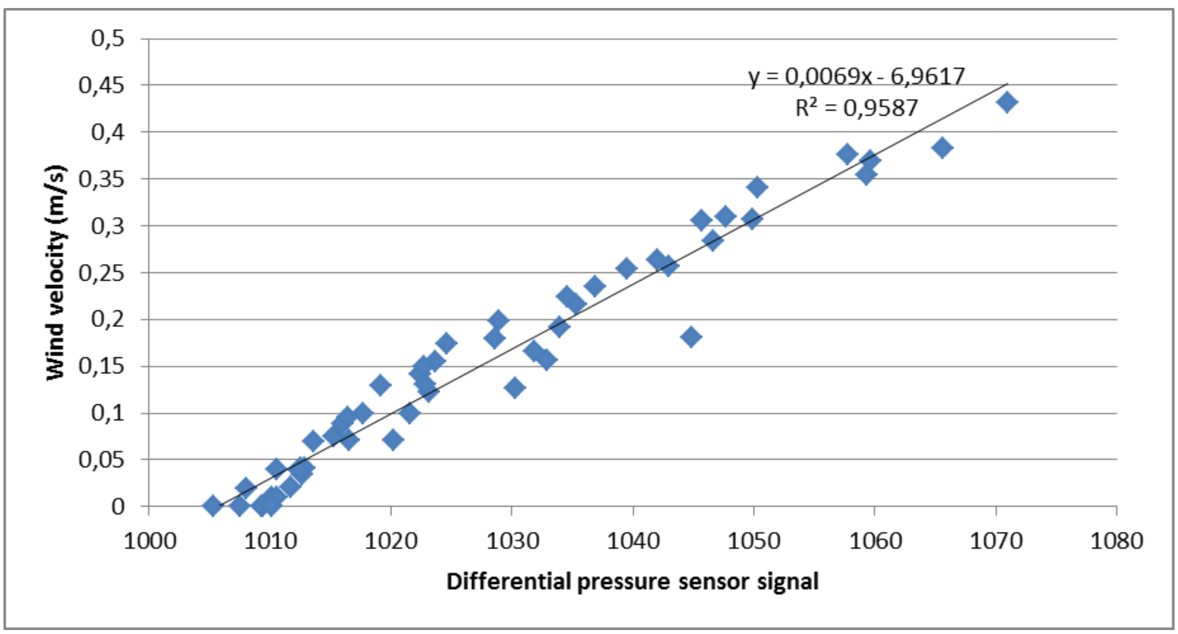

Figure 30: Data measured with both anemometer and S-type Pitot tube on APSs.

APPENDIX F: DIFFERENTIAL PRESSURE SENSOR CALIBRATION

To measure static pressure differences in both sides of each specimen, we used an OMRON differential pressure sensor model D6F-PH0505AD3. The conversion formula given by the manufacturer is

$$DP = \frac{OP - 1024}{60000} 100 - 50 \tag{18}$$

However, this correlated poorly with our measurements. To calibrate, we put a nylon mesh with regular geometry in the test section and at ten different velocities, differential pressure was measured twice with a water column gauge and twice with the differential pressure gauge. The relation was linear and can be appreciated in Figure 31.

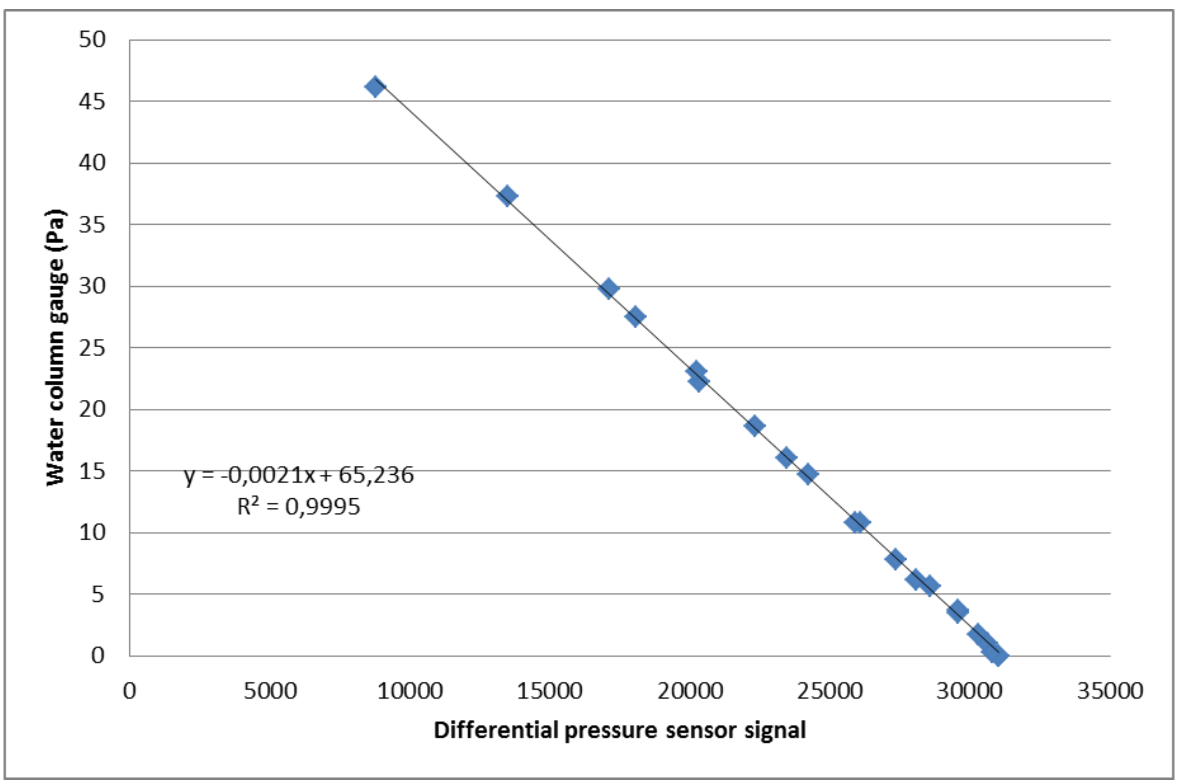

Figure 31: Differential pressure sensor calibration.

APPENDIX G: VELOCITY PROFILE

To have good calculations of permeability, the wind tunnel's velocity profile must be determined. For that purpose six holes were drilled in the wind tunnel's upper face near the fan. Holes were evenly distributed in all the transversal section of that face to measure velocity in eight points below each hole at different depths.

Every point was repeated three times for each different velocity and four different velocities were tested.

All data was exported to MATLAB, where each velocity matrix was extended by four columns (two by side) and by two rows (one on top and one on the bottom) full of zeros. The two newly added and most internal columns were filled with the average velocity of the most external rows measured, as it is assumed they behave similarly.

All other added row and column components rest with a value of zero as they represent the velocity on the walls.

To better represent the physics of the problem, a Lagrange interpolation with two degrees of freedom was implemented.

The first step to implement a Lagrange interpolation is to define one factor for each coordinate as follows,

$$L_{n,k}(x) = \prod_{\substack{i=0 \\ i\neq k}}^{n} \frac{x - x_i}{x_k - x_i} \tag{19}$$

$$L_{m,l}(y) = \prod_{\substack{j=0 \\ j\neq l}}^{m} \frac{y - y_j}{y_l - y_j} \tag{20}$$

Then if the function to be interpolated is called $f(x, y)$, the resulting Lagrange interpolation $P_n(x, y)$ is defined as

$$P_n(x,y) = \sum_{k=0}^{n} \sum_{l=0}^{m} f(x_k, y_l)\, L_{n,k}(x)\, L_{m,l}(y) \tag{21}$$

In our case it is easy to see that $L_{n,k}(x) = L_{m,l}(y)$ in the entire domain, as partitions are the same in both coordinates. In a matrix form it could be written as.

$$P = L'FL \tag{22}$$

where F is the modified extended matrix, L is a matrix filled with factors for each F component and P is the resulting interpolated matrix.

Once the interpolation was done, the flow was calculated by assigning a velocity value to the center of each small division of the tunnel, and multiplying it by its area. Linear relations were obtained to relate flows with anemometer readings in their test place (see Figure 32 and Figure 33).

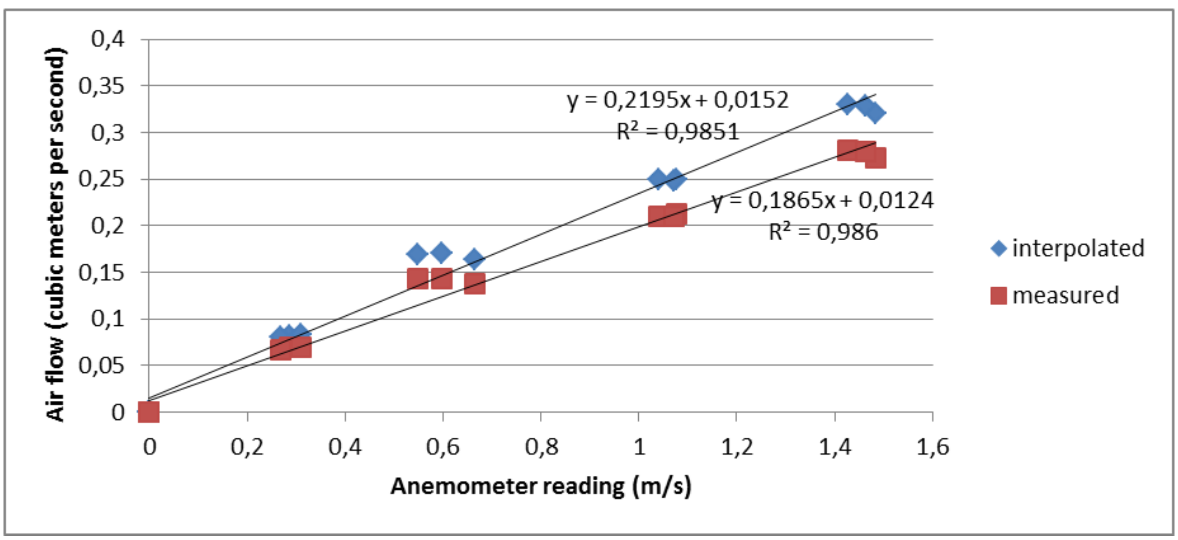

Figure 32: Flow and anemometer reading relations when interpolating and directly using the measured values in specimens with HPS geometry.

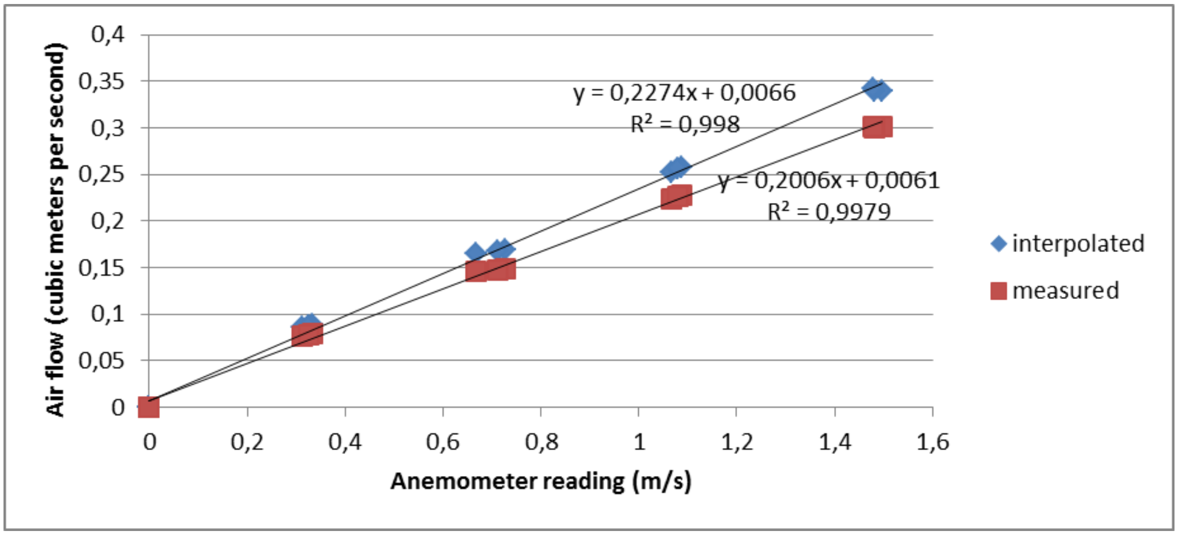

Figure 33: Flow and anemometer reading relations when interpolating and directly using the measured values in specimens with VPS and APS geometry.

As an example, velocity profiles when interpolated and when measured, taking into account only the extended measurements can be graphically seen in Figure 34. Not all measurements are shown as few changes were appreciated.

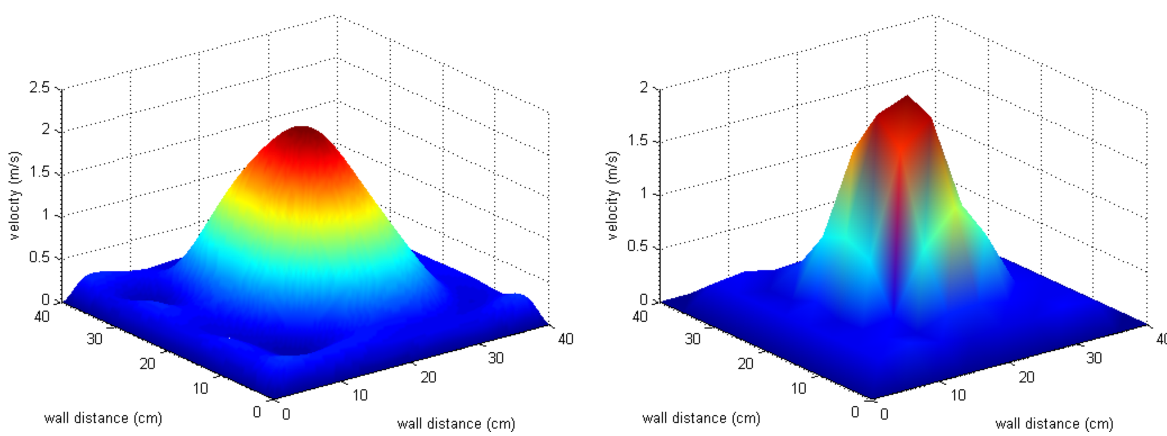

Figure 34: velocity profile at 2.88 m/s in a HPS, interpolated in left and just extended measurements in right.