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Characterization of heat transfer between phases inside a porous medium as applied to vegetal set representations

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ABSTRACT

Convective heat transfer between vegetal sets and the surrounding air in the context of forest fires has not yet been fully investigated and understood in existing studies. This process may have a great influence on many environmental problems such as forest fires. This study is devoted to the computational heat transfer characterization of tree structures. These structures were generated by Iterated Function Systems (IFS) and the fluid flow was computed using balance equations (mass, momentum, heat, etc.). The heat transfer was then characterized using the macroscopic Stanton number on several tree structures. The main objective of this study was to demonstrate that the macroscopic Stanton number only depends on the macroscopic Reynolds number using a power law. In addition, the power law exponent was found to be quasi-constant for all the configurations tested in this work and it tends to be universal.

1. Introduction

The main process involved in fire propagation during forest fires is widely accepted to be radiation emitted by flames and absorbed by vegetation (long range heating). During this heating phase, vegetation temperature reaches the threshold where pyrolysis takes place. Cellulose and other wood compounds, like hemi-cellulose or lignin mainly degrade into carbon monoxide and carbon dioxide [1–3]. Other chemical compounds such as methane (CH_4) and hydrogen (H_2) in lesser proportions, can also be found in pyrolysis products. Usually, the combustion reaction in the gaseous phase considers the combustion of carbon monoxide with oxygen [2]. A flame develops above the vegetation, heating other vegetation and thus leading to fire propagation. Radiative heat transfer can be considered as the main process involved in the propagation of fire on litter or low-lying vegetation (bush fires). However, when fire propagation is driven by wind, the convective heat transfer can become just as important as the radiative transfer [4].

Moreover in many landscapes, especially in the Mediterranean region, the vegetation is not uniformly spread out, both along the horizontal axis (propagation surface) and along the vertical axis (from the ground level to the tree crown). The vegetation set can be classified into three groups according to height: low-lying vegetation (litter, grass, etc.), mean-lying vegetation (*Quercus Coccifera*, *Arbutus Unedo*, etc.) and crowns (composed of pine needles, leaves and branches). Each kind of vegetation is associated with a specific class of fires, namely ground fires, surface fires and crown fires respectively. Crown fires are the most dangerous and destructive types of fire and also the most difficult to control [5,6]. The vertical transition of fire from ground level to the tree crowns is caused by flames that heat the upper vegetal stratum where the fire can propagate. This is typically how crown fires start. In these cases, the main heat transfer responsible for this vertical transition is convective heat transfer rather than radiative heat transfer.

The characterization of heat transfer by convection between a vegetal structure and ambient air is important if we are to understand the behaviour of crown fires. This is the main subject of the present study.

Studying heat transfer by convection in a fire propagation model is a complicated task. The main difficulty for modelling is to define at what scale fire propagation will be observed. The physical processes involved in the burning of vegetation and spreading of a fire take place at different scales which we will list here so as to be clear [7]. The first scale denoted by l_b is the microscopic scale and is related to small vegetation parts. Fig. 1(a) shows a representation of the vegetal matter. At the microscopic scale, the wood is a composite porous material made up of a solid phase, a liquid phase and a gaseous phase, all three are involved in drying and pyrolysis. The second scale is the mesoscopic scale denoted by l_w. Fig. 1(b) shows a unit component of a vegetal structure. The interlacing of vegetation elements (twigs, leaves, branches, etc.) can again be defined as a composite medium made up of two phases, the wood or vegetal phase and a gaseous phase. The associated scale is the mesoscopic scale. The third scale is the macroscopic scale denoted by l_f. Fig. 1(c) illustrates a vetegal set defining the macroscopic scale. The macroscopic scale is defined by upscaling from the mesoscopic one and by the mixture of vegetation and gas as a continuous equivalent

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Nomenclature

h	heat transfer coefficient (W/m^2/K)
L	macroscopic length (m)
l_b	microscopic scale (m)
l_f	macroscopic scale (m)
l_w	mesoscopic scale (m)
n	interpolation order of IFS (–)
N_{exp}	number of experiments on each tree (–)
n_i	local meshing order (–)
n_t	number of transformations (–)
Q_{ij}	heat exchange from j phase to i phase (W/m^3)
s	contraction (–)
S_{tree}	total surface of tree (m^2)
$\overline{T}$	mesoscopic temperature of fluid phase (K)
T_{mean}	mean macroscopic temperature of fluid phase (K)
T_0	inlet fluid temperature (K)
$\overline{U}_i$	ith component of mesoscopic fluid phase velocity, (m/s)
V_{env}	envelope volume (m^3)
V_{mean}	mean macroscopic velocity of fluid phase (m/s)

Greek symbols

χ	heat transfer coefficient (W/m^3/K)
Φ	porosity (–)
ξ	rotation angle according the second axis (3D IFS) (rad)
θ	rotation angle according the third axis (3D IFS) (rad)
φ	rotation angle according the first axis (3D IFS) (rad)
σ	specific area of the equivalent medium (m^2/m^3)

List of abbreviations

Gr	Grashof number
IFS	Iterated Function Systems
LAI	Leaf Area Index
Re	Reynolds number
Ri	Richardson number
St	Stanton number

medium. We chose to use the latter scale for the study described in this paper. A combustion model of vegetation describes the processes involved in a propagation model at this scale. For instance, authors such as Grishin [2] or Séro-Guillaume and Margerit [7] have formulated several systems of balance equations to simulate the combustion of vegetation.

An averaging method was used to model heat transfer by convection at the macroscopic scale. At this scale vegetation may be considered as a continuum medium. Usually averaging methods provide media with one temperature because the different phases are supposed to be at thermal equilibrium. Indeed the small elements of the canopy such as leaves and twigs are considered as thermally thin and thus can be assumed at homogeneous temperature. These elements exhibit a larger area of exchange with air than is the case for the rest of the vegetal structure. Consequently these elements tend to reach a state of equilibrium with the surrounding air. Therefore this study assumes that the small elements do not participate in the global heat transfer. The ratio of heat diffusivity between wood and air is around 100 and the assumption of infinite conduction can be considered as suggested by Kuwahara et al. [8]. Consequently the temperature within the solid phase can be assumed to be constant.

To obtain a model at macroscopic scale it is necessary to upscale a mesoscopic model using any homogenisation method [9–11]. In this paper, the model used is the one developed by Séro-Guillaume and Margerit [7]. It was obtained by the averaging method of Marle [12] wherein closure equations are obtained by considering that the entropy production is positive (usually in a linear approximation between forces and fluxes). The Marle method can be developed further by using extended thermodynamics [13] where the phase space is extended with values of thermodynamical quantities and their gradient or their flux. A complete expression set for the equivalent medium parameters was thus obtained. Using averaging method, a model with two temperatures can be written as [7]:

$$\Phi\rho_f C_{pf}\left(\frac{\partial T_f}{\partial t} + \mathbf{U}_f \cdot \nabla T_f\right) - \nabla \cdot \left(\lambda_f \nabla T_f - \mathbf{Q}_\mathbf{f}^\mathbf{r}\right) = Q_{fs} + R_f \quad (1)$$

$$(1-\Phi)\rho_s C_{ps}\frac{\partial T_s}{\partial t} - \nabla \cdot \left(\lambda_s \nabla T_s - \mathbf{Q}_\mathbf{s}^\mathbf{r}\right) = Q_{sf} + R_s \quad (2)$$

In Relations (1) and (2), T_f and T_s are respectively the averaged temperatures of the gas and of the solid phases, $\mathbf{U}_f$ is the averaged velocity of the gas phase, λ_f and λ_s are the heat conductivities of the two equivalent phases, Q_f^r and Q_s^r are the radiative fluxes and R_f and R_s are the heat sources due to chemical reactions, Φ is the porosity. Q_{fs} and Q_{sf} represent the heat exchanges between the solid and fluid phase. The parameter values of the equivalent medium are often unknown and should be evaluated solving balance equations at a lower scale on a representative cell.

In Relations (1) and (2), the heat exchange Q_{ij} value is considered positive if the i phase receives heat from the j phase. A balance equation can be established concerning the heat exchange at location $\mathbf{x}$ representing one element of the boundary between the solid and the fluid phase:

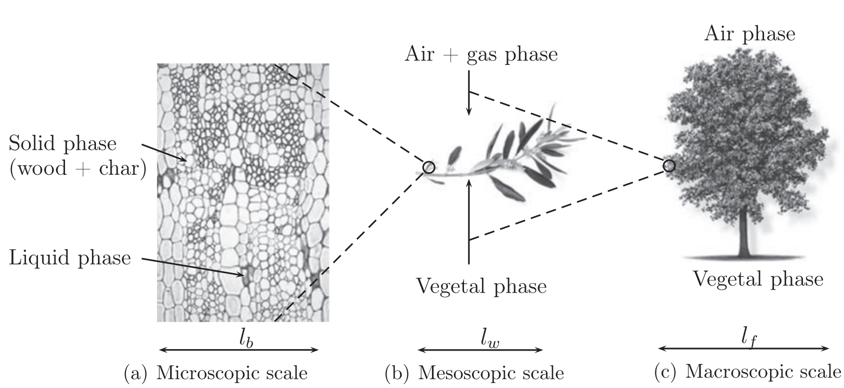

Fig. 1. Description of different scales and phases of vegetation.