



# Effective thermal conductivity models applied to wood briquettes



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## ABSTRACT

Three electrical resistive-circuit models were used to determine the effective transverse and longitudinal thermal conductivity of a wood cell as a constituent element of briquettes chips. The models were applied to the briquettes at 0% moisture content and equilibrium moisture content. With the increase in moisture content above equilibrium moisture content, but below fiber saturation point, both fiber swelling and increase in chips interspaces occurred, so that a change in the cell geometry and model was necessary. Since the transverse series resistive model overestimated the thermal conductivity and the transverse parallel resistive model underestimated the thermal conductivity, the wood cells were combined into serial and parallel circuits until the difference between models became insignificant. General equations were developed in the paper, describing effective transverse thermal conductivity of combined cells. Experimental measurements of thermal conductivity significantly validated the resistive models.

## 1. Introduction

Biomass briquetting can be defined as the densification or compaction of biomass material by the application of pressure, increasing the bulk density of the biomass material and thus its energy density. Briquettes are differentiated from pellets by their size. Pellets typically have a length of 5–30 mm, compared to briquettes which can range from 30 mm to 200 mm in diameter and from 50 mm to 400 mm in length. The advantages of briquetting are: the bulk density of the material is increased, the energy content per unit volume of material is increased, a homogeneous product is obtained from a heterogeneous mix of materials, and a highly cohesive product is obtained from materials that might otherwise be difficult or expensive to process [1]. Biomass fuel properties for the combustion analysis are grouped into physical, chemical, thermal and mineral properties. Physical properties and features include density, porosity, particle size and shape distribution, related to fuel preparation methods. Important chemical properties for combustion are the elemental analysis, proximate analysis and higher heating value. Thermal properties are specific heat, thermal conductivity and emissivity that vary with moisture content, temperature and degree of thermal degradation [2,3]. Knowing the thermal properties of biomass briquettes and pellets is important for modeling the combustion process. Effective thermal conductivity and specific heat of bulk wood pellets are also important properties for studying self-heating during their storage. A packed bed of pellets is assumed in Refs. [4,5] to be a continuous homogeneous porous system

with effective thermal properties. The line heat source method was used to determine the effective thermal conductivity and specific heat of bulk wood pellets with moisture content ranging from 1.4% to 9%, wet basis (w.b.). The single pellet thermal conductivity was estimated from the effective thermal conductivity of the packed bed system by using the parallel distribution of the solid particles and from the packing porosity. Using the transient plane source technique, Sjöström and Blomqvist [6] measured the specific heat and thermal conductivity of bulk wood pellets within a temperature range of 22–120 °C. They also investigated the possibility of measuring those properties on individual pellets while studying the moisture content dependence. The effect of moisture content on thermal properties of alfalfa pellets was studied by Fasina and Sokhansanj [7] using the line heat source method for pellet moisture content of 7.5–18% w.b. The effective thermal conductivity of softwood bark and softwood polydispersed char particle beds as a function of particle size distribution has been studied by means of the linear packing theory and unit cell model of heat conduction [8]. Specific heat and particle thermal conductivity of softwood, softwood bark and softwood char were comparatively measured at temperatures between 40 and 140 °C by Gupta et al. [9].

Wood is an anisotropic material with a complex and heterogeneous structure and the thermal conductivity is different if heat is transferred perpendicularly or in parallel with the fiber axis. There are several models describing thermal conductivity of wood and porous materials. Siau [10] developed a theoretical model to describe the effective thermal conductivity of wood by using an electrical analogy (equivalent

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Nomenclature		Subscripts	
$a$	cell lumen dimension (m) (Eq. (9))	$A$	series (transverse flow)
$a$	coefficient (Eq. (29))	$b$	briquette
$b$	coefficient (Eq. (30))	$bw$	bound water
$EMC$	equilibrium moisture content (%)	$B$	parallel (transverse flow)
$FSP$	fiber saturation point (30% MC in the cell wall)	$cw$	cell wall
$i$	number of combinations	$d$	dry
$k$	thermal conductivity (W/mK)	$eff$	effective
$L$	overall cell dimension (m)	$exp$	experimental
$m$	mass (kg)	$g$	gas
$MC$	moisture content (%)	$i$	number of combinations
$P$	porosity	$L$	longitudinal (related to briquette)
$R$	thermal resistance (K/W)	$R$	radial (related to briquette)
$V$	volume (m <sup>3</sup> )	$w$	wet
$V\%$	volume fraction	$\perp$	transverse (related to cell)
<b>Greek letters</b>		$\parallel$	longitudinal (related to cell)
$\alpha$	second weighting factor	$1$	one cell
$\phi$	diameter (m)	<b>Superscript</b>	
$\rho$	density (kg/m <sup>3</sup> )	$'$	new
$\omega$	dimensionless length		
$\xi$	first weighting factor		

resistive-circuit model). The proposed one cell model with unit overall dimensions represents all longitudinally-oriented cells. It consists in cross and side walls and lumen only with dead air. Another theoretical model for the prediction of wood thermal conductivity in radial and tangential directions for a large range of moisture contents was reported in Ref. [11]. The geometric models were set up based on microscopic observations: earlywood/latewood percentage, cell wall percentage and arrangement in the two directions. A two-dimensional finite element model for the prediction of the effective thermal conductivity for various densities and moisture contents of wood was developed by Gu and Hunt in a series of papers [12–15]. As compared to Siau's wood cell model with unit dimensions, the model developed in Ref. [15] has the full length  $L$  which includes an external bound water layer. Thunman and Leckner [16] developed a theoretical model for wood effective thermal conductivity estimation during different stages of combustion. Their geometrical model is a quadratic cell with three layers: solid, water and gas. The thermal conductivity modeling is applied to both wood and char, since wood maintains its fiber structure during thermal conversion. The authors suggest that the model can also be applied to pellets and chipboards.

The thermal conductivity of different wood species has experimentally been measured by using different methods since several decades and the literature offers useful data. More recently, Yu et al. [17] contributed to existing knowledge in this area by adding data about other species, investigating the thermal conductivity variations with density, temperature and moisture content.

As regards porous materials (heterogeneous, composite materials or granular, particulate materials), a significant number of effective thermal conductivity models have been proposed [18–24]. They are empirical or theoretical, specific to a given class of materials. Carson et al. [18] proposed a distinction between two basic types of isotropic porous materials: particulate-type materials as external porosity materials (the conduction pathway is through the dispersed phase) and foams, sponges or honeycomb-structures as internal porosity materials (the heat transfer pathway is through the continuous phase). They assigned the existent models and their bounds to the two classes of materials. The effective thermal conductivity of a heterogeneous material is strongly affected by its composition and structure. Wang et al. [19] proposed a method for modeling the thermal conductivity of

heterogeneous materials with known composition and fixed micro-structure by using combinations of six fundamental structural models (series, parallel, two forms of Maxwell-Eucken, Effective Medium Theory, co-continuous). All models are independent, with different structures and model values. The same authors developed a unifying equation for five fundamental effective thermal conductivity structural models. New models can be derived by using the proposed method based only on the component volume fractions and thermal conductivities [20]. Xu et al. [22] predicted effective thermal conductivity of composites from the analogy between electric and thermal fields that satisfy Laplace equation. They employed two approaches, by solving Laplace equation and by equating the composite to a circuit network of conductors. Suplicz et al. [23] proposed in their work a new semi-empirical model for predicting and fitting thermal conductivity of two phase composites, which was derived from the rule of mixtures. The new model provided a better fit than other conventional theoretical models. Geometrical parameters of metal foams on thermal and hydraulic phenomena were analyzed by Kumar et al. [24]. They derived a relationship between geometrical parameters and effective thermal conductivity by using an electrical resistor model in order to describe the thermal conductivities of constituent phases.

In contrast to wood, which is an anisotropic and heterogeneous biological porous material, pellets and briquettes are considered to be isotropic because of the random orientation of fibers during the briquetting process. To the best of our knowledge, there is less information on thermal conductivity of a single wood pellet or briquette, and no model that can describe the effective thermal conductivity.

The objectives of the research reported below were to investigate if and to what extent effective thermal conductivity models of wood can also be applied to wood briquettes. To this end, three electrical resistive-circuits assuming transverse and parallel heat flux paths were used to analyze the wood cell when briquettes moisture content ranged from 0% to equilibrium moisture content and from equilibrium moisture content up to the maximum moisture content (24.5%, dry basis) permissible for briquettes to maintain their shape.

## 2. Materials and experiment

Briquettes made of a softwood and hardwood mixture were used as

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