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Numerical study of timber solar drying with application to different geographical and climatic conditions in Central Africa

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ABSTRACT

This paper presents a numerical investigation of an indirect solar dryer for wood, using an absorber placed directly behind the transparent cover on the top of the dryer with a layer of air separating it from the cover. The floor and north wall are insulated and painted in black. The dryer is very simple to build and electrical energy is only used for the fan. Applications are done on three tropical woods with 50 mm thick most utilized in Central Africa: obeche (*Triplochilon scleroxylon*), iroko (*Chlorophora excelsa*) and sapele (*Entandrophragma cylindricum*). Comparisons between the numerical results and those experimentally obtained are given and the performances of this solar dryer are discussed under the weather conditions of seven towns in Central Africa region located in six different countries. Satisfactory agreement between experimental and numerical results is then obtained. With an average initial moisture content ranging between 0.4 and 0.48 kg/kg, the average final water contents are ranged from 0.15 to 0.18 kg/kg after 21 days in Yaoundé during the months of November and December 2004. Modeling was applied from November 1st to the November 30th, to Sapele wood with 50 mm thick and 0.4 kg/kg initial moisture content dried in Bangui, Brazzaville, Douala, Kinshasa, Libreville and Yaoundé until the final moisture content, which can vary from 0.13 to 0.1 kg/kg. Solar energy per cubic meter of wood was ranging from 2 to 4.3 GJ/m^3 with a maximal thermal efficiency between 12 and 47%. Ndjamena's climate is not good to use solar drying because of its low air absolute humidity that gives a fast drop in the moisture content and consequently destroys the wood board quality. Bangui, Brazzaville, Douala, Kinshasa, Libreville and Yaoundé give satisfactory alternative drying conditions using the studied solar dryer. However, it is important to use a solar collector in those six towns in order to reduce the effect of the air absolute humidity and improve the drying kinetic.

1. Introduction

An essential element for the development of a country is its disposition of energy. As stated by Arto et al. (2016), the energy requirements, to maintain high level of development of the developing countries, are very low. In the actual context, where research of the energy is permanent, joining sustainable development by using renewable energies is imperative. Drying is known as an intensive process that consumes a considerable amount of energy. In sawmill, energy dedicated to the drying operations is 7 to 12 time the energy dedicated to the sawing operations (Negrie and Blaison, 2017). In wood sector, drying is important because it reduces transport costs, biological attacks, distortion, cracks development in sawn timber (Bell et al., 2014). Consequently, several researches were directed in order to perform drying process adequately with an optimum operating conditions and energy expenses. According to Tsoumis and cited by Awadalla et al. (2004) and Bentayeb et al. (2008), the needed energy for drying wood using conventional dryers range from 600 to 1000 kWh/m^3 depending on wood type and thickness. Applied to dry pine wood (*Pinus pinaster*) from 120% to 14% moisture content with 27 mm thickness, conventional kiln driers need 494 kWh/m^3 of heat energy and 32 kWh/m^3 (28 kWh/m^3 in the case of solar kiln driers) of electrical energy for ventilation (Loureiro et al., 2007). The report of the Energy Efficiency and Conservation Authority (EECA, 2005) affirms that conventional vented kilns needed an energy amount of about 3.2 GJ/m^3 (Bell et al., 2014). In the case of agricultural products, Brooker et al. (1974) found that using high temperature drying processes, with both continuous and discontinuous application, required up to 6.9 MJ of energy per kg of water extracted. Using a forced convection solar drier dotted with gravel as heat storage material for chili drying, Mohanraj and Chandrasekar (2009) have obtained a specific moisture extraction rate equal to 0.87 kg/kWh. In developing countries, converting electrical

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Nomenclature

C_{pa}	mass heat of the air (J/(kg K))
C_{pto}	mass heat of the black body (J/(kg K))
C_{pb}	mass heat of the wood (J/(kg K))
C_{pp}	mass heat of the roof slope (polyethylene) (J/(kg K))
C_{ppl}	mass heat of the wall (polyethylene) (J/(kg K))
E_{air}	input energy from hot air (J)
E_b	desorption heat (J/kg)
E_{DrE}	drying energy (J)
E_{evap}	energy used to evaporate liquid water (J)
E_{fan}	electrical energy for ventilation (J)
E_{input}	input energy (J)
E_{loss}	energy losses afterΔt drying time (J)
E_{SolInp}	input solar energy (J)
E_{sorpt}	bound water energy (J)
e_{st}	thickness of the stick (m)
E_w	energy used to heat humid wood (J)
$F_{bb\text{-}b}$	geometric factor black body-wood (–)
$F_{pl\text{-}ciel}$	geometric factor between wall and sky (–)
$F_{pl\text{-}to}$	geometric factor between wall and black body (–)
$F_{p\text{-}ciel}$	geometric factor between roof slope and sky (–)
$F_{to\text{-}b}$	geometric factor between black body and wood (–)
G_i	global radiation on the roof slope (W/m^2)
G_{il}	global radiation on the wall (W/m^2)
h_b	convective transfer between wood and air (W/(m^2 K))
h_{cb}	interior convective coefficient between the wood stack and the air (W/(m^2 K))
h_{cext}	convective coefficient between exterior air and wall (W/(m^2 K))
h_{ci}	interior convective coefficient between the roof slope and the air (W/(m^2 K))
h_{cil}	interior convective coefficient between the wall and the air (W/(m^2 K))
h_{cto}	interior convective coefficient between the black body and the air (W/(m^2 K))
HR	air relative humidity (%)
h_{vext}	convective coefficient between exterior air and the roof slope (W/(m^2 K))
h_{vint}	convective coefficient between interior air and the roof slope (W/(m^2 K))
K	mass global transfer (kg/(m^{2}s))
L	latent heat of evaporation (J/kg)
$\dot{m}$	mass rate flow (kg/s)
m_a	mass of the drying air (kg)
m_o	anhydrous mass of the wood (kg)
m_p	mass of the roof slope (kg)
m_{to}	mass of the black body (kg)
R	constant of perfect gases (8.314 J/(mol K))
S_b	exchange surface of the wood (m^2)
S_{bb}	black body surface (m^2)
S_p	surface of the roof slope (m^2)
S_{pl}	surface of the wall (m^2)
t	drying time (s)
T_a	interior air temperature (K)
T_{aE}, T_{aext}	temperature of the air exterior of the dryer (K)
T_b	wood temperature (K)
T_{ciel}	temperature of the sky (K)
T_{pl}	temperature of the wall (K)
T_{to}	black body temperature (K)
V_{air}	air velocity inside the drying chamber (m/s)
V_{ext}	ambient air velocity (outside the dryer) (m/s)
V_{dryer}	volume of the dryer (m^3)
V_p	volume of the wood stack (m^3)
X	wood water content (kg water/kg dry wood)
X_{eq}	the equilibrium water content of the wood species (kg water/kg dry wood)
X_{fsp}	humidity at the fibre saturation point of the wood species (kg water/kg dry wood)
Y_E	inlet air humidity of the dryer (kg/kg)
Y_S	inside air humidity of the dryer (kg/kg)
$\sigma = 5.67 \times 10^{-8}$W/(m^{2}K^4)	Boltzmann coefficient
ε	porosity of the wood stack (–)
η	thermal efficiency of the solar dryer (%)
ρ_a	air density (kg/m^3)
ρ_{alb}	albedo (–)
Δt	time step (h)
α_P	absorption coefficient of the roof slope (–)
α_{Pl}	absorption coefficient of the wall (–)
α_{to}	absorption coefficient of the black body (–)
τ_p	transmittivity coefficient of the polyethylene (–)

energy to a source of heat is considered as expensive due to the prohibitive cost of the electrical energy. Some conventional wood dryers use a fossil energy that deliver pollutants to the environment and the increase in fossil fuel prices, which will be reverberated on the price of the final wooden article at a high price. Vented kilns and heat pump kilns generate respectively 345 and 25 kg $CO_{2\text{-eq}}$ per cubic-meter of sawn timber (Bell et al., 2014). Reviewing all these disadvantages, the use of solar energy for drying process gives a possibility to reduce consumption of non-renewable sources such as carbon and petroleum (Murthy, 2009). Contrary to all conventional dryers using fossil fuel, solar dryers give most opportunities to reduce the price of the wooden article because of the use of solar energy which is free and abundant in the tropical regions. In the case of Cameroon, the monthly global solar irradiation varies between 5.8 kWh/(m^2 day) in the great north region and 4 kWh/(m^2 day) in the great south region (Abissi-Tagne, 2015). For example, Ayangma et al. (2008) used solar data of 20 years in Garoua (great north) and have obtained an estimation of solar irradiation near 5.743 kWh/(m^2 day). Taking into account all regions of Cameroon, the average incident solar energy was approximating 4.9 kWh/(m^2 day) (Njomo and Wald, 2006). Solar energy has great potential for many low temperature applications and it can be used directly in the drying process to reduce its cost (Lopez-Vidana et al., 2013). It can be considered as one of the most favorable options to contribute to the energy demand with extensive applications in industry (Baharoon et al., 2015; Helvaci and Khan, 2015).

A great part of Central Africa forests is located in basin of Congo, the second tropical forest in the world after Amazonian basin. Central Africa forests have a social and economic importance both informal and formal sectors in all countries of this sub region. Forestry exploitation is the main purveyor of private jobs. The wood producers and wood users are constantly confronted to the challenge of improving the product quality and quantity. During the drying process, considerable quantities are destroyed because the operating conditions which include temperature, air humidity and air flow rate were not suitably chosen. In developing countries, most wood users don't have enough financial support to dry wood using conventional dryers. They need dried wood and dryers with low investment and easy to operate and maintain, such as wood solar dryers with low cost equipment. In a recent study on application of the wood solar drying in political capital of Cameroon (Yaoundé) done by Abissi-Tagne (2015), only 4% of wood users have a good idea on the moisture content required for the stability needed for interior or exterior use, 2.5% know the price of wood drying and 65% use an open-air drying. Thus, it is important to build simple wood solar dryers in order to reduce the percentage of open-air drying that takes