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Thermal modeling of the forced convection Sandwich Greenhouse drying system for rubber sheets

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ABSTRACT

In this paper, a novel "Sandwich Greenhouse" for rubber sheet drying is proposed. Using solar energy as the only heat source instead of traditional smoke house that requires firewood, it eliminates shortcomings such as skilled labor monitoring requirement, possible fire hazard, and darken-color rubber sheets due to soot particle contamination. Our greenhouse is specially designed to retain solar energy within, while minimizing the heat loss to the outside environment. The mathematical models are developed to predict the convection mass transfer coefficient and to study the thermal behavior during the drying of rubber sheets under our proposed greenhouse design. Validated with experimental observations, the models show good agreement with the actual experimental data. The experiment demonstrates an effectiveness of our proposed Sandwich Greenhouse, as the temperature of the rubber sheet is 15 °C and 5 °C higher than the ambient temperature during the daytime and nighttime, respectively. As a result, the moisture content of the rubber sheets can decrease from 36.4% to 2.8% in fewer than 2 days.

1. Introduction

Natural rubber is a vital agricultural commodity, which is used in the manufacture of a wide range of products. Sheet rubber, a majority form of marketed natural rubber, could be classified into Air Dried Sheet (ADS) and Ribbed Smoked Sheet (RSS), depending on their drying method [1]. ADS is dried by hot air, whereas RSS is dried in a smoke house. In sheet rubber preparation, latex is initially coagulated and rolled into a 3–4 mm thick sheet. The wet sheets are then drip-dried in a shade for a few hours before being placed in a drying chamber or a smoke house to remove the rest of the moisture. To get the best-quality sheet rubber, the sheets must be gradually dried with a relatively low temperature on the first day and with higher temperature (but not exceeding 60 °C) on subsequent days at low relative humidity. The sheets being dried in the smoke house dry faster than open-sun-drying and are free of oxidation cased by UV radiation.

There are various types of smoke house, depending on many aspects, such as drying time, heat source, labor requirement, and ventilation, among many others. Firewood and biomass are generally used in the conventional sheet rubber drying process. However, it has recently received less demand due to high rise in fuel cost and high loss of energy during the drying process [2,3], apart from a requirement of skilled workers to closely monitor the temperature throughout the drying period, which is crucial to good quality dried rubber sheet. Human error may lead to low-quality sheets and sometimes to severe damages, such as fire in the smokehouse if the kiln temperature is not monitored carefully. It has also been shown that soot particles from wood combustion in the rubber-sheet smoking process may affect the market price unfavorably of the RSS due to its darken color and soot particles on the dried rubber sheet. Moreover, it is known that typical smoke house produces large differences in temperature and velocity, causing non-uniform drying and possibly some blisters and bubbles on the sheet. Lastly, hazardous components and fumes from fuel wood burning could have adverse effect on workers' health.

Due to the shortcomings of a traditional smoke house using firewood for the RSS drying process, an alternative energy for primary heat source has been considered [4]. Breymayer et al. [5] were among the first who developed a drying chamber for RSS rubber drying that incorporates solar air collector with the traditional firewood/biomass smoke house. This type of drying system utilizes the solar energy during the day and the firewood/biomass only at night. However, its main drawbacks are still the requirement of the skilled worker at night and risks of fire hazard. In addition, the drying chamber has direct contact with the ambience, which in turn has high heat loss from the system. Kaewnok et al. [6] have improved the hybrid system above that reduces the heat loss by placing a drying chamber within a greenhouse. However, since

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Nomenclature

a	constant for equation solving process
A	area (m^2)
C	specific heat capacity of humid air (J/kg °C)
h	convective heat transfer coefficient (W/m^2 °C)
$I(t)$	solar radiation (W/m^2)
K	thermal conductivity of humid air (J/m^2 °C)
M	mass (kg)
MC	moisture content in dry weight basis
$\dot{m}$	air velocity (kg/s) (measured from Testo 425 Thermal Anemometer)
m_{ev}	moisture removal (kg)
Pr	Prandtl number
$P(T)$	partial vapor pressure at temperature T (N/m^2)
$\dot{Q}_e$	rate of heat utilized to evaporate moisture (J/m^2 s)
r	reflectivity (dimensionless)
Re	Reynolds number
R^2	coefficient of determination
$RMSE$	root mean square error
t	time (s)
T	temperature (°C)
U_i	over all heat loss (W/m^2 °C)
x	constant of Eq. (34)
X	characteristic dimension (m)
y	constant of Eq. (34)
Z	constant of Eq. (32)

Greeks letters

α	absorptivity (dimensionless)
γ	average relative humidity (decimal)
λ	latent heat of vaporization (J/kg)
μ	dynamic viscosity of humid air (kg/m)
ρ	density of humid air (kg/m^3)
∞	soil underneath

Subscripts

0	at initial state
1,2,3,4	number constant of Eqs. (13) and (14)
a, $a1$, $a2$	ambience, air inside 1st and 2nd heating room, respectively
brk	brick (concrete slab)
cc	concrete slab covering
cr	concrete slab covering → air inside the drying chamber
dry,Rb	dry-weight basis of rubber
e	east wall of the drying chamber
er	east wall of the drying chamber → air inside the drying chamber
$er1$	east wall of the drying chamber → air inside 1st heating room
f, f_1, f_2	floor (drying chamber), floor of 1st and 2nd heating room, respectively
fr	floor (drying chamber) → air inside the drying chamber
$f\infty$	floor (drying chamber) → soil underneath
$ground$	soil underneath
n	constant of Eq. (27)
n, $n1$, $n2$	north wall (drying chamber), north wall of 1st and 2nd heating room, respectively
$n1r1$, $n2r2$	north wall → air inside 1st and 2nd heating room, respectively
$n1a$, $n2a$	north wall → ambient air outside the greenhouse
nr	north wall (drying chamber) → air inside the drying chamber
r, $r1$, $r2$	air inside the drying chamber, air inside 1st and 2nd heating room, respectively
r	correlation coefficient
Rb	rubber sheet
Rr	rubber sheet → air inside the drying chamber
W	water
w	west wall of the drying chamber
wr	west wall of the drying chamber → air inside the drying chamber
$wr2$	west wall of the drying chamber → air inside 2nd heating room

firewood is still used, its main drawbacks must also be reconsidered.

A solar thermal drying can exclusively be used for rubber sheet drying, eliminating the fuel wood usage altogether. Solar-assisted greenhouse is commonly employed to increase the thermal energy storage inside the greenhouse during the day or to transfer excess heat from inside the greenhouse to the heat storage area. The heat is then recovered at night to satisfy the heating needs of the greenhouse [7]. Many types of solar drying systems have been designed and tested for drying sheet rubber and other produces [8,9]. Tirawanichakul et al. [10] have proposed a solar air collector system that is placed inside a transparent-covering green house. This system uses solar energy as the only heat source. However, due to its direct contact with the sunlight, the rubber's quality tends to degrade, and the drying chamber has direct contact with the ambience, which increases the heat loss.

According to the past researches and studies, we can infer that to achieve a good quality dried sheet rubber by utilizing the solar energy, we need to consider the following:

(1) To preserve the rubber quality: the sheet should be completely dried, mold-free, and has consistent color and texture, and no degradation of quality due to direct contact with the ultraviolet radiation.
(2) To be cost effective: eliminate or minimize skilled worker, maximize the fuel efficiency, and minimize the overall drying cost.
(3) To retain the heat within the system, which can be used when no sunlight is available.
(4) To reduce the heat loss from the system.

Therefore, in this work, we propose a forced convection solar thermal drying for sheet rubber under a novel "Sandwich Greenhouse", which is specially designed to retain the solar energy within the system, while minimizing the heat loss to the environment. The mathematical models are also developed to predict the convection mass transfer coefficient and to study the thermal behavior during the drying of rubber sheets under our proposed greenhouse design. The models are then validated with actual experimental observations.

The rest of the manuscript is organized as follows. Section 2 provides the design details of our proposed Sandwich greenhouse. Section 3 contains Experiment setup and the instrumentation. Section 4 contains thermal analysis in detail for each component of the greenhouse. Section 5 demonstrates how the heat transfer coefficient of rubber drying is determined, and how to use the thermal modeling in solving equations for determining the temperature and the moisture removal of the greenhouse. Section 6