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Research Paper

Conjugate heat and mass transfer modeling of a new rubber smoking room and experimental validation

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HIGHLIGHTS

- High-efficiency rubber smoking room is designed, constructed and tested.
- Transient conjugate approach is studied in rubber sheet drying by a CFD technique.
- Drying of rubber sheets to include effect of moisture evaporation is investigated.
- The drying time is significantly reduced from 72 to 48 h.

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ABSTRACT

A new rubber smoking room has been designed, constructed and tested for natural rubber sheet smoke drying for better air temperature and flow distributions. Three-dimensional numerical model of rubber sheet drying using a conjugate approach is investigated by a computational fluid dynamics simulation. The optimal 2.5 m × 6.0 m × 3.5 m rubber smoking room contains 40 63.5 mm diameter hot gas supply ducts on the floor and four 0.2 m × 0.2 m and one 0.5 m × 0.5 m ventilating lids on the roof. Velocity and temperature of the drying air, and temperature and moisture content of rubber sheets have been predicted. The experimental and simulation results are in good agreement in terms of statistical parameters. R^2 for temperature and moisture content are 0.980–0.987 and 0.972, respectively, while RMSE are 5.73–6.99 and 2.20. The drying time is significantly reduced from 72 h in a conventional natural-flow smoking room to 48 h in this new design room.

1. Introduction

Natural rubber sheets in the form of ribbed smoked sheet (RSS) are widely used to maintain rubber quality prior to production [1]. Heat and smoke from fuelwood burning are normally used to dry and prolong rubber sheet life. A thorough understanding of heat and mass transfer phenomenon in the rubber sheet drying will guide control of the drying process and thus improve the quality of rubber products. Computational fluid dynamics (CFD) models the fluid flow conditions for predicting the heat, mass and momentum transfer and optimal design in industrial drying processes [2–4]. Various researchers have applied CFD for the analysis and design of rubber sheet drying systems [5–8]. The major problems with existing rubber smoking room are; large variations in temperature (up to 15 °C) and non-uniform flow inside the smoking room which results in poor overall thermal efficiency of the drying system and low-quality RSS production. Improper design of inlet and outlet hot air ducts and inappropriate positions in the smoking room are among the major causes for these problems [5]. Therefore, redesign of the inlet and outlet ducts for maintaining the uniformity in temperature and velocity distributions inside smoke room is needed to enhance overall thermal efficiency and rubber quality. Tekasakul and Promtong [6] increased drying system energy efficiency by improving hot air flow using CFD techniques. The size of modified rubber smoking room was 2.6 m × 6.2 m × 3.6 m. It had 154 hot gas supply ducts of 50 mm diameter on the floor and four 0.25 × 0.25 m ventilating lids at the front and four 0.25 × 0.20 m at the rear side of the roof.

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Although, this model was able to increase uniform drying and reduce fuelwood consumption, RSS drying still takes a minimum 3 days because the flow is by natural convection.

In the previous studies, boundary conditions of convective heat and mass transfer in rubber sheet drying are assumed negligible and only the air phase was simulated [5,6]. Most of previous works have used simple and fast simulation method to compute the heat and mass transfer coefficients at the interface which is non-conjugate approach. These are assumed constant during the drying period for predicting heat and mass transfer [7–12]. Heat and mass transfer coefficients can be used as input to the model. Local heat and mass transfer coefficients are determined from separating a CFD steady-state simulation in the air phase only and these are accounted into unsteady-state simulation [7–10]. This method significantly reduces the computational time. Tekasakul et al. [8] attempted to use the non-conjugated approach in the rubber sheet drying simulation. Results show fair agreement between the experimental and simulation values. However, this approach is not suitable in the forced convection. Simultaneously, heat and mass transfer occurs in both solid and fluid phases during drying. Hence, a conjugate approach is more rational to model drying. It does not require the heat and mass transfer coefficients on the surface of a moist object. These are calculated by running the model [13–24]. Most previous drying process problems have been solved by focusing on heat and mass transfers inside the moist object, and flow fields around are not taken into account [13–18]. Rubber sheet drying process is also a transient conjugate problem, hence, the flow characteristics the drying medium must be considered [19–24].

In the present study, CFD technique using conjugate approach was applied to analyze the heat and mass transfer during the rubber sheet drying period and improve the uniformity in velocity and temperature inside a new rubber smoking room. 3-D turbulent Navier-Stokes equations along with the energy and mass conservation equations of the drying air coupled with the energy and mass conservation equations of rubber sheet were solved. The results were then validated against values obtained from experiment.

2. Experimental setup and instrumentation

A new rubber smoking room was designed and constructed at Saikao cooperative (N7°10′32″:E100°36′52″), located in the Muang District, Songkhla Province, Thailand with an aim to provide uniform velocity and temperature distributions in the drying room. The new rubber smoking room was tested with a full load of 1500 rubber sheets. The room, with dimensions 2.5 m × 6.0 m × 3.5 m, contains 40 63.5 mm diameter hot gas supply ducts at the bottom and four 0.2 m × 0.2 m and one 0.5 m × 0.5 m ventilating lids on the roof, see Fig. 1. The numbers of hot gas supply ducts were less than that proposed by Tekasakul and Promtong [6] and their distribution on the floor was redesigned. The center rear part of the room contains no gas supply ducts to avoid excessive exposure of the rubber sheets to the smoke which causes low quality RSS. The fuelwood was burnt in a 1.2 m diameter cylindrical furnace. Hot air (smoke) was mixed with fresh and recirculated hot air in gravity settling/mixing chamber, and then passed to the drying room under forced convection. Partial recirculation and mixing of exhaust with hot air will reduce fuelwood consumption and improve the thermal efficiency of the drying system. Relative humidity inside the smoking room is maintained by removing humid air through the exhaust vents on the top.

Thermocouples (Type-K) were used for temperature measurement at 12 positions (T1-T12) inside the dryer and one position at the inlet (T13), as shown in Fig. 2. The velocity of inlet air was measured at 3 vertical positions in the inlet duct (V1, V2, V3). Average values from these positions were used. A data logger (Yokogawa, FX112-2-4) recorded the temperature at two minute intervals. Three rubber sheet samples (M1, M2, M3) at different vertical positions were weighed every two hours by a Shimadzu ELB3000 balance.

Experimental uncertainty has been identified for most sensitive observed parameters such as hourly rubber smoke room temperature and rubber sheet sample weight. It is the summation of external and internal percentage uncertainty. The external uncertainty is the least count of the measuring instruments, whereas, internal uncertainty is calculated as [26]:

$$\%\ \text{internal uncertainty} = \frac{U}{\text{mean of total observations}} \times 100 \quad (1)$$

where

$$U = \frac{\sqrt{\sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2}}{N} \quad (2)$$

σ is the standard deviation:

$$\sigma = \frac{\sqrt{\sum (X - \overline{X})^2}}{N_0} \quad (3)$$

$X - \overline{X}$ is the deviation of observation from the mean; and N and N_0 are the number of the sets and number of observations in each set, respectively.

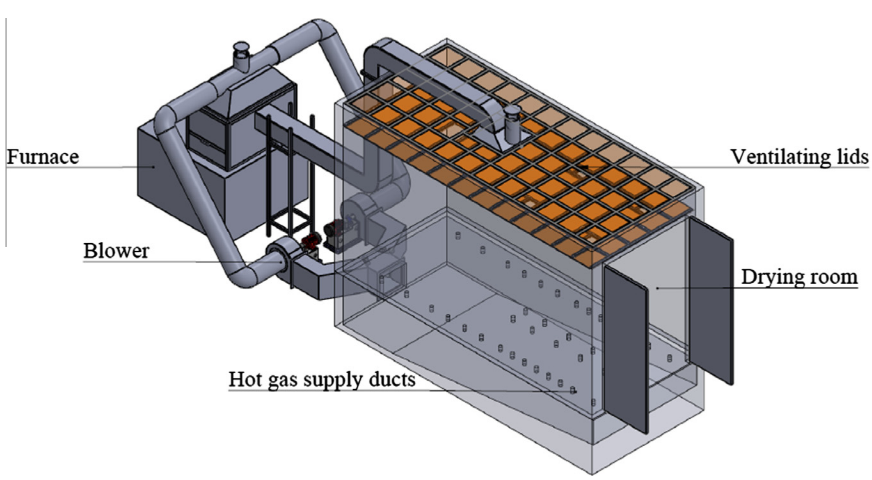

Fig. 1. New rubber smoking room for ribbed smoked sheet drying.