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Research Paper

3D computational fluid dynamics study of a drying process in a can making industry

Surasit Tanthadiloke [a], Warunee Chankerd [a], Ajaree Suwatthikul [a], Patsarawan Lipikanjanakul [a], Iqbal M. Mujtaba [b], Paisan Kittisupakorn [a],*

[a] *Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand*
[b] *School of Engineering, University of Bradford, West Yorkshire BD7 1DP, UK*

HIGHLIGHTS

- A thermal drying oven in a can making industry is simulated via a 3D CFD model.
- Effects of air flow rate in the oven on air velocity patterns.
- Effects of air flow rate in the oven on air temperature.
- Effects of air flow rate in the oven on food-grade lacquer concentration.
- This study would lead to the saving of energy consumption in the oven.

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ABSTRACT

In the drying process of a can making industry, the drying efficiency of a thermal drying oven can be improved by adjusting the volumetric air flow rate of the blower. To maximize drying efficiency, an optimal flow rate is needed. Consequently, a three-dimensional computational fluid dynamics (CFD) is used to provide simulation according to the response of air velocity, air temperature and evaporated solvent concentration with respect to changes in volumetric air flow rate in the drying oven. An experimental study has been carried out to determine the evaporation rate of the solvent. To validate the models, the process data obtained from the CFD is compared with that obtained from actual data. In the accurate models, the simulation results demonstrate that the decrease in volumetric air flow rate provides no major discrepancy of the air velocity patterns in all dimensions and decreases the maximum temperature in the oven. Consequently, this decrease in volumetric air flow rate rapidly increases the evaporated solvent concentration in the beginning and then gradually decreases over the length of the oven. In addition, further reduction of the flow rate gives lower heat loss of the oven up to 83.67%.

1. Introduction

In the can making industry, a food-grade lacquer used for preventing corrosion and chemical reaction inside metal cans [1], is coated on the inner surface of a metal can in order to preserve food quality and prevent contaminants [2]. Normally, the can making process consists of three sections: coating, drying and curing. The process starts by coating the food-grade lacquer solution on both sides of metal sheets which then are sent to a thermal drying oven. Both drying and curing sections are operated inside the oven. In the drying section, air temperature and operating time must be high enough to completely dry the solvent on the surface of the metal sheets. Then, the lacquer is changed from liquid phase to solid phase by forming chemical bonds between the lacquer and the metal sheet surface in the curing section [3].

Generally, parameters relating to the drying efficiency are air velocity, air temperature [4] and evaporated solvent concentration [5]. To increase drying efficiency, the volumetric air flow rate of a blower on the parameters is studied. However, in the real process, varying the air flow rate is rarely allowed due to high investment cost and time involved.

Computational fluid dynamics (CFD) has been widely applied to provide the dynamic behavior such as concentration distributions [6], velocity profiles [7], velocity patterns [8] and temperature

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* Corresponding author.

E-mail addresses: paisanpse@hotmail.com, paisan.k@chula.ac.th (P. Kittisupakorn).

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Nomenclature

A_s	surface area of a metal sheet (m^2)
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	proportionality constants in the standard k-ε turbulence model
C_p	specific heat capacity (J/kg·K)
C_{pa}	specific heat capacity of mixture in the oven (J/kg·K)
C_{po}	specific heat capacity of mixture at outlet surface (J/kg·K)
C_μ	adjustable constant of eddy viscosity in the standard k-ε turbulence model
c_i	concentration gradient of species i (mol/m^3·m)
D_{AB}	mass diffusion coefficient of vapor A through a gas B (m^2/s)
F	volume force (kg/m^2·s^2)
H_v	ventilation heat loss (W)
k	thermal conductivity (W/m·K)
l	turbulent velocity scale (m)
MW_A	molecular weight of substance A (g/mol)
MW_B	molecular weight of substance B (g/mol)
N_i	molar mass of species i (kg/m^2·s)
P_κ	production rate of turbulence kinetic energy (J/m^3·s)
p	pressure (kg/m·s^2)
Q	heat sources (W/m^3)
Q_{vh}	viscous heating (W/m^3)
q_v	volumetric air flow rate (m^3/s)

T	absolute temperature (K)
T_a	oven temperature (K)
T_o	outlet air temperature (K)
t	time (s)
t_e	evaporated time (s)
u	velocity vector (m/s)
V_p	velocity of the metal sheet (m/min)
v_t	kinetic turbulent viscosity (m^2/s)
W_e	weight of evaporated solvent (kg)
W_p	pressure work (W/m^3)

Greek letter

ε	turbulence dissipation (J/kg)
κ	turbulence kinetic energy (J/kg)
μ	viscosity (kg/m·s)
μ_T	eddy viscosity (kg/m·s)
ρ	density (kg/m^3)
σ_ε, σ_κ	Prandtl number in the standard k-ε turbulence model
τ	viscous stress (kg/m·s^2)
Φ_e	evaporation rate (kg/m^2·s)

Mathematic operations

δ	unit tensor
∇	del operator

distributions [9] of several processes with great success. Furthermore, many researchers have reported the modeling and studied the fluid dynamic behavior in several types of ovens such as a convective drying oven [10], a heating oven with natural air circulation [11], a microwave oven [12], a bakery pilot oven [13], a small scale bread-baking oven [14], a paint curing oven [15] and an infrared oven [16].

In this work, a CFD simulation based on a three-dimensional time-dependent model with non-isothermal and transport of diluted species has been used to give the responses of air velocity patterns, air temperature, evaporated solvent concentration and heat loss of the thermal drying oven with respect to volumetric air flow rate. In addition, evaporation rate of the solvent in the developed models is obtained by experiment. The obtained models used in the CFD are validated with actual data gathered from the real process.

2. Experimental study

2.1. Experiment to determine evaporation rate

The evaporation rate of the specific solvent is obtained based on the weight loss of metal sheets coated with solvent; the experiment is carried out with the condition that constant hot air is spread over the surface at constant temperature [17]. The effect of air velocity is assumed to be negligible. In the experiment, a circular sheet of metal, 8 cm in diameter, is used. The experiment starts by heating up the oven temperature to 175 °C. Then, the metal sheet is coated with 0.85 ± 0.05 g of the food-grade lacquer. After that, the coated metal sheet is weighed and placed in the oven. Its weight is recorded at 30, 60, 90, 120, 180, 240 and 300 s, respectively. The velocity of the metal sheet moving through the oven is 2.5 m/min and the evaporation rate is calculated using Eq. (1):

$$\Phi_e = \frac{1}{A_s}\left(\frac{\partial W_e}{\partial t_e}\right) \tag{1}$$

2.2. Configuration of the thermal drying oven

This work focuses on a continuous indirect-fired oven that is used in industry. The CFD geometry of this oven is illustrated in Fig. 1. The oven is 1.2975 m in width, 2.095 m in height and 5.1 m in length [18]. Because of its symmetrical dimensions, either left or right half of the oven has identical behavior. Therefore, only half of the oven is considered in order to reduce the computational time. The definitions of the oven surface are given in Table 1. The solvent used in this work is Butyl Cellosolve (ethylene glycol mono butyl ether; $C_6H_{14}O_2$) and its properties are obtained from the literature [19].

2.3. Modeling and simulation

To develop the models of this process, the following assumptions are made:

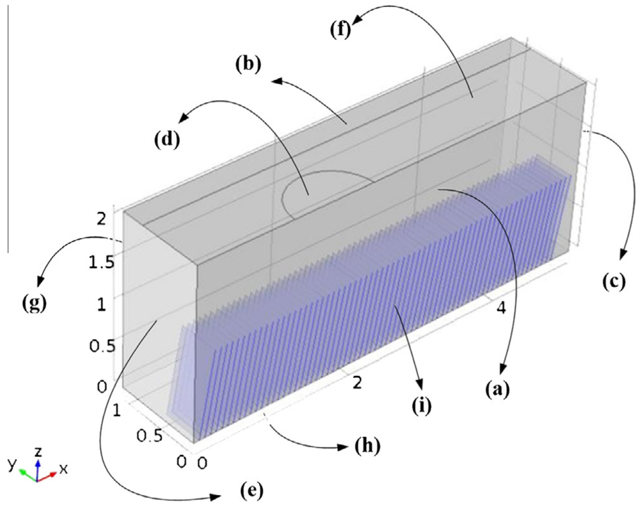

Fig. 1. Geometry of the thermal drying oven.