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3D Computational Fluid Dynamics Study of a Drying Process in a Can Making Industry

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Abstract

In a drying process of a can making industry, a drying efficiency of a thermal drying oven can be improved by adjusting the air volumetric flow rate of a blower. To maximize the 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 air volumetric flow rate the drying oven. The experimental study has been carried out to determine evaporation rate of the solvent. To validate the model, the process data obtained from the CFD is compared with those obtained from actual data. With the accurate model, the simulation results demonstrate that the decrease in air volumetric flow rate gives no major discrepancy of the air velocity pattern in all dimensions, decreases the maximum temperature in the oven, and 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%.

Keyword: CFD, Velocity pattern, Temperature distribution, Concentration distribution, Heat loss, Can making process

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1. Introduction

In a can making industry, a food-grade lacquer used for preventing corrosion and chemical reaction inside metal cans [1], is coated on inner surface of metal can in order to preserve food quality and prevent contaminants [2]. Normally, a can making process consists of three sections: coating, drying, and curing. The process starts with coating the food-grade lacquer solution on both sides of metal sheets which then 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 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 the drying efficiency, air volumetric flow rate of a blower on the parameters is studied. However, varying the air flow rate in the real process is rarely allowed considering to the product's quality.

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 distributions [9] of several processes with great success. Furthermore, many researchers have reported the modelling 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, the 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 pattern, air temperature, evaporated solvent concentration and heat loss of the thermal drying oven with repect to air volumetric flow rate. In addition, an evaporation rate of the solvent in the developed model is obtained from experiment and the obtained model used in the CFD is validated with actual data gathering 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 of constant hot air pass through the surface at constant temperature [17]. The effect of air velocity is assumed to be negligible. An 8-centimeters circle shape of metal sheet is used in the experiment. This experiment starts with heating up the oven temperature to 175 $^{\circ}$C and then the metal sheet is coated with 0.85 ±0.05 g of the food-grade lacquer. After that, the coated metal sheet is weighted and placed in the oven. Its weight is recorded at 30, 60, 90, 120, 180, 240, and 300 seconds, 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).

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

2.2 *Configuration of the thermal drying oven*

This work focuses on a continuous indirect-fired oven that uses in a real industry. The CFD geometry of this oven is illustrated in Fig. 1. The dimensions of the oven are 1.2975 m width, 2.095 m height, and 5.1 m 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 ethylene glycol mono butyl ether ($C_6H_{14}O_2$) or called Butyl Cellosolve and its properties are obtained from the literature [19].

2.3 *Modelling and simulation*

To develop the models of this process, assumptions are made as follows.

- Air humidity in the oven is ignored.
- Metal sheets in the oven are located and moving along the oven.
- Butyl Cellosolve concentration is only observed in the mixing air in the oven.
- Evaporation is not occurred at an inlet air surface.
- Evaporation rate is assumed to be identical throughout the metal sheets surface but varying along the length of the oven.

Models are derived from conservative equations in Cartesian coordinate with time dependent and based on the turbulent Reynolds Averaged Navier-Stokes equation (RANS) [20]. The standard k-ε turbulence flow model, consisting of a turbulence kinetic energy (κ) and a viscous dissipation (ε) equation, is used for providing the dynamic behavior of fluid flow in complex geometries [12]. The non-isothermal model is generated from the combination of mass and heat transfer models coupled with the transport of diluted species. Equations derived are written as follows.

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{2}$$

Momentum conservation equation

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = -\nabla p - [\nabla \cdot \tau] + F \tag{3}$$

Energy conservation equation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + Q_{vh} + W_p \tag{4}$$

From Eq. 3, the viscous force (τ) can be presented by

$$\tau = -\mu(\nabla u + (\nabla u)^t) + \left(\frac{2}{3}\mu - \mu_T\right)(\nabla \cdot u)\delta \tag{5}$$

Turbulence kinetic energy equation

$$\frac{\partial(\rho\kappa)}{\partial t} + \rho(u \cdot \nabla)\kappa = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\kappa}\right)\nabla\kappa\right] + P_\kappa - \rho\varepsilon \tag{6}$$

Viscous dissipation equation

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \rho(u \cdot \nabla)\varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\kappa\right] + C_{\varepsilon 1}\frac{\varepsilon}{\kappa}P_\kappa - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{\kappa} \tag{7}$$

Where, $\mu_T = \rho C_\mu \frac{\kappa^2}{\varepsilon}$ (8)

$$P_k = -\mu_T\left[\nabla u : (\nabla u + (\nabla u)^t) - \frac{2}{3}(\nabla \cdot u)^2\right] - \frac{2}{3}\rho k \nabla \cdot u \tag{9}$$

The boundary conditions of this simulation are listed in Table 2 and the values of adjustable constants i.e. C_μ, σ_k, σ_ε, $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are 0.09, 1.00, 1.30, 1.44 and 1.92, respectively

[21]. The concentration of the evaporated solvent (Butyl Cellosolve) in the oven is calculated from Eq. (10) and Eq. (11) [22]. In addition, the heat loss from the oven can be calculated using Eq. (12).

$$\frac{\partial c_i}{\partial t} + u \cdot \nabla c_i = \nabla \cdot -(D_{AB} \nabla c_i) + \nabla \cdot N_i \tag{10}$$

$$D_{AB} = \frac{4.14 \times 10^{-4} T^{1.9} \sqrt{1/MW_A + 1/MW_B}\ MW_A^{-0.33}}{p} \tag{11}$$

$$H_V = q_V \times \rho \times \left(C_{pa} \times T_a - C_{po} \times T_o\right) \tag{12}$$

In this work, COMSOL multiphysics software with written models developed is used to give the simulation of the process. The grid geometries are generated in free tetrahedral. The grid refinement has been tested with three different grid geometries, i.e. coarse, normal and fine grid, in order to select simulation results with low computational time and high accuracy. From the grid refinement test, simulations with normal and fine grids give the best simulation results compared with the actual data but simulation with normal grid consumes lower computational time of about 20 % than that with fine grid. Accordingly, the normal grid geometries with 777,270 domain elements, 57,043 boundary elements, and 5,713 edge elements are selected for this simulation. To validate the models, the oven temperature is simulated and compared with the actual data at three points. Point 1, 2 and 3 are located at 0.08 m from the top, the middle and the bottom of the metal sheet, respectively. The air volumetric flow rates used in the CFD simulation are divided into 10 cases: case (A) to (J). The flow rate of the case (A) or the conventional case is 1.67 m^3/s, and is reduced by about 10% interval for next cases. Therefore, the flow rates used in case (B) to (J) are 1.50, 1.33, 1.17, 1.00, 0.83, 0.67, 0.50, 0.33 and 0.17

m^3/s, respectively. Simulation results for all cases are compared to evaluate the effects of the flow rate on the parameters.

3. Results

3.1 *Determination of evaporation flux rate*

The experimental results illustrated in Fig 2 show that evaporation flux rate of Butyl Cellosolve changes along the oven length in the range of 0.947 to 0.017 x 10^{-3} $kg/m^2{\cdot}s$. The highest evaporation rate occurs at the entrance of the oven because of the high amount of solvent on the surface of the metal sheet and no accumulation of evaporated solvent in the air around this area [5]. Subsequently, the rate rapidly decreases along the length of the oven to almost zero due to the increasing of evaporated solvent in the air and low amount of solvent remaining on the surface.

3.2 *Validation of the models used in the CFD*

The simulation results, obtained from the developed model, of air temperature profiles at three selected points are validated with the actual data gathered from the industry and illustrated in Fig. 3. These results show that the developed models can represent the actual process and can be used in CFD simulation; the accuracies evaluated between the simulation and actual data at point 1, 2, and 3 are very high with the errors of 5.19%, 4.49%, and 4.73%, respectively.

3.3 *Effect of air volumetric flow rate on air velocity pattern*

The air velocity patterns with the colored contour of the air velocity magnitude at the steady state are shown in Fig. 4. The air initially flows into the oven from the top at the surface (b) and circulates inside the oven. Then the air is pulled out through the air outlet duct by the blower. The air direction in some area at the bottom can be changed by the obstruction of the metal sheets in the oven. The results from all cases demonstrate that the change in air volumetric flow rate gives no major discrepancy of the air velocity pattern in all dimensions and the maximum velocity is corresponding to the air flow rate.

In addition, the study of the air velocity field in 3 directions: x-direction (length of the oven), y-direction (width of the oven) and z-direction (height of the oven) are given in a contour of two-dimensional (x-z plane) and can be used for describing the dynamic behavior in the oven.

3.3.1 *Air velocity field in x-direction*

The default direction of the air velocity in the x-direction is left-to-right. Fig. 5 shows that all cases have similar velocity field but different in the ranges of velocity. The air velocity field at the top of the oven is higher than that at the bottom because of the blockage of the air flow by the metal sheets which leads to very little air flow movement at the bottom. Fig. 6 shows the average air velocity along the length of the oven with different air volumetric flow rates.

The air velocity continuously rises from the entrance and then starts to decrease at the distance around 1.1 to 2.3 m from the entrance. In these distances, the air velocity rapidly changes from the positive to negative values because of the ventilation force from the blower in the z-direction. The air velocity decreases to zero at around 1.7 m from the entrance so the change in air velocity direction takes place at this point.

3.3.2 *Air velocity field in y-direction*

Due to the symmetry in the width of the oven, the air velocity patterns in both left and right sides of the oven are mirror symmetry. Accordingly, the air velocity field across the symmetry boundary is equal to zero.

3.3.3 *Air velocity field in z-direction*

In Fig. 8, the positive and maximum values of air velocity are observed at the area about 0.9 to 2.2 m from the entrance due to the fact that the air is forced to flow up to the top by the ventilation from the blower. After that, the air velocity begins to decrease until its values become negative again because the ventilation force from the blower has no effect.

The upward direction of air velocity is specified as the positive value. Fig. 7 demonstrates that although the velocity fields are slightly different in each case but the magnitudes of the air velocity are rather different according to the air flow rates. The velocity field in some areas at the top has negative values because of the inlet air flows downward into the oven at the surface (b). From Fig. 8, the decrease in the air flow rate causes low ventilation force by the blower and reduce the magnitude of the velocity in the oven. The positive and maximum values of air velocity are observed at the area about 0.9 to 2.2 m from the entrance due to the fact that the air is forced to flow up to the top by the ventilation. Afterward, the air velocity begins to decrease until its values become negative again because the ventilation force by the blower has no effect.

3.4 *Effect of air volumetric flow rate on temperature distribution*

Air temperature distribution affected by different air volumetric flow rates is simulated by giving the initial air temperature 27°C at the entrance and the oven temperature is controlled at 175°C. The CFD simulation results of air temperature in the oven at the steady state in three dimensions are illustrated in Fig. 9. The air temperature distributions in all cases are rarely different because the inlet air temperatures are almost identical. The air temperature is 27°C at the entrance and then is raised to the controlled temperature at around 2 m from the entrance. It can be seen that the air temperature is raised to the controlled temperature in quicker time when the air flow rate is lower due to longer contact time between air and metal sheets.

3.5 *Effect of air volumetric flow rate on evaporated solvent concentration*

Since the concentration of the evaporated solvent has negative association with the evaporation rate, so the highest evaporated solvent concentration takes place at the entrance area due to no accumulation of the evaporated solvent. Fig. 10 demonstrates that the concentration distributions in all cases have the same patterns and the maximum concentration of the evaporated solvent increases when the air volumetric flow rate decreases. This is because when the air volumetric flow rate is low, the evaporated solvent cannot be vented out and therefore the evaporated solvent accumulates inside the oven. As shown in Fig. 11, simulation results are in good agreement with the experiment. The maximum concentration occurs at 0.3 m from the entrance and then gradually decreases due to less of ventilation force from the blower and evaporation flux rate in that area.

3.6 *Effect of air volumetric flow rate of heat loss*

The air flow rate and air temperature at the outlet are directly affected by the heat loss of the oven. The heat loss from the oven can be decreased by lowering the air volumetric flow rates. In addition, the percentages of the heat loss saving are determined based on the conventional case (1.67 m^3/s) and summarized in Table 3. The results show that the heat loss can be saved by reducing the air flow rate. The heat loss saving is up to 83.67% by decreasing the flow rate to 0.17 m^3/s.

4. Conclusion

Three-dimensional computational Fluid Dynamics (CFD) with non-isothermal coupled with the transport of diluted species of a thermal drying oven in a can making process have been developed to study the dynamic behavior of fluids in a drying zone inside the thermal oven. In this study, an unknown parameter needed in the model, evaporation flux rate of solvent (Butyl Cellosolve), has been determined based on experimental data. Effects of air volumetric flow rate on process variables: air velocity pattern, air temperature, evaporated solvent concentration and heat loss of the thermal drying oven, have been investigated.

Experiments have been carried out to obtain the value of evaporation flux rate in the models. It was found that the flux rate is varied along the oven and has the values in the range of 0.947 to 0.017 x 10^{-3} kg/m^2·s. The evaporation flux rate is the highest at the beginning point and gradually decreases along the distance of the oven. With this obtained flux rate, the developed models can acceptably represent the real process with good accuracy; the air temperature obtained from the models are corresponding to the measurement data with the average error of less than 12 %. Air velocity patterns for all cases are almost identical but the velocity magnitude is varied according to air volumetric flow rate. In addition, the air temperature in the oven in all cases starts from an ambient temperature and is raised to the controlled temperature of 175^{o}C. For the concentration of evaporated solvent, the concentration is rapidly increased and then gradually decreased due to the decreasing of evaporation flux rate and the ventilation force of the blower. The study of the effects of air volumetric flow rate on the evaporated solvent concentration represent that the reducing of the air volumetric flow rate causes the increasing of the evaporated solvent concentration. Furthermore, every 10% reducing in air volumetric flow rate from the conventional case increases the heat loss saving by 10.40 %, 19.81 %, 30.30 %, 39.61 %, 48.23 %, 59.68 %, 68.60 %, 71.13 % and 83.67 %, respectively.

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Nomenclature

A_s	Surface area of a metal sheet (m^2)
$C_{\mathcal{E}1}$, $C_{\mathcal{E}2}$	Proportionality constants in the standard k-Ɛ 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-Ɛ 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	Air volumetric flowrate (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)
$\mathrm{V_p}$	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-Ɛ turbulence model

τ Viscous stress ($kg/m \cdot s^2$)

Φ_e Evaporation rate ($kg/m^2 \cdot s$)

Mathematic operations

δ Unit tensor

∇ Del operator

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