The Study of Thermal process and Temperature Calibration for a Vacuum Drying Oven Based on Numerical Simulation

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Abstract. Vacuum drying technique is widely used in food processing, pharmaceutical and other industries which need to be calculated regularly. In order to establish temperature calibration method for vacuum drying oven, temperature profile needs to be studied. In this paper, a three-dimensional (3D) unsteady mathematical model has been developed to study heat transfer in a vacuum drying oven. Governing equations are discretized in implicit form by using the control volume method. PRESTO! scheme was used for the discretization of the pressure modified equation. SIMPLE algorithm is adopted to solve the coupling of pressure and velocity. The natural-convection flow forced by buoyancy force was numerically calculated based on Boussinesq assumption. Results of the model calculation showed that temperature distribution in the vacuum drying oven significantly changed when the pressure in the oven is close to vacuum. Temperature uniformity in the vacuum drying box increases with the increase of vacuum degree. It is not appropriate to directly investigate the temperature uniformity of the vacuum drying oven by using JJF 1101-2019. The results can be used to lay a theoretical foundation for the establishment of calibration method for vacuum drying oven.

Keywords: Temperature calibration; Vacuum drying oven; Numerical simulation; Unsteady model.

1. Introduction
Vacuum drying technique is used to dry sample under low pressure where the boiling point of water is lower than that of under atmospheric pressure. Compared with drying technology at atmospheric pressure, vacuum drying technique can dry the material at normal temperature or even lower temperature, which is widely used in food processing, pharmaceutical and other industries[1,2]. Vacuum drying oven is one of the key equipments used in vacuum drying technique. The accuracy of temperature measurement inside the oven has an important impact on the drying samples and the quality of the products. Therefore, it is necessary to calibrate the temperature of vacuum drying oven regularly. At present, there is no national calibration standard for vacuum drying oven in China, and the calibration of temperature in vacuum drying oven is usually carried out by referring to JJF 1101-2019[3]. However, due to the change of heat transfer mechanisms in vacuum drying oven, JJF 1101-2019 is probably not suitable for temperature calibration of vacuum drying oven. Heat transfer mechanisms inside the vacuum drying oven include natural convection and radiation. Natural convection heat transfer has been studied by many researchers through mathematical models. Kuznetsov[4] established a mathematical model to study turbulent natural convection within a rectangular enclosure. Boussinesq assumption and k–ε turbulence model were used in the model. Horvat[5] established two-dimensional mathematical models for a square cavity where internal heat generation within to study natural convection. Both laminar and turbulent natural convections were considered in the models with Rayleigh numbers ranging from $10^6$–$10^{11}$. Tou[6] studied the effects of
inclination on heat transfer in a rectangular enclosure filled with liquid by developing a mathematical
model. Yang [7] establish a 2D unsteady model to study natural heat transfer in a tall rectangular cavity
by using direct numerical simulation method. Yang [8] developed a three-dimensional mathematical
model to study natural convection in annulus with Rayleigh number ranging from 10 to 10^6. SIMPLE
algorithm is adopted to solve the coupling of pressure and velocity.

The purpose of this paper is to develop a mathematical model to study temperature profile in a vacuum
drying oven. Temperature changes over time at different locations in the vacuum drying oven and
temperature distribution on the symmetric vertical surface under different pressures at a certain time
are obtained. Temperature uniformity in the vacuum drying oven was analyzed. The results can be
used to lay a theoretical foundation for the establishment of calibration method for vacuum drying
oven.

2. Establishment of the Model

2.1. Physical Model and Assumptions

The working space of the vacuum drying oven is cuboids. Air is used as the working media. To
develop a mathematical model for the vacuum drying oven, the Boussinesq assumption [9] is accepted. In
the assumption, the density in the buoyancy term of the governing equations varies with temperature
and can be calculated as Eq. 1, while density in other terms of the governing equations are assumed to
be constant.

\[
\rho = \rho_0 [1 - \beta (T - T_0)]
\]

where \(T\) is the temperature of air, \(K\), \(T_0\) is the reference temperature, \(K\), \(\rho_0\) is the reference density, \(kg/m^3\).

2.2. Governing equations

Continuity equation:

\[
\frac{\partial (\rho)}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

Momentum equation:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} + \frac{\partial (\rho vu)}{\partial y} + \frac{\partial (\rho wu)}{\partial z} = -\frac{\partial p}{\partial x} + \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho wv)}{\partial z} = -\frac{\partial p}{\partial y} + \eta \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \eta \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) - \rho g
\]

Energy equation:

\[
\frac{\partial (\rho uT)}{\partial x} + \frac{\partial (\rho vT)}{\partial y} + \frac{\partial (\rho wT)}{\partial z} = \frac{\lambda}{c_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

where \(t\) is the time, \(s\); \(u\) is the velocity in \(x\) direction, \(m/s\); \(v\) is the velocity in \(y\) direction, \(m/s\); \(w\) is the velocity in \(z\) direction, \(m/s\); \(p\) is the pressure inside the vacuum drying oven, \(Pa\); \(\eta\) the dynamic
viscosity, \(kg/(m\cdot s)\); \(\lambda\) is the thermal conductivity of air \(W/(m\cdot K)\); \(c_p\) is the specific heat at constant
pressure, \(J/(kg\cdot K)\).
Radiation between the inner walls is another way for heat transfer in the vacuum drying oven. Since air is the working medium in vacuum drying oven, which does not participate in radiation heat transfer, S2S model is used to solve radiation heat transfer.

### 2.3. Initial and Boundary Conditions

#### (1) Initial conditions

\[ T = 293.15K, t = 0 \]  
\[ P = P_0, t = 0 \]  

#### (2) Boundary conditions

\[ T_L = 323.15K, u=0, v=0, w=0 \text{ (on the left sidewall of the vacuum drying oven)} \]  
\[ T_R = 313.15K, u=0, v=0, w=0 \text{ (on the right sidewall of the vacuum drying oven)} \]  
\[ q = 0, u=0, v=0, w=0 \text{ (on the other walls of the vacuum drying oven)} \]

The \( q \) in Eq.(11) is the heat flux through the wall, \( w \).

### 2.4. Numerical Method

To solve the natural heat transfer mathematical model in the vacuum drying oven, the control volume method is used to discretize the governing equations together with boundary condition and initial condition in implicit form. And the discretized equations are solved by the separate solver. First-order implicit scheme was used for unsteady term. Second-order windward scheme was used for the convection term, and PRESTO! scheme was used for the discretization of the pressure modified equation. SIMPLE algorithm is adopted to solve the coupling of pressure and velocity.

### 3. Verification of the Model

To verify the model, temperature field in vacuum drying oven under normal pressure was measured. AA level industrial platinum resistance thermometers and temperature inspection instrument are used as temperature measuring equipment. In order to reduce the influence of temperature sensors on the tightness of vacuum drying oven, only two industrial platinum resistance thermometers are arranged at the center of upper and lower surfaces respectively. The wire of the thermometers is led out from the door of the oven, and temperature value of platinum resistance is read by the temperature inspection instrument. Table 1 shows the comparisons of computed and measured temperatures. The temperatures calculated by the model are consistent with the experimental data well. The maximum error of the computed temperature is -0.66 °C, which indicates that the mathematical model developed in the paper can be used to simulate natural heat transfer in vacuum drying oven.

| Testing points       | Measured results(°C) | Computed results(°C) | Absolute error(°C) |
|----------------------|----------------------|----------------------|--------------------|
| At the center of upper surface | 47.51               | 46.85               | -0.66              |
| At the center of lower surface    | 43.87               | 43.35               | -0.52              |

### 4. Results and Discussion

Three parallel planes were selected along the height direction of the vacuum drying box, and nine points were selected on the plane shown in Figure 1. Among those points, \( P_1\text{-}P_8 \) were located near the eight corners of the vacuum drying box, 50 mm away from the vacuum drying oven wall and \( P_0 \) was located at geometric center of the vacuum drying oven. Figure 2 shows temperature changes with time at different positions in the vacuum drying oven under atmospheric pressure and close to vacuum. As can be seen from the figure, temperature curves can be divided into two stages. Temperatures rise
rapidly at initial heating stage, and with the increase of time temperature curves tend to be stable. The final temperature differs at different positions in the vacuum drying oven. In other words, temperature distribution in the vacuum drying oven is not uniform under cases of both atmospheric pressure and close to vacuum.

![Figure 1](image1.png)

**Figure 1.** Distribution of temperature analysis points.

![Figure 2](image2.png)

**Figure 2.** Changes of temperature over time at different locations in vacuum drying oven.

![Figure 3](image3.png)

**Figure 3.** Temperature distribution on the symmetric vertical surface under different pressures at the time of 400s.

Figure 3 shows temperature distribution on the symmetric vertical surface under different pressure at the time of 400s. In the cases of $P = 101325$ Pa, temperature in the upper of the surface is higher than in the lower of the surface. However, when the pressure in the oven is close to vacuum ($P = 1013$ Pa), temperature distribution on the surface changes significantly, temperature on the right of the surface is higher than on the left of the surface. This is because, in the cases of $P=101325$Pa, there is a lot of air
in the vacuum drying oven, and natural heat transfer plays an important role. However, in the case of \( P = 1013 \) Pa, there is little air in the oven, and heat transfer is mainly carried out by radiation.

![Figure 4. The changes of temperature uniformity under different pressures.](image)

Temperature uniformity is defined as the difference between the highest and the lowest temperatures of 9 points shown in Figure 2. The greater the uniformity, the more unevenly the temperature field is distributed. Figure 4 shows the changes of temperature uniformity under different pressures in the vacuum drying oven. The temperature uniformity inside the vacuum drying oven decreases with the increase of time under the pressure of 101325 Pa. Temperature field inside the vacuum drying box becomes more uniform, and the final temperature uniformity of the vacuum drying oven temperature is 5.8°C. While, under the pressure of 1013 Pa, temperature uniformity curve in the vacuum drying oven reached stability quickly, and the final temperature uniformity is 3.1°C. Compared with vacuum, the temperature distribution under normal pressure is more uniform.

5. Conclusion

A 3D unsteady mathematical model for simulation natural-convective flow and heat transfer in the vacuum drying oven was established in this paper. Boussinesq assumption was accepted to model natural convection and S2S radiation model was used to calculate radiative heat transfer. The conclusions were obtained as follows.

(1) Compared with pressure of 101325Pa, temperature distribution in the vacuum drying oven significantly changed when the pressure in the oven is close to vacuum. This is because, in the cases of one atmosphere, heat transfer by natural convection plays an important role. However, when the pressure is close to vacuum, heat transfer is mainly carried out by radiation.

(2) Temperature distribution in the vacuum drying oven is not uniform under cases of both atmospheric pressure and vacuum. With the decrease of pressure, temperature uniformity in the vacuum drying box increases for radiation heat playing a more and more important role with the increase of vacuum degree.

(3) Under both vacuum and atmospheric pressure, the temperature uniformity in the vacuum drying oven does not meet the requirements of JJF1101-2019 (no more than 3°C). Therefore, it is not appropriate to directly investigate the temperature uniformity of the vacuum drying oven by using JJF 1101-2003.

(4) Since the temperature distribution in the vacuum drying oven is very different from that in the drying oven at atmospheric pressure, it is suggested that wireless temperature equipments should be used to calibrate temperature in the vacuum drying oven under vacuum. Therefore, the calibration results can reflect the temperature distribution under the working state of vacuum drying oven.
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