Radiation Heat Transfer of In-line Infrared Halogen Lamp Tube of Vacuum Freeze-drying

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Abstract

In recent years, the vacuum freeze-drying technology has been widely applied in material science, but it still has the disadvantage of long drying time. Among various vacuum freeze-drying heating technologies, the thermal radiant heating is the cleanest, safest and quickest. Therefore, this study employed the CFD software CFD-ACE* to simulate the thermal radiation phenomenon of three-dimensional in-line halogen lamp tube heating. The model was a cylindrical vacuum chamber with a diameter of 0.355m and a length of 0.5m, with 2 pieces of drying materials placed between heating lamp tubes. This study considered natural convection occurred inside the vacuum chamber to explore the influence of setting density of 9 halogen lamp tubes and 2 kinds of distance between lamps and drying materials upon heating uniformity, where the total heating power of the lamp tubes is 10 and 100W. It aimed to improve the heating uniformity of drying materials while conforming to energy efficiency and providing dried materials with better appearance. The results showed that the denser setting density of halogen lamp could enhance the uniformity of heating temperature distribution of materials. Furthermore, under fixed setting density of lamp tubes, although increasing the distance between halogen lamps and drying materials would decrease the average heating temperature of materials, the heating temperature of materials would be more uniform. The results can serve as a reference to the designer of heating lamps for vacuum freeze-drying equipment of thermal radiation.

Keywords: Radiation, Freeze-drying, Heat transfer, vacuum

I. Introduction

In recent years, the vacuum freeze-drying technology has been widely applied in material science, but it still has the disadvantage of long drying time. Among various vacuum freeze-drying heating technologies, the thermal radiant heating is the cleanest, safest and quickest. Therefore, this study employed the CFD software CFD-ACE* to simulate the thermal radiation phenomenon of three-dimensional in-line halogen lamp tube heating. Furthermore, numerical methods were employed to predict and analyze the heating mechanism of the heat radiation to provide related design suggestions to reduce the freeze-drying equipment costs, energy consumption, shorten product manufacturing time, improve product yield and expand the vacuum freeze-drying technology applications. The review of literature in the past a few years relating to vacuum freeze-drying system and heat transfer study is as follows:

The issue of concern in this study is the halogen lamp tube heating uniformity of drying materials. However, heating uniformity is very important to the slow and expensive manufacturing process while vacuum freeze-drying process energy consumption has been mentioned in the literature in many occasions. For example, the energy required in the sublimation of frozen water during the primary drying process [1-7], the energy required to remove the bond water during the primary and secondary drying processes [2-8], the energy required to keep the vacuum of the manufacturing chamber [3,9-13], all of the above energy consumptions are closely related to drying time. Therefore, proposals to shorten and manage drying time have been made in literature in many occasions [3,9-13]. In early literature[11,12], it was studied that, during the primary drying process, under fixed drying area and drying temperature, the radiation heat and manufacturing process chamber pressure were controlled to shorten drying time. The disadvantage was that the study was on primary drying only without taking into consideration of bond water and the heat below or around the drying materials.

Regarding the shortening of drying time, in some literature it was illustrated [14-22] microwave might be employed as the heat source to speed up the vacuum freeze-drying. In all of these occasions in literature, microwave was believed to have very good application potentials in vacuum freeze-drying manufacturing process for foodstuffs. Many people proposed many mathematical models to describe the microwave vacuum freeze-drying process. Copson first put forward in 1962 the pseudo steady-state model followed up by similar models proposed by many others [15, 18, and 19]. Ma and Peltre [23] proposed the one-dimensional transient model to be the first model able to describe the microwave vacuum freeze-drying transient process. Afterwards, Ma and Peltre [18, 19] spent more efforts in improving the accuracy of Copson's model, and Ang et al. [20] expanded it into a two-dimensional model to be able to describe non-isotropic materials. It can be learnt from literature that [24] the air-drying, freeze drying, and freeze drying with far-infrared radiation methods were employed in potato for comparison of drying time. And it was proved that the freeze drying with far-infrared radiation method can save more drying time. In addition, radiation heat, shelf type vacuum freeze-drying and microwave were integrated as the source of heat in some studies as suggested by literature [19][25-27].

In some occasions of the literature, computer numerical simulation of vacuum freeze-drying was carried out including using finite difference method [6, 28-30], finite volume method [31-33]. As given grid point...
finite volume method can result in relatively stable computation process, one-dimensional or two-dimensional detailed computation discussions were made in some studies as well [31, 32].

II. Radiation Heat Transfer of Vacuum Freeze-drying

Vacuum freeze-drying a continuous process, respectively, of the freezing process, the primary drying process (or sublimation), and the secondary drying process (or desorption). The sublimation process in low temperature/low pressure environment is achieved through continuous pumping by vacuum pump of the vacuum chamber. When the vacuum chamber pressure is sufficiently low, heat up the materials to make the ice within the materials sublime and the sublimation vapor is condensed by condenser while the dry air was pumped out of the vacuum chamber by the vacuum pump.

As the vacuum freeze-drying technology was first widely applied in food and pharmaceutical industries, the vacuum freeze-drying machines used in the two industries are mainly of shelf type design as it is mainly characterized as all the above vacuum freeze-drying manufacturing process steps are integrated in a same manufacturing process chamber. Therefore, most of the current vacuum freeze-drying machines are of shelf type design with the main manufacturing process steps as follows:

1. The drying materials are placed in liquid at ambient temperature on the shelf of the process chamber, and the drying materials are frozen by low temperature shelf.
2. The primary drying and the secondary drying are done by the reduction of process chamber pressure and the gradual warming of the shelf.
3. When the drying materials meet up with the drying standards, the process chamber is restored from the vacuum condition to one atmospheric pressure condition.
4. Take out the drying materials out of the process chamber of pressure restored to one atmospheric pressure and complete all vacuum freeze-drying procedures.

It can be learnt from the above descriptions that the shelf has two functions, respectively, of reducing temperature to freeze drying materials and raising temperature to provide heat to the drying materials. However, the biggest disadvantage of the shelf type vacuum freeze-drying machine as applied in other industries is the too long time for freezing and drying. The reason is that the shelf heat transfer mechanism is relied for heat transfer in the product freezing/drying processes. Hence, the integration of the vacuum freeze-drying process in a process chamber as an advantage turns out to be a fatal disadvantage thanks to the too long process. The disadvantage of long time process of the shelf type vacuum freeze-drying time is more conspicuous in case of applications in products of poor thermal sensitivity, large handling capacity and relatively low price.

In order to improve the above-mentioned disadvantages to enable the vacuum freeze-drying technology to be more widely applied in other industries, it has become a considerably important topic to shorten the material manufacturing time, speed up material drying rate and enhance product yield. To solve this problem, the following steps are taken to enhance product yield:

1. Use air cooling refrigerator to freeze products.
2. Product primary and secondary drying are conducted through the process chamber pressure reduction and heat transfer mechanism of the heat radiation.
3. When the drying materials meet up with the drying standards, the process chamber is restored from the vacuum condition to one atmospheric pressure condition.
4. Take out the drying materials out of the process chamber of pressure restored to one atmospheric pressure and complete all vacuum freeze-drying procedures.

Regarding the above-mentioned process steps, the products can first be frozen in large quantity in air cooling refrigerator. After freezing, the products are put into the vacuum manufacturing chamber in batch for secondary/primary drying procedures by heat radiation. The biggest advantage of this manufacturing process is the ability to freeze products in large quantity and reduce shelf of the vacuum freeze-drying machine. Hence, the shelf, the secondary refrigerant heat exchanger, low temperature fluid transfer pump, the cooling system refrigerant sub-system device can be reduced, and the control process as well as the related control components can be simplified. However, the difficult points this technology is required to overcome include how to effectively use the vacuum chamber space to design heat radiation structure and how to select what type of heat radiation components. In addition, how to effectively control the heat transfer volume to avoid the melting of the products is also an important topic. Hence, this study, with respect to the in-line halogen lamp tube heating structure as illustrated in Figure 1, employed the numerical simulation CFD software to predict and analyze the heat radiation type vacuum freeze-drying technology, focusing on the impact of halogen lamp tube density and the change of the distance between the tube and the materials on the material surface heating uniformity.
Case simulation of this study: comparative analysis of different combinations of halogen lamp tube density, tube-material distance and tube total heat volume, case numbers are as shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1 simulation case numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halogen lamp tube density</td>
</tr>
<tr>
<td>Halogen lamp tube total number</td>
</tr>
<tr>
<td>Tube distance (m)</td>
</tr>
<tr>
<td>Halogen lamp tube total heat volume (W)</td>
</tr>
<tr>
<td>Total heat volume Heat Flux (W/m²)</td>
</tr>
<tr>
<td>Tube-material distance</td>
</tr>
<tr>
<td>0.015 m</td>
</tr>
<tr>
<td>0.045 m</td>
</tr>
<tr>
<td>Halogen lamp tube total heat volume (W)</td>
</tr>
<tr>
<td>Total heat volume Heat Flux (W/m²)</td>
</tr>
<tr>
<td>Tube-material distance (m)</td>
</tr>
<tr>
<td>0.015</td>
</tr>
<tr>
<td>0.045</td>
</tr>
</tbody>
</table>

III. Numerical Method

In this study, the software suite CFD-ACE™ developed by ESI Group was employed to simulate the heat transfer phenomenon of the heat radiation drying mechanism with a view to identifying better heat radiation method. During the heat radiation vacuum freeze-drying process, CFD was mainly employed for drying material surface temperature distribution. And that CFD software was able to be employed for numerical simulation in vacuum environment. Mainly on the basis of model full size conditions and setting process vacuum, the gas mean free path was calculated at first \( \lambda = 0.0714 \) cm. afterwards, work out with the mean free path and chamber diameter \( Kn \) (Knudsen number) \( = 0.00201 \), being less than 0.01, hence the gas inside the chamber can be regarded as a viscous flow and an rough vacuum.

When using the Flow model for simulation, in vacuum, the atmosphere density \( (\rho) \) dropped with decreasing pressure. Therefore, work out with the model full size conditions, \( Re \) (Reynolds number) \( = 0.2233 \), being far smaller than 2200. As a result, the air flow is a laminar flow. Hence, in simulation, turbulent flow impact on the overall fluid field was not discussed. The detailed numerical methods relating to CFD-ACE™ can refer to the manual of the software for instructions, relevant key points of which are briefly introduced below.

- Governing Equations

CFD-ACE™ uses finite volume method for the discrete governing equations, which include the continuity, momentum, energy and the heat radiation
model equations. The heat radiation model uses the discrete ordinate method; and the equations are as listed below:

Continuity equation (Continuity)
\[ \nabla \cdot (\rho \mathbf{V}) = 0 \]

Momentum equation (Momentum)
The x-component of the momentum:
\[ \frac{\partial}{\partial x} \left( \rho u \right) = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) + \rho f_x \]
The y-component of the momentum:
\[ \frac{\partial}{\partial y} \left( \rho v \right) = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right) + \rho f_y \]
The z-component of the momentum:
\[ \frac{\partial}{\partial z} \left( \rho w \right) = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left( \mu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial w}{\partial y} \right) + \rho f_z \]

Heat transfer equation (Heat transfer)
\[ \nabla \cdot (\rho \mathbf{V} \cdot k \mathbf{T}) = \nabla \cdot (\rho \mathbf{V} \cdot (\lambda \nabla T)) \]

Heat radiation equation
The heat radiation equation setting adopted the discrete ordinate method most widely applied in engineering industries:

\[ C_m \frac{\partial u_m}{\partial x} + \left( \frac{\partial u_m}{\partial y} \right) \frac{\partial u_m}{\partial y} + \left( \frac{\partial u_m}{\partial z} \right) \frac{\partial u_m}{\partial z} = -(\alpha_m + \alpha_{mH}) u_m + \sum_{m} \alpha_{mH} f_{mH} \]

· Boundary Setting and Computing Lattice for the

Simulation

Figure 1 illustrated the in-line halogen lamp tube heating structure. In the simulation cases of this study, the impact of lamp shade design on the heating of the halogen lamp tube was not considered. As lamp shade design was a very important link, however, to lower the possible impact of related factors, this study focused on the impact of the halogen lamp tube density and the change of lamp tube-material distance on the material surface heating uniformity at first. Therefore, in the pre-process, the in-line halogen lamp tube heating structure model was simplified as shown in Figure 2. The model was a cylindrical vacuum chamber with a diameter of 0.355m and a length of 0.5m. The vacuum chamber made of stainless steel was 0.003m in thickness with a coating of 0.005m polystyrene on the exterior surface as the insulation material, which had a very tiny k value, being presumed as adiabatic. The vacuum chamber door was of acrylic material of a thickness of 0.03m. Two pieces of stainless steel (length 0.3m, width 0.24m and thickness 0.008m) were placed in between the heating lamp tubes within the chamber. The mesh material tray was left out in simulation while the halogen lamp tube was 0.3m in length and 0.01m in diameter and the single tube radiation area was 0.00942m² (excluding both ends of the lamp tube). In simulation analysis, combinations of different halogen lamp tube of 10, 100W (total lamp tube heat volume) and model changing parameters were compared in setting with heat flux as the source of heat (W/m²); and the chamber vacuum was set at 70mTorr (about 9.31Pa), the interior and exterior walls as well as the ambient temperature were all set at 300K; properties of various materials were as shown in Table 2. In the execution of the program, in order to speed the convergence of the program, the linear relaxation values of the pressure, temperature, viscosity and density were all 0.7 while the converging conditions were set as:

\[ R_{EP}^P = 10^{-2} \]

\( R_{EP}^P \) represented all the computation mesh residual of n iterative generation and \( R_{EP}^U \) referred to the maximum residual in all the iterative processes after m iterative generation, \( \varphi \) represented the individual parameters such as P, T, V, Rad.

Figure 2 simplified in-line halogen lamp tube heating structure model
Grid independent analysis was based on Case1-5 because Case1-5 had most halogen lamp tubes and the smallest tube-material distance compared with others. Therefore, it was easiest to produce a grid of high density in mesh. To keep mesh quality and follow the grid establishment principles, the number of grids it established would be relatively increased. Hence, the number of grids as confirmed in the Case1-5 Grid independent analysis was served as the number of grids for all the cases in this study. The number of grids for Case1-5 Grid independent analysis was based on Test2, and comparisons were made by increasing or decreasing by 1 time of number of grids for Test1 and Test3. The grid number comparison and result analysis were as illustrated in Table 3 and Figure 3 respectively. Figure 3 (a) illustrated the simulation of grid established with all the grids being hexahedron in the pre-process. And the simulation results can be illustrated from the model Z axis section as illustrated in Figure 3 (b) that the temperature distribution by numerical simulation and prediction was the same. Hence, Test1~Test3 grids can serve as the benchmarks for the number of grids in other cases. However, considering the saving of computation resources, the number of grid of Test 1 was served as the basic value of the computation grid.

### Table 2 material properties [35]

<table>
<thead>
<tr>
<th>material/property</th>
<th>( \rho (\text{kg/m}^3) )</th>
<th>( \text{Cp (J/kg \cdot K)} )</th>
<th>( k (\text{W/m \cdot K}) )</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>1150</td>
<td>1460</td>
<td>0.19</td>
<td>0.5</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1040</td>
<td>1200</td>
<td>0.12</td>
<td>0.5</td>
</tr>
<tr>
<td>Pyrex</td>
<td>2225</td>
<td>835</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Steel</td>
<td>7900</td>
<td>470</td>
<td>48</td>
<td>0.17</td>
</tr>
</tbody>
</table>

### Table 3 Grid independent grid comparison

<table>
<thead>
<tr>
<th>Case1-7</th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid number</td>
<td>93,636</td>
<td>194,400</td>
<td>438,660</td>
</tr>
</tbody>
</table>

(a) model grid/mesh

(b) Z axis cross sectional temperature distribution

Figure 3 Grid independent result comparison
IV. Results and Discussions

Regarding the numerical simulation results after treatment, the temperature Legend of various cases were represented by different ranges to clearly present the temperature distribution. Observe and analyze the model’s five temperature distribution cross-sections from the numerical simulation results: respectively, Figure 4 (a) X axis section was defined as A section being the cross-section of the vacuum chamber, Figure 4 (b) Z axis was defined as B–E, representing the up and lower surfaces of the drying materials, and Figure 7 Case 1-1B red marks represented the position facing the Door (the same in all cases). The result analysis was discussed in three aspects according to the case combinations, respectively, halogen lamp tube density, halogen lamp tube-material distance and the wattage of the halogen lamp tube.

First, Figure 5~Figure 8 was described briefly for the convenience of the follow-up analysis: (1) Figure 5 and Figure 6, respectively, represented the Z axis cross-sectional temperature distributions of the halogen lamp tube total heat volume10W and 100W. In all the 10W cases, temperature Legend represented the range from 319.5K~310K; and in all the 100W cases, temperature Legend represented the range from 420K~370K. (2) Figure 7 and Figure 8, respectively, illustrated the Y axis cross-sectional temperature distribution of the halogen lamp tube total heat volume 10W and 100W. In cases of 1-1~1-6 as illustrated in Figure 7, the material surface temperature ranges were about 319.4K~318.7K, 311K~310.7K, 319K~318.5K, 311K~310.6K, 318.4K~318K, 310.7K~310K; and the cases 2-1~2-6 as illustrated in Figure 8, the material surface temperature ranges were about 414K~311K, 374.5K~372.8K, 415K~311K, 376.5K~375K, 414.5K~411.5K, 376.5K~375K.

**Halogen lamp tube setting density**

If observe the impact of halogen lamp tube on material heating uniformity from a single factor of the halogen lamp tube setting density, from Figure 5 and Figure 6, the material central X axis cross-sectional temperature distribution, in all the 10W halogen lamp tube cases, the increasing halogen lamp tube setting density would expand the high temperature range of the material center and was able to reduce the temperature gap between the material center and edge. However, there was no such result in 100W halogen lamp tube cases. It might be that the energy of 100W was far greater than 10W in given initial ambient temperature. Such phenomenon can also be seen from the Y-axis material surface temperature distribution as illustrated in Figure 7 and Figure 8. Compared with the cases 1-1~1-6 as illustrated by Figure 7 B, it can be apparently found that when the halogen lamp tube setting density increased, the temperature gap between the material center and the edge would drop. Hence, it can be observed that the increasing halogen lamp tube setting density was positive on heating uniformity.

**Halogen lamp tube-material distance**

Regarding the halogen lamp tube-material distance, the temperature distribution gap between 15mm and 45mm can be found as illustrated in Figure 5 and Figure 6. When the distance increased, the material surface overall temperature would drop due to relatively long distance of radiation. However, the increasing radiation distance might be one of the reasons for increasingly even temperature distribution in the range of the material center to the edge. And such phenomenon can also be found by observing the results as illustrated in Figure 7 and Figure 8. Moreover, the surface temperature of the lower layers of materials was relatively evener and higher than that of the upper layer. Except for cases 2-2, 2-4 and 2-6, combining this phenomenon and Figure 5 and Figure 6, it can be found out that the halogen lamp tube, the difference of relative positions of vacuum chamber leading to the difference in irradiation angle might enable the lower layer materials to have better irradiation range and also reminded us of the importance of the lamp shade. However, regarding the contradictions of Cases 2-2, 2-4 and 2-6, no reasonable explanations might be proposed at the moment, pending further discussion.

**Halogen lamp tube wattage**

Regarding the halogen lamp tube wattage, it can be found from Figure 7 and Figure 8 that the direct effect of the increase in halogen lamp tube total heat volume was the energy given by the lamp tube to the materials. However, the relative increase of the total heat volume would also increase the temperature changes of the material surface. Observing closely, the total heat volume 10W heating uniformity would be better than 100W. Hence, the halogen lamp tube wattage had to be determined by the properties of the drying materials and make a better efficiency selection in between the drying speed and heating uniformity.
Figure 4 cross-section position

(a) Model X axis cross-section

(b) Model Z axis cross-section

Door
Figure 5 Model Z axis cross-section temperature distribution (10W)
Figure 6 Model Z axis cross-section temperature distribution (100W)
Figure 7 Model Y axis cross-section temperature distribution (10W), 1/1
Figure 7 Model Y axis cross-section temperature distribution (10W), 1/2
Figure 8 Model Y axis cross-section temperature distribution (100W), 1/1
Figure 8 Model Y axis cross-section temperature distribution (100W), 1/2
V. Conclusion
This study discussed natural convection occurred inside the vacuum chamber to explore the influence of setting density of 9 halogen lamp tubes and 2 kinds of distance between lamps and drying materials upon heating uniformity, and employed the lamp tube total heat power 10 and 100W as the case study combinations. The following two conclusions can be reached by numerical simulation analysis: (1) the increasing halogen lamp setting density might increase the drying material heating uniformity; (2) at given lamp setting density, increasing halogen lamp tube-material distance would increase material heating uniformity despite the drop in average temperature of the drying materials. The study results would provide a reference to designers on the heating lamp devices in the design of the heat radiation type freeze-drying equipment.

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References


