Temperature distribution of air source heat pump barn with different air flow

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Abstract. There are two type of airflow form in tobacco barn, one is air rising, the other is air falling. They are different in the structure layout and working principle, which affect the tobacco barn in the distribution of temperature field and velocity distribution. In order to compare the temperature and air distribution of the two, thereby obtain a tobacco barn whose temperature field and velocity distribution are more uniform. Taking the air source heat pump tobacco barn as the investigated subject and establishing relevant mathematical model, the thermodynamics of the two type of curing barn was analysed and compared based on Fluent. Provide a reasonable evidence for chamber arrangement and selection of outlet for air source heat pump tobacco barn.

1. Introduction

Tobacco cured is one of the most important stages in the tobacco production, and the equipment of tobacco barn is the key factor to determine the baking performance. At present, the most widely used is bulk curing barn [1], it can be divided into air rising and drop according to the indoor airflow direction of tobacco filled room [2], the two types curing barns were used, however, it needs to be proved by theoretical and practical baking to distinguish what kind of airflow pattern is more conducive to tobacco curing.

In the actual curing process, there are many factors affecting the curing performance of two air flow forms, including the filling of tobacco filled room, physical properties of tobacco leaf, baking process (stage length, temperature, wind speed etc.) At present, people can only decide the layout and structure of tobacco barn according to curing experience, lack of theoretical guidance. Therefore, it’s necessary to seek a better method to simulate and analyse the temperature and airflow distribution of the two types of tobacco barn, and obtain better tobacco barn structure. At present, numerical simulation of the temperature and air distribution in the curing barn has been studied by scholars through the computational fluid dynamics software, analysed the uniformity of temperature and air distribution in the tobacco filled room, they obtain reasonable air mass for tobacco curing[3]. However, it did not put forward a reasonable structure and layout of the curing barn. In order to solve this problem, based on the above research, thermodynamic analysis and comparison of the two types of
curing barn are completed using Fluent to obtain a better tobacco barn form which has better curing performance.

2. Analysis of the structure and curing process of the two types of tobacco barn

2.1. The comparison of two types of curing barn
The air rising and drop curing barn are almost identical in the shape and structure, the main difference is that the installation and location of each component in the heating room is different, the position of the air inlet and outlet on the heat insulation wall are also different. The air inlet of air rising curing barn is located in the bottom of heat insulation wall, the outlet in the top, and the condenser in the heating room is installed on the upper part of the axial flow fan, as shown in Figure 1 (a). The air inlet position and the layout of the condenser and the axial flow fan of the air drop curing barn are opposite to the air rising. As shown in Figure 1. (b).

2.2. Analysis of curing process of The Two types curing barn
The process of tobacco curing to dry the water in tobacco leaves is heat exchange between hot air and tobacco leaves, take air source heat pump as the research object. The indoor air at first is heated by the condenser in the heating room, and then send into tobacco filled room from the inlet by the axil flow fan. For air rising curing barn, hot air gradually rising from the bottom of the tobacco filled room to the to, after fully contacting with the tobacco leaves, the air return to the heating room from the upper outlet, while the air flow form is opposite in air drop curing barn. The air flow of the two in curing process is as shown in Figure 1.

![Figure 1. Comparison of Air Flow Form of Two Types of Curing Barn](image)

3. Computational Models

3.1. Computational model of the curing barn
In order to compare the temperature and air distribution in the tobacco filled room of the two types of tobacco barn, the other conditions are consistent of the two types of calculation model, except that the inlet and outlet are swapped. The structural parameters of the tobacco filled room are shown in Table 1.

| Types            | Length (mm) | Width (mm) | Height (mm) |
|------------------|-------------|------------|-------------|
| Tobacco Filled   | 8000        | 2700       | 3550        |
| Room Size        |             |            |             |
| Inlet Size       | ×           | 2600       | 400         |
| Outlet Size      | ×           | 1400       | 440         |

3.2. Research hypothesis of computational domain model
This study uses $k - \varepsilon$ two equation three-dimensional turbulence models. In order to simplify the problem, and to facilitate the mathematical description and solving, under the
same curing condition, without considering tobacco leaves in the tobacco filled room. And make the following approximation:

(1) There are room door, observation window, humidity window and so on in the tobacco barn, from the point of view of simplifying mathematical model, it is considered that the physical parameters are same to the wall;

(2) The air in the curing barn is considered as ideal gas that can't be compressed;

(3) The airflow is low speed incompressible flow, the heat consumption can be ignored caused by the viscous force of fluid;

(4) Because the temperature of the hot air is not high, so only the convection is considered, the radiation is not;

(5) Without considering the influence of air leakage (the tightness of air in curing barn is good); and the ventilation and drainage of the barn is smooth.

3.3. Flow control equation
For the study of the curing barn, the flow of air in tobacco filled room is a steady three-dimensional incompressible turbulent flow, so the flow and heat transfer in the curing barn should satisfy the following control equations:

(1) Continuity equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \mu_i) = 0
\]

In equation (1):
\( \rho \) — Fluid Density; \( \mu_i \) — Fluid velocity along \( i \) direction.

(2) \( N-S \) Equation:

\[
\frac{\partial}{\partial t} (\rho \mu_i) + \frac{\partial}{\partial x_j} (\rho \mu_i \mu_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i
\]

In equation (2):
\( \rho \) — Static pressure; \( \tau_{ij} \) — Stress vector; \( \rho g_i \) — Gravity component along \( i \) direction;
\( F_i \) — Other energy sources due to resistance and energy.

(3) Energy conservation equation:

\[
\frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x_i} (\rho \mu_i h) = \frac{\partial}{\partial x_i} (k + c_i) \frac{\partial}{\partial x_i} + S_h
\]

In equation (3):
\( h \) — Entropy; \( k \) — Molecular conductivity; \( k_{\tau} \) — Transmission rate due to turbulent flow;
\( S_h \) — Defined volume source.

(4) \( k-\varepsilon \) equation

\( k \) Equation:

\[
\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu_i + \frac{\mu_t}{\sigma_t} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon
\]

\( \varepsilon \) Equation:

\[
\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu_i + \frac{\mu_t}{\sigma_t} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + c_{\mu_t} \frac{\varepsilon}{k} (G_k + G_b) - \frac{\varepsilon}{k} (G_k + G_b)
\]

(5) In equation (4), (5):

\( \mu_i \) — Laminar viscosity coefficient; \( \mu_t \) — Turbulent viscosity coefficient;

\[
\mu_t = \rho \mathcal{C}_\mu \frac{k^2}{\varepsilon}
\]

\( G_k \) — Turbulent kinetic energy generated by a laminar velocity gradient;
\( G_b \) — Turbulent kinetic energy generated by buoyancy;
3.4. Physical properties and related parameters
The whole peripheral structure of the barn use the same high thermal insulation material: polyurethane, the medium indoor used to cure tobacco is the heated air. The physical parameters of the selection of insulation material and air: density, thermal conductivity, pressure specific heat capacity and viscosity are shown in Table 2.

| Material     | Density (kg/m\(^3\)) | Conductivity (W/m·K) | Specific heat capacity at constant pressure (J/kg·K) | Viscosity (kg/m·S) |
|--------------|----------------------|----------------------|------------------------------------------------------|-------------------|
| Polyurethane | 35–40                | ≤0.025               | 2380–370                                             | ×                 |
| Air          | 1.225                | 0.0242               | 1006.43                                              | 1.79e-05          |

3.5. Boundary condition
The air inlet of the curing barn is used as the inlet boundary, and the type selection is set as inlet velocity; the air outlet of the barn is set as the outlet boundary, and the pressure of the airflow is the standard atmosphere, the temperature is same to the external environment. The wall of the curing barn and the roof are treated as convection heat transfer boundary condition, and the floor is approximately treated as an adiabatic boundary condition.

4. Calculation result analysis and processing
4.1. Analysis of temperature and velocity field
The air supply condition in actual curing and the experimental result were considered, so set the inlet air velocity as 5m/s, the temperature as 320K, and take the section \( y = 0 \) as observation object.

It could be seen from the speed vector diagram in Figure 2. (a), (b), the air speed in the air rising curing barn is a little higher at the inlet and outlet, and the rest of the speed distribution is basically uniform. However, the speed in air drop barn at the inlet and outlet is observably higher than other domain and the distribution is not uniform; it could also be seen from Figure 2. (c), (d) that: the distribution of temperature in the curing barn is more uniform than that of the drop type. Therefore, it is concluded that the air rising type is more conducive to the tobacco curing.
Figure 2. Temperature and velocity vector diagram of two kinds of curing barn

4.2. Data node selection
Temperature is an important factor for tobacco curing, in order to fully prove that air rising type curing barn is better for curing, thermodynamic analysis and comparison were completed after the change of initial inlet temperature condition. This paper compared the results through selection of temperature data node of the curing barn, and then calculated the mean and standard deviation of these data [4-6].

Air source heat pump barn belong to bulk curing barn, the National Tobacco Bureau issued a corresponding technical specification for construction of bulk curing barn, and the specification provides the basic structure, main equipment and technical parameters of the barn [7]. The number of the tobacco-shed in the barn is generally designed as three. In order to make the analysis more reasonable, the two kinds of curing barn are both considered the temperature distribution in three directions: the length, width and height the. The data collection points are selected as follows:

![Data collection points](image)

Figure 3. Data node selection

(1) Three sections were selected in the width direction of the tobacco filled room, as shown in Figure 3. (a):

Section 1: \( y = 0.7 \), Medium section: \( y = 0 \), Section 2: \( y = -0.7 \); 

(2) 9 data collection points are selected on each cross section, as shown in Figure 3. (b)

|      | Air rising | Air drop |
|------|------------|----------|
|      | Section 1  | Section 2| Section 1  | Section 2  |
| 1    | 316.8      | 316.9    | 316.8      | 315.8      |
| 2    | 316.5      | 316.8    | 316.6      | 316        |
| 3    | 316.4      | 316.6    | 316.1      | 315.5      |
| 4    | 316.1      | 316.2    | 316        | 315.1      |
| 5    | 316.1      | 316.4    | 315.8      | 315        |
| 6    | 316.2      | 316.5    | 316.2      | 315.3      |
| 7    | 316.6      | 316.8    | 316.6      | 316        |
| 8    | 315.9      | 316.5    | 316.4      | 315.6      |
| 9    | 316        | 316.1    | 316        | 315.4      |
| Mean | 316.4      | 315.5    | 315        | 315.4      |
| Std  | 0.317      | 0.364    |            |            |

Table 3. Temperature value of data node
Inlet velocity: \( V = 5 \text{ m/s} \) Inlet temperature: 320K

4.3. Data analysis and processing
Data points are selected according to the above rules, under different initial conditions, each barn can get 27 data. Tobacco curing is carried out in stages and the temperature of each stage is gradually increased, the temperature range from 35°C to 70°C, selected initial temperature from 35°C, then selected by the intervals: 5°C, and calculated the standard deviation according to the equation:

\[
\sigma = \sqrt{\frac{(x_1-\bar{x})^2 + (x_2-\bar{x})^2 + \cdots + (x_n-\bar{x})^2}{N}}
\]

The standard deviation of temperature node of the two barns under different initial inlet temperature is obtained as follows:

| Temperature | 35°C | 40°C | 45°C | 50°C | 55°C | 60°C | 65°C | 70°C |
|-------------|------|------|------|------|------|------|------|------|
| Air rising  | Mean | 307.25 | 312.23 | 317.26 | 322.26 | 327.26 | 332.26 | 337.26 | 342.26 |
|             | Std. deviation | 0.083 | 0.081 | 0.079 | 0.082 | 0.083 | 0.084 | 0.084 |
| Air drop    | Mean | 306.84 | 311.86 | 316.85 | 321.86 | 326.85 | 331.85 | 336.85 | 341.93 |
|             | Std. deviation | 0.106 | 0.169 | 0.111 | 0.115 | 0.105 | 0.109 | 0.108 | 0.286 |

Figure 4. (a) mean of node temperature of the two under different temperatures  
Figure 4. (b) standard deviation of node temperature of the two under different temperatures

As Table 2. shows, when inlet temperature is 320 K, standard deviation of air rising type is less than air drop, and the node temperature is closer to current inlet temperature. Standard deviation reflects the degree of dispersion between node temperature and mean in current condition. The value is lower, the temperature are more uniform. Therefore, when the inlet temperature is 320K, temperature distribution is more uniform in air rising type curing barn.

It could be concluded from these standard deviations in Table 3: under the same initial conditions, temperature distribution is more uniform in air rising type curing barn, therefore, air rising type curing barn is more conducive for tobacco curing.

5. Conclusions
It is the first time to use Fluent to analyze the distribution of temperature and airflow of the two types of curing barns, and calculate the standard deviation through uniformly selecting the Collection Points. The main conclusions are as follows:

- The temperature of each node in air rising type curing barn is closer to the inlet temperature under the same inlet temperature;
- The standard deviation of each node temperature in the air rising curing barn is smaller than that of the air drop under the same inlet temperature.
- Due to the more uniform distribution of temperature and airflow, the air rising type is more conducive to the tobacco curing.

It can be used as a basis for selecting the most suitable tobacco curing structure in the actual construction.

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