A Correlation Model of Thermal Entrainment Factor for Single Air Curtain without Back Panel Airflow

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Abstract. Thermal entrainment factor (TEF) is an important parameter to describe the cold preservation performance of a display cabinet. In order to calculate the TEF of a display cabinet rapidly and accurately, the method of establishing a correlation model based on computational fluid dynamics (CFD) simulation results is presented and the correlation model of TEF for typical single air curtain is developed in this paper. The TEF for single air curtain without back panel airflow can be regressed by an exponential function of Reynolds number and deflection modulus.

1. Introduction
Vertical open display cabinets are extensively used in supermarkets. In a vertical open display cabinet, one or more forced-air curtains are used to separate the refrigerated food inside the cabinet from the ambient air in the store, therefore the outside warm air have little influence on the refrigerated food. As a result, the cold preservation performance of air curtain plays a very important role in the quality of the freezing food.

The thermal insulation effect of air curtain is often described by the thermal entrainment factor (TEF) [1-3]. For the constant supply temperature of air curtain, the higher TEF means higher air curtain return temperature and larger sensible heat through air curtain, which indicates that the larger capacity refrigerating compressor is required.

The TEF for air curtain is a dimensionless parameter and dependent on the display cabinet construct, air curtain supply parameters and environmental parameters. Therefore it may be described by a function of several dimensional parameters, which is so-called “correlation model”. This correlation model can reflect a lot of influencing parameters in a simple format, and so it has better generalization than an experimental correlation, while the calculation is faster than CFD simulation.

The TEF for air curtain may depend on many parameters such as air curtain velocity, air curtain temperature, air curtain width, air curtain height and ambient temperature, therefore the development of correlation model of TEF for air curtain should be based on large quantity data. Since it is difficult...
to obtain a large quantity of experimental data, the correlation model is established based on the data produced by CFD simulation.

2. The dimensionless form of the TEF for air curtain

2.1. The definition of the TEF for air curtain

The TEF for air curtain is defined as [1-3]:

$$X = \frac{T_r - T_s}{T_a - T_s}$$  \hspace{1cm} (1)

where $T_r$, $T_s$ and $T_a$ are the return temperature, the supply temperature of air curtain and the ambient temperature, respectively. A higher $X$ means $T_a$ plays more important role in $T_r$ than $T_s$, while a lower $X$ indicates $T_s$ shows more influence on $T_r$ than $T_a$.

2.2. The dimensionless analysis of the TEF for air curtain

Based on the above assumptions, the TEF for air curtain $X$ is dependent upon several parameters: air curtain supply velocity $u_s$, air curtain supply temperature $T_s$, air curtain width $W_s$, air curtain height $H$, and ambient temperature $T_a$, namely:

$$X = f(u_s, T_s, W_s, H, T_a)$$  \hspace{1cm} (2)

As the TEF for air curtain is a dimensionless parameter, it is desired to reflect the relationship between the TEF and other dimensionless parameters in the correlation model. The flow and heat transfer of air curtain are influenced by momentum, viscous forces and the transverse force, therefore the TEF for air curtain can be considered being depended on the Reynolds number $Re$ [4-5] and the deflection modulus $D_m$ [6-12].

$$Re = \frac{\rho_s u_s W_s}{\mu_s}$$  \hspace{1cm} (3)

$$D_m = \frac{\rho_s u_s^2 W_s}{(\rho_c - \rho_w)gH^2}$$  \hspace{1cm} (4)

where $\rho_s$, $u_s$, $\mu_s$, $W_s$, and $H$ are the supply density, supply velocity, supply laminar viscosity, width and height of air curtain, respectively; $\rho_c$ and $\rho_w$ are the cold side density and warm side density of air curtain, respectively. The Reynolds number $Re$ indicates the ratio of momentum and viscous forces, while the deflection modulus $D_m$ denotes the ratio of air curtain momentum to transverse forces caused by temperature difference either side of the air curtain, therefore $Re$ and $D_m$ can generally describe the flow and heat transfer status of air curtain.

Therefore, Eq. (2) can be expressed as the dimensionless form, namely:

$$X = g(Re, D_m)$$  \hspace{1cm} (5)
3. The data source of correlation model of TEF for air curtain
The correlation model of TEF for air curtain depends on the data produced by CFD simulation. Therefore, CFD simulation on typical display cabinets should be done and the predicted data should be analyzed.

3.1. The structure of display cabinet and the CFD simulation model
The display cabinet with single air curtain is simulated by CFD, which is shown in Figure 1.

![Figure 1. Single air curtain in a display cabinet.](image)

In order to simulate the display cabinet accurately and lay the good foundation for the correlation model of TEF for air curtain, the modified two-fluid model \(^{(13)}\) is adopted to simulate the cabinets with single air curtain.

3.2. The computational cases
Forty-one computational cases for single air curtain are listed in Table 1, where five parameters are taken into account: air curtain velocity \(u_s\), air curtain temperature \(T_s\), air curtain width \(W_s\), air curtain height \(H\), and ambient temperature \(T_a\).

| No | \(u_s\) (m.s\(^{-1}\)) | \(T_s\) (°C) | \(W_s\) (m) | \(H\) (m) | \(T_a\) (°C) |
|----|-----------------|--------------|-------------|--------|--------------|
| 0  | 0.7             | 0.0          | 0.096       | 1.7    | 25.0         |
| 1  | 0.3,0.4,0.5,0.6 | 0.0          | 0.096       | 1.7    | 25.0         |
|    | 0.8,0.9,1.0,1.1 |              |             |        |              |
| 2  | 0.70            | -4.0,-3.0,-2.0,-1.0 | 0.096 | 1.7    | 25.0         |
|    | 1.0,2.0,3.0,4.0 |              |             |        |              |
| 3  | 0.70            | 0.0          | 0.06,0.07,0.08,0.09 | 1.7    | 25.0         |
|    | 0.10,0.11,0.12,0.13 |              |             |        |              |
| 4  | 0.70            | 0.0          | 0.096       | 1.3,1.4,1.5,1.6 | 25.0 |
|    | 1.8,1.9,2.0,2.1 |              |             |        |              |
| 5  | 0.70            | 0.0          | 0.096       | 1.7    | 21.0,22.0,23.0,24.0 |
|    |                 |              |             |        | 26.0,27.0,28.0,29.0 |

Table 1. Computational cases of vertical open display cabinet with single air curtain.
3.3. The analysis of computational results
The influence of dimensionless numbers \( Re \) and \( D_m \) on the TEF for air curtain can be known by analyzing the CFD simulation results, as shown below.

(1) The influence of Reynolds number \( Re \) on the TEF for air curtain \( X \)
The relationship between TEF and Reynolds number \( Re \) is shown in Figure 2. From the figure, the TEF decreases with the increase of \( Re \) for either single air curtain. This is consistent with other research \(^5\). From a physical point of view, the higher Reynolds number \( Re \) of air curtain means the cold air curtain can reach the bottom of display cabinet more easily and the return temperature of air curtain is lower. However, when Reynolds number \( Re \) reaches a certain value (about 4000), the decrease rate of TEF is lower with the increase of \( Re \). Therefore, it is not necessary to adopt large velocity of air curtain excessively.

![Figure 2. Relationship between the TEF X and the Reynolds number Re of single air curtain.](image)

(2) The influence of deflection modulus \( D_m \) on the TEF for air curtain \( X \)
Figure 3 shows the relationship of the TEF vs. \( D_m \). From the results in the figure, a rise in \( D_m \) decreased the TEF for air curtain. As \( D_m \) indicates the ability of air curtain to prevent the ambient air from entering the cabinet, a higher \( D_m \) denotes easier sealing air curtain, lower return temperature and smaller TEF for air curtain.

![Figure 3. Relationship between the TEF X and the deflection modulus Dm of single air curtain.](image)
4. The correlation formula regression of TEF for air curtain

From Figures 2 and 3, it can be inferred that the relationship between $X$ and $Re \& Dm$ is close to an exponential function. As $0 \leq X \leq 1$ is satisfied, the following correlation formula can be used to fit the TEF for air curtain without BPA:

$$X = \text{EXP}(a_1Re^{a_2}D_m^{a_3})$$

where $X$ is the TEF for air curtain without BPA, and $a_1, a_2$ and $a_3$ are the undetermined constants. $a_1$ is less than zero.

Table 2 lists the regressed values of $a_1, a_2$ and $a_3$.

|   | $a_1$ | $a_2$ | $a_3$ |
|---|-------|-------|-------|
|   | -1.08435 | 0.14789 | 0.32153 |

5. Conclusion

Based on the CFD simulation of display cabinet with single air curtain, the correlation model of TEF for air curtain is developed in this paper. The main conclusions are listed below:

1. The TEF for air curtain depends upon two dimensionless parameters including Reynolds number, and deflection modulus. From the CFD results, the TEF for air curtain decreases with the improvement of Reynolds number and deflection modulus.

2. The relationship between the TEF for air curtain and Reynolds number & deflection modulus can be regressed by an exponential function in a display cabinet without BPA.

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References

[1] H.K. Navaza, B.S. Hendersona, R. Faramarzib, A. Pourmovaheda, F. Taugwalder. Jet entrainment rate in air curtain of open refrigerated display cases. International Journal of Refrigeration, 2005, 28(2):267-275.

[2] Y.G. Chen, X.L. Yuan. Experimental study of the performance of single-band air curtains for a multi-deck refrigerated display cabinet. Journal of Food Engineering, 2005, 69(3):261-267.

[3] P. D’Agaro, G. Cortella, G. Croce. Two- and three-dimensional CFD applied to vertical display cabinet’s simulation. International Journal of Refrigeration, 2006, 29(2):178-190.

[4] Y.G. Chen, X.L. Yuan. Simulation of a cavity insulated by a vertical single band cold air curtain. Energy Conversion and Management, 2005, 46:1745-1756.

[5] B.S. Field, E. Loth. Entrainment of refrigerated air curtains down a wall. Experimental Thermal and Fluid Science, 2006, 30(3):175-184.

[6] A.M. Fostera, M.J. Swaina, R. Barrett. Effectiveness and optimum jet velocity for a plane jet air curtain used to restrict cold room infiltration. International Journal of Refrigeration, 2006, 29:692–699.

[7] J.J. Costa, L.A. Oliveira, M.C.G. Silva. Energy savings by aerodynamic sealing with a downward-blowing plane air curtain-A numerical approach. Energy and Buildings, 2006, 38(10):1182-1193.

[8] L.P.C. Neto, M.C.G. Silva, J.J. Costa. On the use of infrared thermography in studies with air curtain devices. Energy and Buildings, 2006, 38, 1194–1199.

[9] A.M. Fostera, M.J. Swaina, R. Barrett. Three-dimensional effects of an air curtain used to
restrict cold room infiltration. Applied Mathematical Modeling, 2007, 31:1109–1123.

[10] R.H. Howell, M. Shibata. Optimum heat transfer through turbulent recirculated plane air curtains. ASHRAE Transactions, 1980, 86(1):188-200.

[11] F.C. Hayes, W.F. Stoecker. Design data for air curtain. ASHRAE Transactions, 1969, 75:168-180.

[12] N.Q. Van, R.H. Howell. Influence of initial turbulence intensity on the development of plane air curtain jets. ASHRAE Transactions, 1976, 82 (1):208-228.

[13] K.Z. Yu, G.L. Ding, T.J. Chen, Modified two-fluid model for air curtains in open vertical display cabinets, International Journal of Refrigeration, 2008, 31(3):472–482.