

Numerical Study on Refrigeration Characteristics of Refrigerated Cabinet based on SIMPLE Algorithm

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Abstract In order to study the refrigeration characteristics of the refrigerated cabinet, a refrigeration characteristic analysis program based on the SIMPLE algorithm was developed using Fortran. The working condition was simulated and verified. The results show that the simulation results of the refrigeration characteristic analysis program developed with Fortran are basically consistent with the results carried out by commercial CFD Fluent software. In the early stage of the refrigeration process, due to the low temperature of the evaporator coil, the air near the evaporator coil was cooled first, and the density increased, resulting in a downward flow. Driven by natural convection, the air temperature inside the refrigerated cabinet gradually decreased, and at the same time, a large-scale vortex was generated in the cavity of the lower part of the refrigerated cabinet. As time progressed, the air in the cabinet was cooled to a certain extent, the air temperature difference in different regions decreased, the temperature gradient in the cabinet decreased, and the intensity of natural convection decreased. Finally, the temperature dropped to 278.15K and remained unchanged.

Keywords: refrigeration characteristics, refrigerated cabinet, SIMPLE algorithm, numerical simulation, Fortran program, Fluent software

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1. Introduction

Refrigerated cabinets are widely used electrical equipment in many supermarkets and grocery stores. They are often used to store and refrigerate beverages. The characteristics of the refrigerated cabinet, such as the air flow field and temperature distribution in the cabinet, greatly affect the storage period and storage quality of food. Many scholars have devoted to the researches on refrigerated cabinets. Nattawut Chaomuang et al. [1] applied numerical simulation and experimental research methods to study the influence of various design parameters and operation conditions on the performance of the refrigerated display cabinet. Giovanni Cortella et al. [2] simulated the temperature field of a vertical refrigerated cabinet under different operating conditions based on the streamfunction-vorticity formula and the LES turbulence model. Xueqiang Li et al. [3] found out a suitable operational range to satisfy different ambient conditions for open refrigerated display cabinet. Kazuhiro Fukuyo et al. [4] developed a new air-supply cooling system and applied CFD codes to simulate the internal flow field and temperature field of refrigerated cabinets. A higher cooling rate was achieved with the new air-supply cooling system. R. Elarem et al. [5], W. Lu et al. [6] and

Tanathep Leungtonkum et al. [7] proposed a novel design of a PCM heat exchanger. Experimental studies and numerical simulation were applied to study the influence of PCM on the velocity and temperature fields. However, there is a lack of self-developed refrigeration characteristic analysis program for the refrigerated cabinet. It is necessary to develop such kind of analysis program for the refrigerated cabinet which can be applied for the further research on the design optimization of the refrigerated cabinets.

This paper takes a vertical refrigerated cabinet widely used for storing beverages as an example. A refrigeration characteristic analysis program for the refrigerated cabinet is developed with Fortran based on the SIMPLE algorithm [8]. Numerical research is carried out to study its working characteristics under the start-up process. The internal air flow field and temperature distribution in the process of starting up until it reaches a steady state are simulated and analyzed. The commercial CFD Fluent software [9] is used for verification to provide further data and reference for the operation of refrigerated cabinets.

2. Geometric Model

The model of vertical refrigerated cabinet analyzed in this paper is shown in Figure 1 below. The height of the

refrigerated cabinet is 1620mm, the width is 780mm, and the length is 1047mm. The cooling method used is direct cooling, and the working temperature range of refrigerated cabinet is 0-10°C. 2D model is used for simulation without considering the variation of internal air parameters along the length direction. In Figure 1, the lower left corner is the compressor, the left side is the evaporation coil as the cold source, and the right side is the door of the refrigerated cabinet. Since the air flow field inside the compressor is not considered, the compressor part is directly ignored when modeling the refrigerated cabinet, and only the air flow and heat transfer inside the refrigerated cabinet are considered.

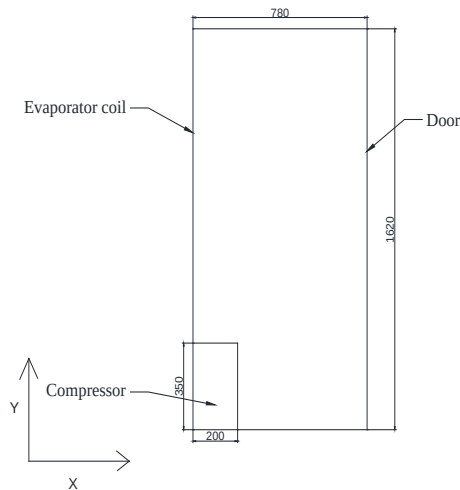


Figure 1. Geometric model of refrigerated cabinet

3. Mathematics Model

To simplify the problem, it is assumed that no objects are placed inside the refrigerated cabinet and the air flow along the length direction is ignored. 2D model is applied to simulate the flow field and temperature field along the height and width direction. Air inside the refrigerated cabinet is assumed to be a Newtonian fluid, the flow form is laminar, and the air on the wall surface of the refrigerated cabinet satisfies the no-slip boundary condition. Viscous dissipation of the fluid is ignored by adopting Boussinesq approximation. Radiant heat transfer within the air and external environment is ignored.

The governing equation of the air in the refrigerated cabinet is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + g \alpha (T - T_0) \quad (3)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

Where u is the velocity in the x direction, the unit is m/s; v is the velocity in the y direction, the unit is m/s; p is the pressure, the unit is Pa; T is the temperature, the unit is K; ρ is the density, the unit is kg/m³; T_0 is the reference temperature, the unit is K; C_p is the specific heat at constant pressure, the unit is J/(kg·K); ν is the kinematic viscosity, the unit is m²/s; α is the coefficient of thermal expansion, the unit is 1/K. In this case, the coefficient of thermal expansion is constant at 0.00335K⁻¹. k is the thermal conductivity of air, the unit is W/(m·K); g is the acceleration of gravity, taken as 9.8m/s².

At the initial moment $t=0$, the internal temperature of the refrigerated cabinet is the same as the ambient temperature of 298.15K. The initial velocity is equal to zero. $u=v=0$. The evaporation coil on the left is set as a constant temperature boundary condition, and its temperature is 278.15K. The rest of the walls and the door are set as adiabatic boundary conditions because the heat loss is small compared to the heat transfer between evaporator coil and the air inside the cabinet.

4. Results Analysis

4.1. Analysis of Results Simulated by Fortran Program

Based on the refrigerated cabinet model established above, using the finite volume method and SIMPLE algorithm, a program for analyzing the refrigeration characteristics of the refrigerated cabinet with a wide range of applications and accurate simulation results was written in Fortran language, and the internal air flow field and temperature distribution inside the refrigerated cabinet during the start-up until reaching the steady state were simulated.

At the beginning of the simulation, mesh independence test was done. The number of nodes affects the accuracy of the iterative calculation results. The larger the number of nodes, the higher the simulation accuracy, but the corresponding computer calculation amount also increases, and the calculation time is longer [10]. Therefore, when determining the number of nodes, it is necessary to take both into account, not only to make the simulation accuracy meet the requirements, but also to avoid the computer from being overloaded.

The temperature of a point which is close to the evaporator coil (35mm, 785mm) at different moments in the first 20 minutes was used as the criterion to verify the mesh independence. Simulation results obtained by Fortran program are shown in Table 1, and the curves are drawn as shown in Figure 2.

Table 1. Mesh Independence Test

number of nodes	Temp. at 1 min./K	Temp. at 5 mins./K	Temp. at 10 mins./K	Temp. at 20 mins./K	maximum relative error/%
103120	296.72	285.39	282.82	281.11	0.3
361192	296.34	285.73	282.59	280.48	0.081
506855	296.10	285.81	282.43	280.27	0.0071
812546	296.11	285.81	282.41	280.26	-

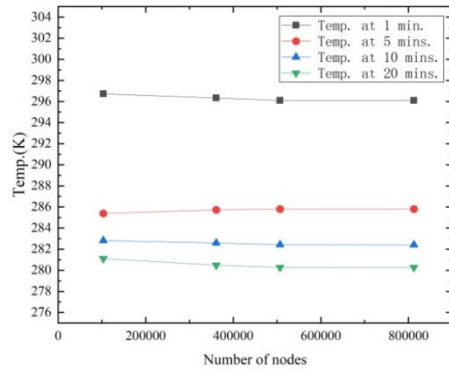


Figure 2. The relation between temperatures and node numbers

From Figure 2, it can be found that when the number of nodes is greater than 506855, the temperature basically no longer changes with the increase of the number of nodes. Even if the number of nodes is increased, the change of temperature is very small, and the maximum relative deviation is within 0.1%, so the mesh independence verification is established, and the number of nodes finally selected is 506855.

Figure 3 below shows the streamlines and velocity contours inside refrigerated cabinet at different moments simulated by the Fortran program, and Figure 4 below respectively shows the temperature contours at different moments during the start-up process.

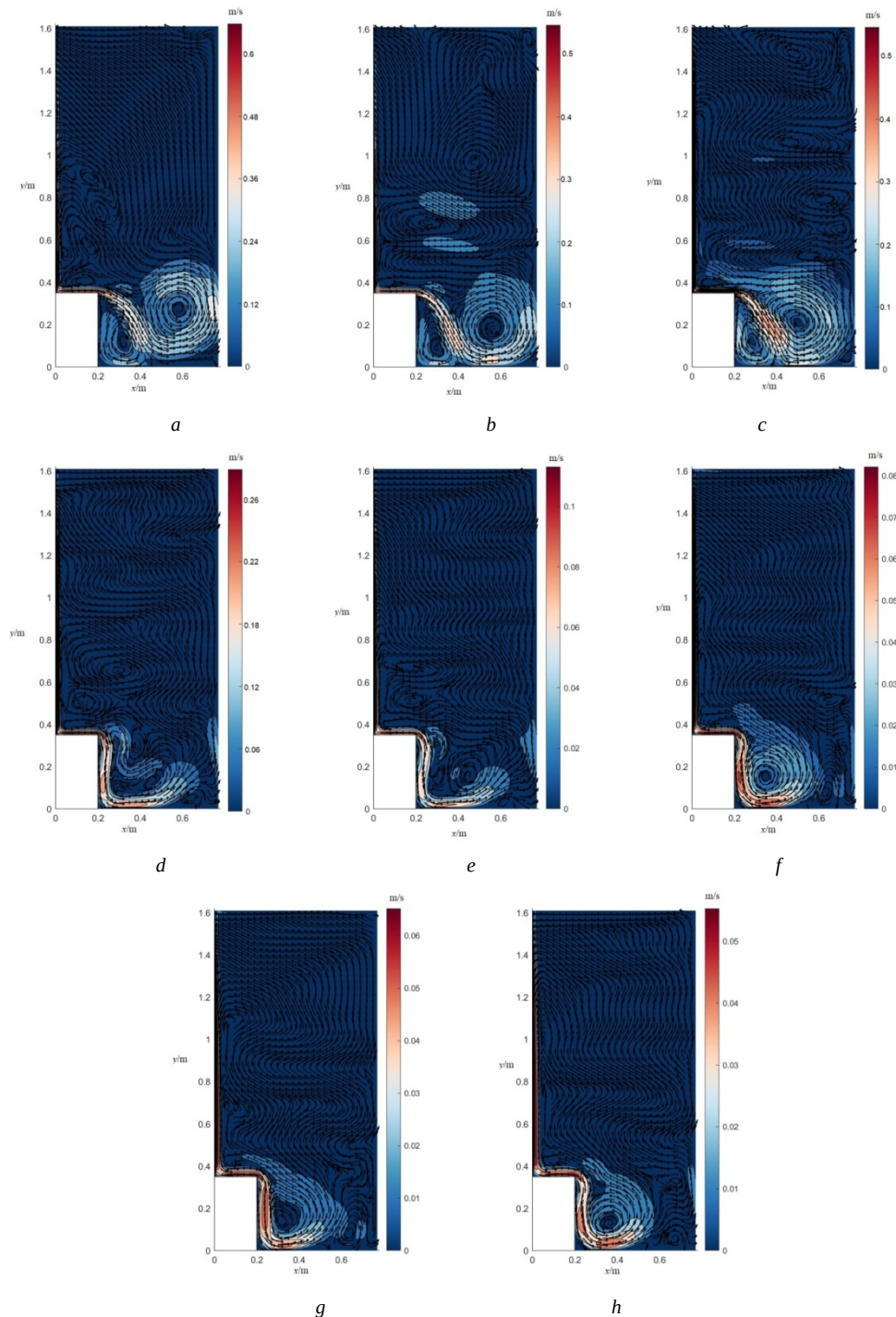


Figure 3. Streamlines and velocity contour inside refrigerated cabinet at different moments (a) at 30s, (b) at 1 minute, (c) at 2 minutes, (d) at 5 minutes, (e) at 10 minutes, (f) at 20 minutes, (g) at 30 minutes, (h) at 40 minutes

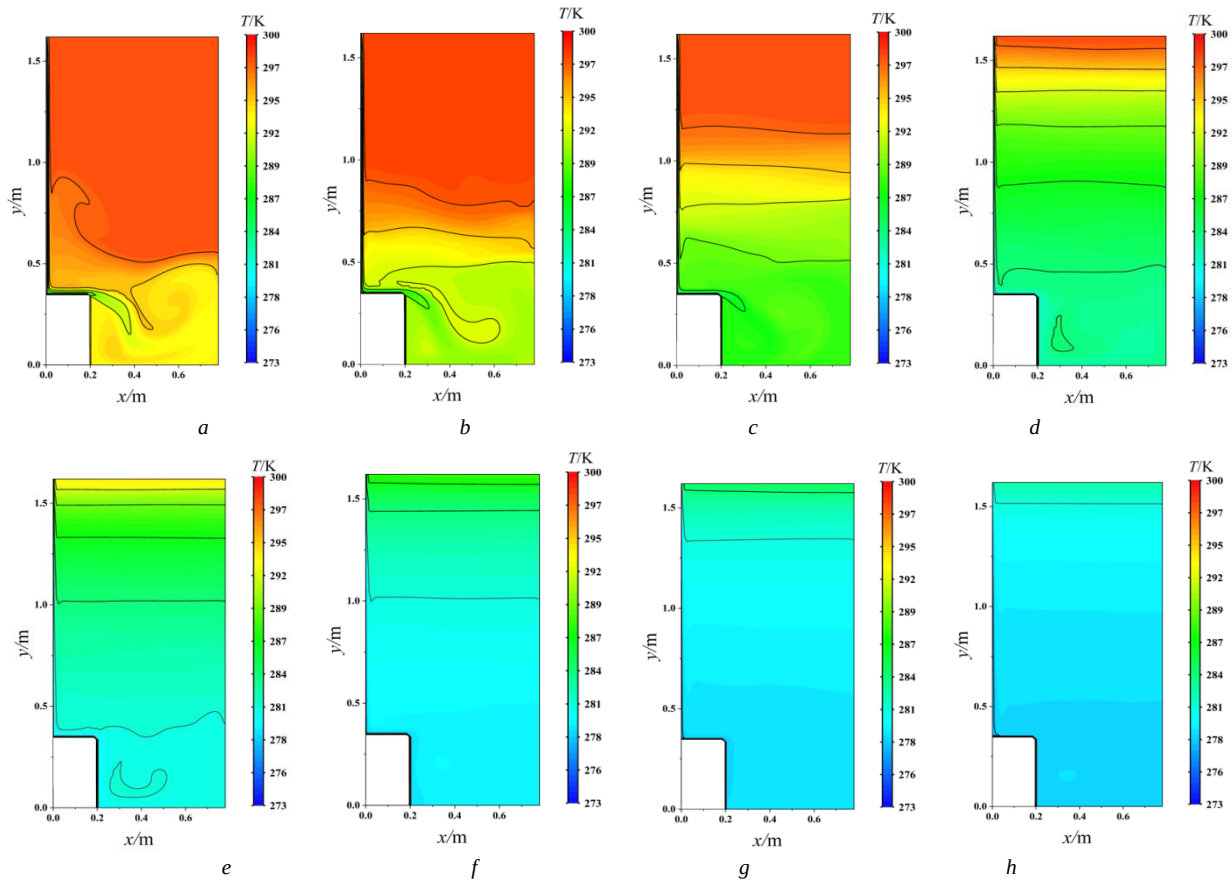


Figure 4. Temperature distribution inside refrigerated cabinet at different moments (a) at 30s, (b) at 1 minute, (c) at 2 minutes, (d) at 5 minutes, (e) at 10 minutes, (f) at 20 minutes, (g) at 30 minutes, (h) at 40 minutes

From the temperature contours shown in Figure 4, it can be seen that due to the low temperature of the evaporating coil at the beginning of the refrigeration process, the air near the evaporator coil was cooled first, and the density increased, resulting in a downward flow. Driven by natural convection, the temperature of the air near the evaporator coil decreased and the low temperature continued to develop downward, and at the same time, large-scale vortexes which can be seen in Figure 3 were generated in the lower cavity of the refrigerated cabinet. In the later stage of the refrigeration process, the temperature gradually decreased from bottom to top, the temperature difference between different regions gradually decreased, the natural convection effect weakened, and the temperature field dropped to 278.15K and remained unchanged.

4.2. Analysis of Results Simulated by Fluent

ANSYS Designmodeler was used to carry out two-dimensional modeling of the vertical refrigerated cabinet, and then Mesh software was applied to mesh it. The mesh model was imported into Fluent software. The Fluent solver chosen to simulate the problem was based on pressure. Unsteady state button was clicked, and the gravity field was turned on. The Laminar flow model is selected. Boussinesq approximation was activated in the material setting. The governing equations are discretized by the finite volume method, the convection and diffusion terms are in the second-order upwind form, and the governing equations are solved using the SIMPLE algorithm.

Figure 5 shows the velocity vector fields at different moments after turning on the refrigerated cabinet. Similar

to the results obtained by Fortran program, when the refrigerated cabinet was turned on, as the air close to the evaporator coil was cooled in the first place, the density changed, and the air near the evaporator coil flowed downward, resulting in natural convection. In the lower cavity of the refrigerated cabinet, it can be found that the natural convection of the air created eddies. As time progressed, the air in the cabinet was cooled to a certain extent, the air temperature difference in different regions decreased, the temperature gradient in the cabinet decreased, and the intensity of natural convection decreased.

Figure 6 shows the temperature field of the air in the cabinet at different moments. By observing temperature contours, it can be found that the temperature of the air in the cabinet changed from the bottom first, and the temperature of the bottom area was lower than that of other areas. This is because the air around the evaporator coil was cooled first, its density increased, and it flowed downward. After the downward flowing cold air interacted with the wall, vortexes were generated in the lower cavity of the refrigerated cabinet. The generation of vortexes is conducive to the mixing of hot and cold air molecules and promotes heat transfer. In the initial 5 minutes, the temperature gradient of the air in the cabinet was large, and the rate of temperature drop was fast. As time went by, the air in the cabinet was cooled to a certain extent, the temperature gradient in the cabinet decreased, the intensity of natural convection weakened, and the rate of change of temperature in the cabinet decreased slowly after 10 minutes. At about 43 minutes, the air temperature in the cabinet dropped to 278.15K and no longer changed with time.

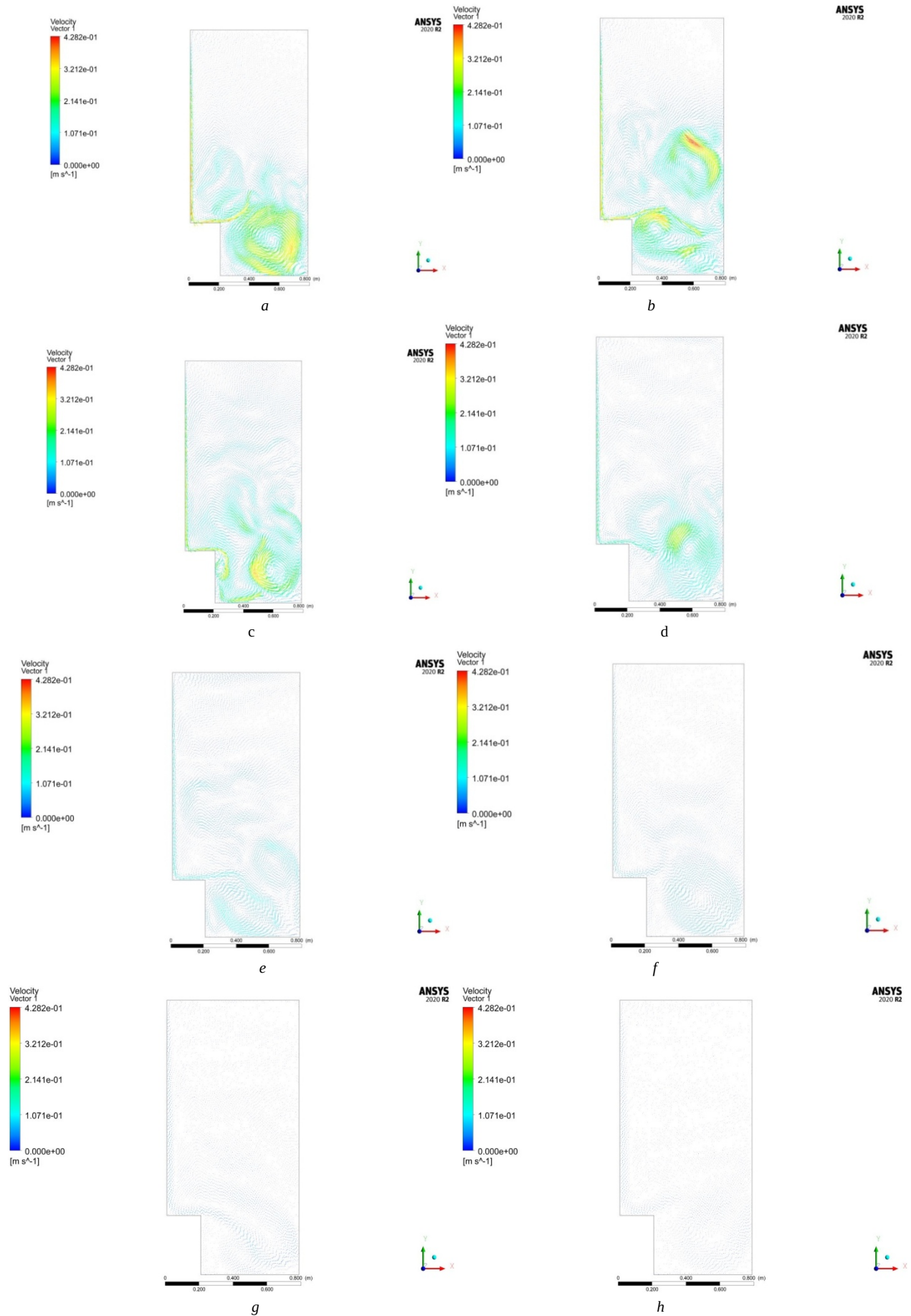


Figure 5. Velocity vectors inside refrigerated cabinet at different moments (a) at 30s, (b) at 1 minute, (c) at 2 minutes, (d) at 5 minutes, (e) at 10 minutes, (f) at 20 minutes, (g) at 30 minutes, (h) at 40 minutes

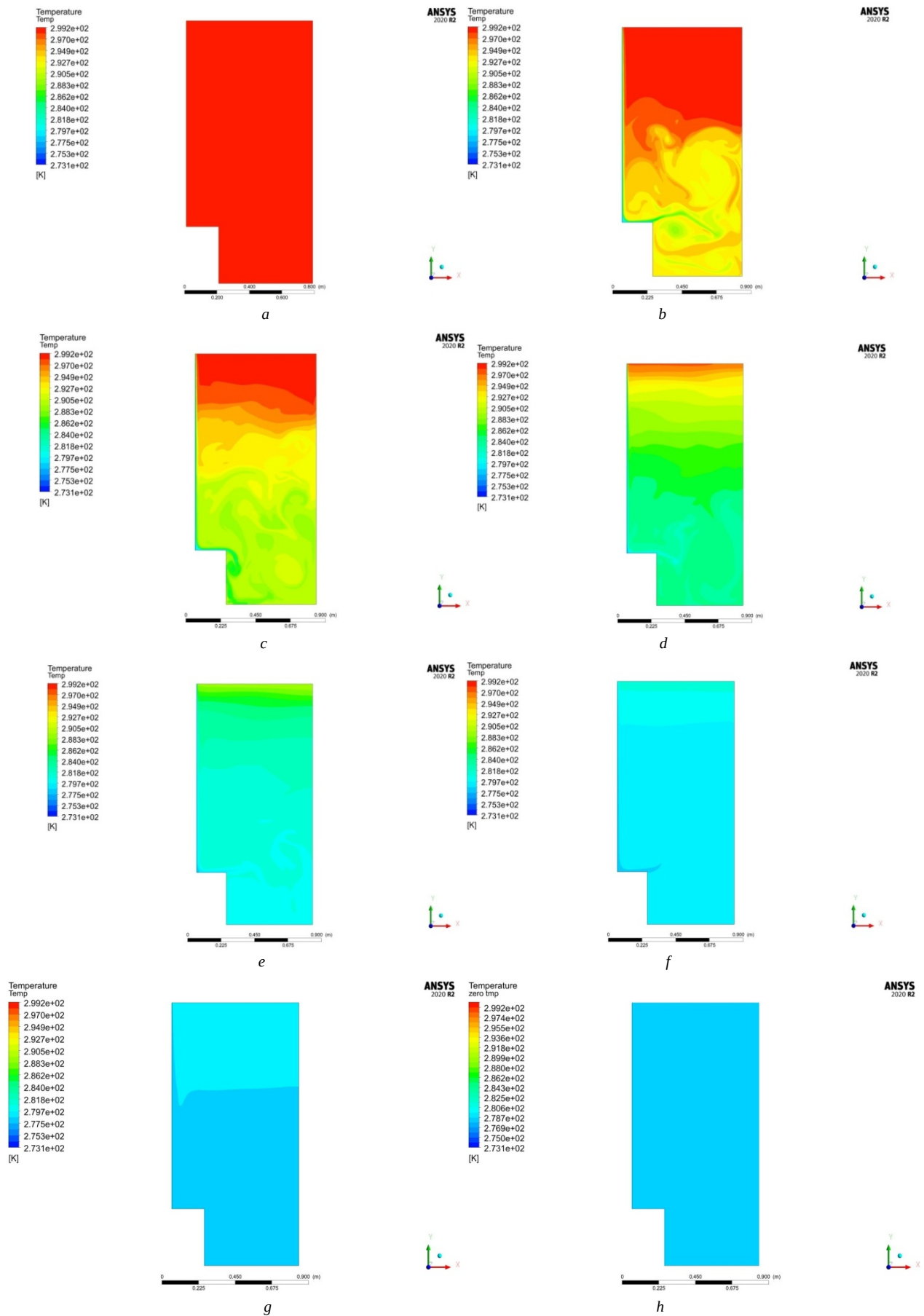


Figure 6. Temperature distribution inside refrigerated cabinet at different moments (a) at 0s, (b) at 1 minute, (c) at 2 minutes, (d) at 5 minutes, (e) at 10 minutes, (f) at 20 minutes, (g) at 30 minutes, (h) at 43 minutes

4.3. Results Comparison

By comparing Figure 3 (results simulated by Fortran program) and Figure 5 (results simulated by Fluent), it can be seen that the velocity field at each moment is quite different in the upper area of the refrigerated cabinet, but the absolute value of the velocity is small. The position and velocity value of large-scale vortexes can be obtained from the velocity vectors simulated by Fluent, which

agrees quite well with the results simulated by the Fortran program.

By comparing Figure 4 (results simulated by Fortran program) and Figure 6 (results simulated by Fluent), it can be seen that the distribution of the temperature at each moment is basically the same. In order to further analyze the refrigeration characteristics, histograms are presented in Figure 7 below to show the area proportion of different temperature ranges in the cabinet at different moments.

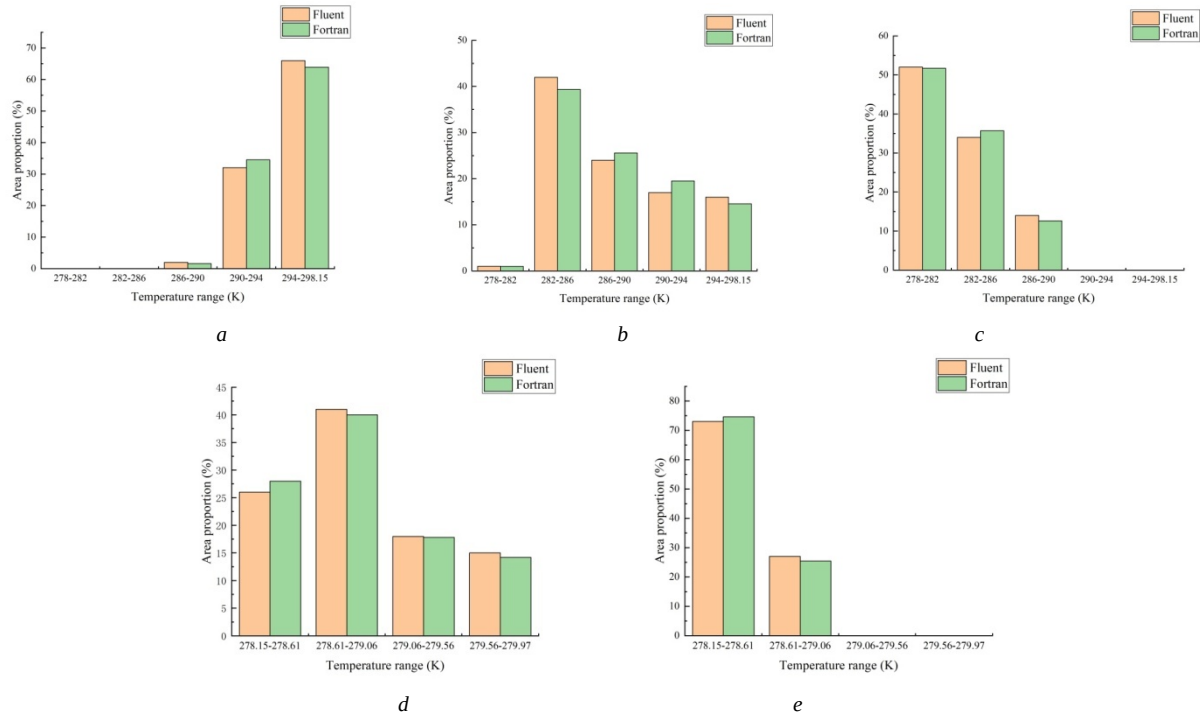


Figure 7. The area proportion of different temperature ranges in the cabinet at different moments (a) at 1 minute, (b) at 5 minute, (c) at 10 minutes, (d) at 25 minutes, (e) at 35 minutes

The area proportion of the temperature range in the refrigerated cabinet is a key parameter to analyze the refrigeration characteristics, because for the storage of beverages, we often pay more attention to the temperature range required for storage rather than a specific temperature.

Figure 7 shows that as time went by, the proportion of the low-temperature area in the cabinet gradually increased, and the proportion of the high-temperature area gradually decreased, and the difference between the results simulated by Fortran program and results simulated by Fluent is basically negligible. The maximum absolute error is 2.83%. As a result, the results simulated by Fortran program are basically reliable and can effectively simulate the refrigeration characteristics.

5. Conclusion

In this paper, a refrigeration characteristic analysis program for the refrigerated cabinet was developed and a numerical study was carried out. The change process of the internal air flow field distribution and temperature distribution in the process of starting up until reaching a steady state was simulated, and the following conclusions are obtained:

- (1) In the early stage of the refrigeration process of the refrigerated cabinet, the temperature difference between different regions was large, the air around the evaporator coil was cooled first, the density increased, and a downward flow was generated, and a large-scale vortex was generated in the lower cavity of the refrigerated cabinet.
- (2) The overall temperature of the refrigerated cabinets gradually decreased from bottom to top. As time went by, the temperature difference between regions gradually decreased, and the effect of natural convection weakened. The overall temperature field dropped to 278.15K and remained unchanged.
- (3) The refrigeration characteristics analysis program developed with Fortran is reliable. The simulation results of the program are basically consistent with the simulation results of the Fluent software. The overall temperature distribution is not much different, the velocity field and the large-scale vortex structure are slightly different but they are basically the same. This study can provide reference for further researches.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author, W.L. upon reasonable request.

Author Contributions

Conceptualization, W.L.; methodology, W.L. and T.L.; software, W.L. and T.L.; validation, T.L.; formal analysis, W.L.; investigation, W.L. and T.L.; writing—original draft preparation, W.L.; writing—review and editing, T.L. and Y.H.. All authors have read and agreed to the published version of the manuscript.

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