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Experimental Study of Natural Convection in a Closed Cavity (Static Type Domestic Fridge)

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ABSTRACT

This work provides an analysis of the thermal flow and behavior of the (load-free) refrigerator compartment. The main goal was to compare the thermal behavior inside the refrigerator cavity to the freezer door (home refrigerator) effect and install a fan on the freezer door while neglecting the heat transmitted by thermal radiation. Moreover, the velocity distribution, temperature, and velocity path lines are theoretically studied. This was observed without affecting the shelves inside the cabinet and the egg and butter places on the refrigerator door as they were removed and the aluminum door replaced with a glass door. This study aims to expand our knowledge about the temperature and flow fields of this refrigerator model. Finally, the development of this work highlights the importance of numerical simulation in the search for improvements in the design of this refrigerator model, which may assist refrigerator manufacturers.

Keywords: Domestic refrigerator, close cavity, Refrigeration, Natural convection, cavity.

دراسة تجريبية للحمل الطبيعي في تجويف مغلق (ثلاجة منزلية)

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الخلاصة

يقدم هذا العمل تحليل التدفق والسلوك الحراري للمقصورة في الثلاجة (بدون حمل). الهدف الرئيسي هو مقارنة السلوك الحراري داخل تجويف الثلاجة لتأثير باب الفريزر لـ (ثلاجة المنزل) وتركيب مروحة على باب الفريزر. علاوة على ذلك ، تم دراسة توزيع السرعة وخطوط مسار درجة الحرارة والسرعة نظريًا. لوحظ ذلك دون وجود الأرفف داخل المثصورة وأماكن المخصصة

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للبيض والزبدة على باب الثلاجة حيث تمت إزالتها واستبدال باب الألمنيوم بباب زجاجي. تهدف هذه الدراسة إلى توسيع معرفتنا حول مجالات درجة الحرارة والتدفق لنموذج الثلاجة هذا. أخيرًا ، يسلط تطوير هذا العمل الضوء على أهمية المحاكاة العددية في البحث عن تحسينات في تصميم نموذج الثلاجة هذا ، مما قد يساعد مصنعي الثلاجات.

الكلمات الرئيسية: الثلاجة المنزلية، تجويف مغلق، تبريد، الحمل الطبيعي، تجويف.

1. INTRODUCTION

Home refrigerators are available and widely used globally, with nearly one billion fridges located worldwide**(Laguerre and Flick, 2004)**. The demand for refrigerators varies according to the area's population, consumption, and economy, consumption and economy. There are three types of refrigerators: Static, Brewed, and No Frost. **(Fig.1)** illustrates the three types. In the first type, Static **(Fig. 1a),** the heat is transferred by the mechanism of natural convection that occurs due to air movement. Evaporator location (horizontal/vertical, top/bottom cab) determines the cold and warm application zones. The second type, Brewed **(Fig. 1b)**, is similar to the first type except that it is equipped with a fan. No-Frost type **(Fig. 1c)** contains a fan located inside the back wall of the refrigerator, which forces air to flow over the evaporator before entering the cold room **(Fig. 2) (Laguerre, 2010).** It is not preferable to place delicate food in the area near the evaporator, where the temperature is less than 0℃ **(Laguerre and Flick, 2004)**. It has been observed that the temperature of foods near the top of the refrigerator is higher than the temperature of foods near the bottom, which means that the temperature of the food increases with the increase in height **(Laguerre, Remy, and Flick, 2009)**. Since the air near the cold wall is directed downward, and the air near the hot wall is directed upward **(Laguerre, Ben Amara, and Flick, 2005),** the temperature is higher at the bottom of the refrigerator model, and the lower air temperature has been observed in the absence of foods **(Laguerre *et al.*, 2008) and (Gupta, Ram Gopal, and Chakraborty, 2007)**. Also, it was noticed that when there were grooves in the door shelves, and the steel glass shelf was also changed to a wire shelf, the air is allowed to pass through it and to avoid the points of clogging inside the fresh food room. It was found that the average temperature inside the cavity was reduced and the energy used was also reduced **(Belman-Flores, Gallegos-Muñoz, and Puente-Delgado, 2014)**. **(Miroshnichenko and Sheremet, 2018)** showed numerous configurations of the enclosures with different initial and boundary conditions, heat source locations, and radiative properties of medium and walls had been considered under the effects of various parameters such as the Rayleigh and Prandtl numbers, surface emissivity, cavity inclination angle, thermal properties. **(Karatas and Derbentli, 2017)** worked on the convection inside a cavity by adopting different dimensions and depth stability. Experiments are conducted on rectangular cavities with dimensions of 1, 2.09, 3, 4, 5, and 6. All six cavities are 340 mm high and deep. 210 mm. The length of the socket was changed to obtain different rectangular cavities. **(Wang, Zhao, and Tian, 2019)** used a rectangular cavity model with a porous structure to study dual diffusion mixed convection using numerical simulation.

This work aims to develop experimental data on temperature distribution in empty static and brewed domestic refrigerators. The aim was to better understand the heat transfer mechanism by natural convection and with a fan in the refrigerator and use this data to validate the modeling.

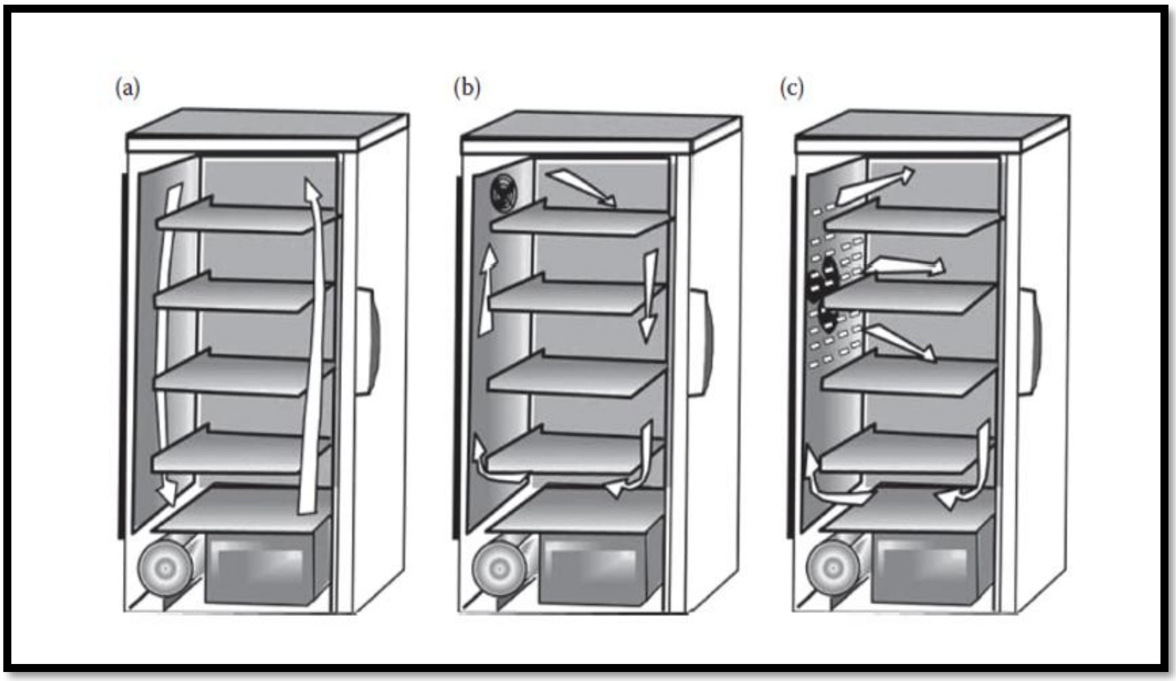


Figure 1. Types of refrigerators.

2. MATERIALS AND METHODS
2.1 Refrigerator model

The static refrigerator (without a fan) was located in an area with a room temperature of 23 ℃. The internal dimensions of the refrigerator model **Fig.(2a)** are 0.5 × 0.5 ×1.13 m (length × width × height). It was divided into three areas: the freezer, fresh food, and vegetable, as shown in **Fig.(2b).** The dividers between the fresh food area and the vegetable area have been removed and merged into one area, as shown in **Fig.(2c),** and the development of thin metal wires to stabilize the thermocouples on it, as in Fig. **(3).** The walls of the refrigerator are completely insulated. Three walls are made of aluminum with heat insulation inside, and the fourth wall is the door that was replaced by a door made of aluminum frame and double glass (glass thickness was 6 mm and air thickness between glass walls was 10 mm), as shown in the **Fig.(2a).** The freezer is internal with internal dimensions 30 × 43 × 20.5 cm (length × width × height).

Figure 2. Refrigerator model.

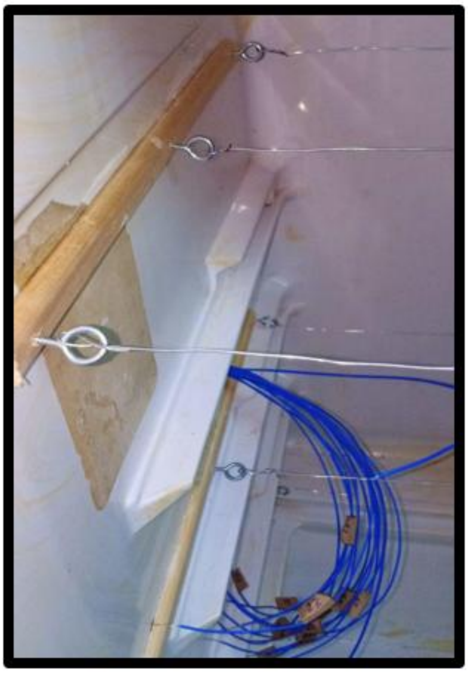


Figure 3. Thin metal wires to stabilize the thermocouples.

2.2 Temperature measurement

Thirty copper-chrome thermocouples K-Type were used for temperature measurement. Twenty-seven thermocouples were installed inside the refrigerator compartment on a thin metal wire as in **Fig. (4).**

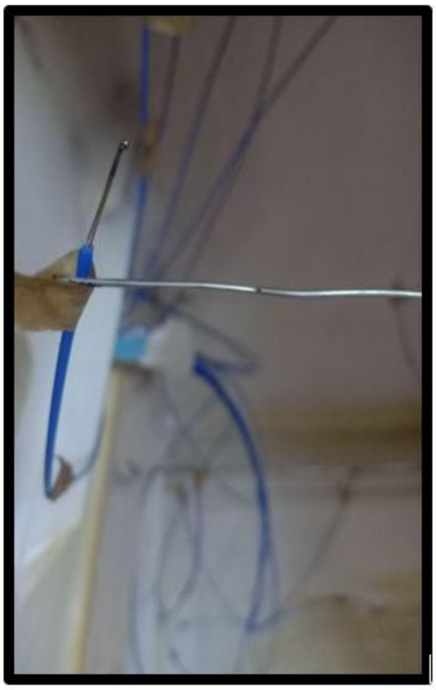


Figure 4. Copper-chrome thermocouples K-Type.

They were inserted by puncturing the sidewall of the refrigerator **Fig. (5).** The other three thermocouples were installed inside the freezer.

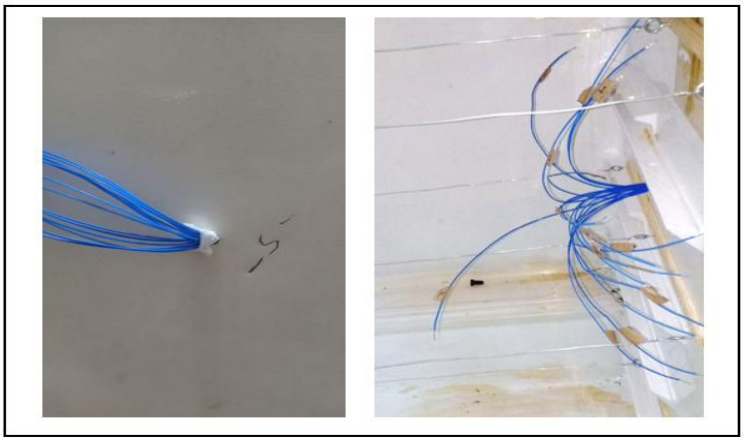


Figure 5. Thermocouples Installation locations.

The air temperature was measured at three height levels (17, 32 , and 46 cm) from freezer and for each height, nine measurements of air temperature were recorded at different locations (three near the left wall, three in the middle, and three near the right wall) as shown in **Fig.(6)** and **Fig.(7).**

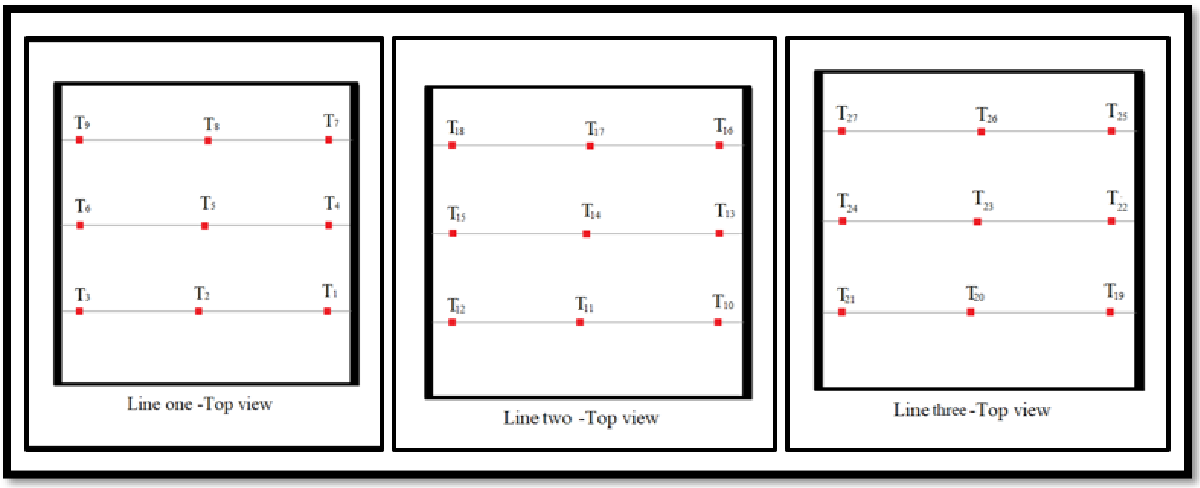


Figure 6. Diagram showing the locations of the thermocouple.

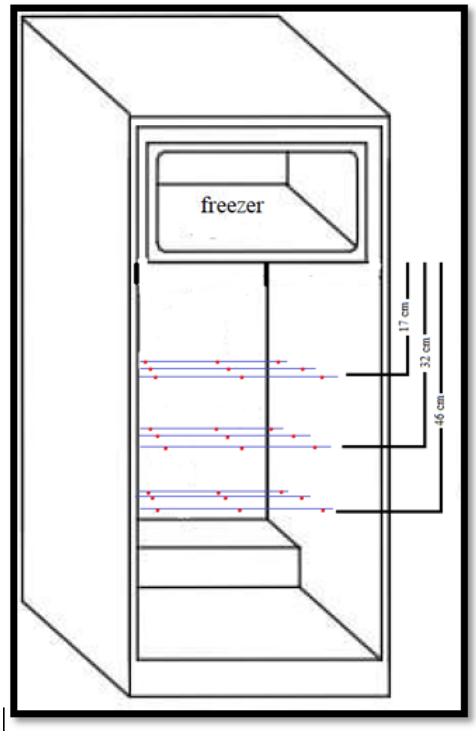


Figure 7. Diagram showing the locations of the thermocouple.

3. EXPERIMENTAL PROCEDURE:

After installing the test rig and the measuring devices, experimental work has been done for three cases as follows

3.1 Case 1 (With Freeze Door)

1- Power on the refrigerator and waited for 24 hours until the steady-state condition was achieved, **Fig.(8)**.
2- Waiting for the compressor to stop, the temperature recording was started.
3- By thermocouple selector, the thermocouple was selected, the reading was recorded according to its location.

Figure 8. Case 1 (With Freeze Door).

3.2 Case 2 (Without Freeze Door):

1- The freezer door was removed from its place, so the freezing cavity remained open to the hollow of the refrigerator, as shown in **Fig.(9).**
2- The refrigerator was started and waited for 24 hours until the steady-state condition was achieved.
3- After waiting for the compressor to stop, the temperature recording was started.
4- By thermocouple selector, the thermocouple was selected, the reading was recorded according to its location.

Figure 9. Case 2 (Without Freeze Door).

3.3 Case 3 (With a freezer door with a fan installed in it):

1- The freezer door was removed from its place, and the fan was fixed on the freeze door place, where the air was pushed from the freezer into the refrigerator cavity **Fig. (10).**
2- The refrigerator was started, and the fan has waited for 24 hours until the steady-state condition was achieved.
3- After waiting for the compressor to stop, the recording of the temperature was started.
4- By thermocouple selector, the thermocouple was selected, the reading was recorded according to its location.

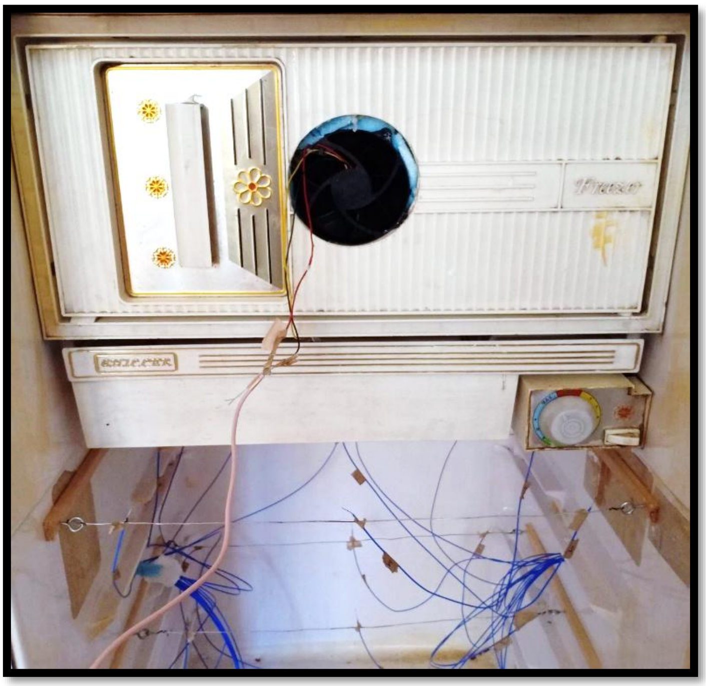


Figure 10. Case 3 (With a freezer door with a fan installed in it).

4. THEORETICAL MODEL AND NUMERICAL SOLUTION

A numerical analysis was used, and the focus was on the flow of liquids in the air inside the refrigerator. The analysis of thermal behavior inside the refrigerator is the main aim in addition to the effect of air velocity on the temperature gradient inside the refrigerator compartment. The following assumptions were taken for the governing equations:

1- Steady-state conditions.

2- Incompressible flow.

3- Three-dimensional problems.

4. Turbulent flow.

Density is calculated using the Bossiness approximation. Conservation equations adapt the model, taking into account static properties, and the Bossiness equation in the y component of The Naiver-Stokes equation **(Belman-Flores and Gallegos-Muñoz, 2016).**

Continuity equation:

$$\rho\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_x}{\partial y}+\frac{\partial u_x}{\partial z}\right)=0$$

Momentum equations:

Component x:

$$u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}+u_z\frac{\partial u_x}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{\partial^2 u_x}{\partial z^2}\right)$$

Component y:

$$u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_y}{\partial z}=g_y\beta(T-T_\infty)+\frac{\mu}{\rho}\left(\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_y}{\partial z^2}\right)$$

Component z:

$$u_x\frac{\partial u_z}{\partial x}+u_y\frac{\partial u_z}{\partial y}+u_z\frac{\partial u_z}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 u_z}{\partial x^2}+\frac{\partial^2 u_z}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)$$

Energy equation:

$$\rho c\left(u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}+u_z\frac{\partial T}{\partial z}\right)=K\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$

The density difference term calculated from the simplified equation:

$$\rho_\infty-\rho=\rho\beta(T-T_\infty)$$

4.1 Geometric model

The actual cavity geometry of the refrigerator with the shape was constructed by ANSYS-FLUENT 13 with the evaporator inside the refrigerator of the refrigerator size mentioned above for the three cases.

4.2 Numerical simulation

Because the governing equations cannot find an accurate final solution to the model, the numerical solution has been re-sorted using the ANSYS software to reach the required results and solve the problem. The 3D shape was plotted using the xyz axis.

4.3 Boundary Conditions

Boundary conditions are specified for the vertical and horizontal walls of the refrigerator As the side and upper walls are insulated, and the door is at room temperature 23℃. The internal domain (zones) that shares common areas (faces) does not require whichever boundary condition; it has been just delimited as a fluid. To simulate the flow and heat transfer through the refrigerator

4.4 Mesh Independence Test

In order to obtain good accuracy in the solution and reach the correct result, the mesh must be excellent by controlling the mesh element number. Therefore, a sufficient number of items is necessary, but this is accompanied by such obstacles as increased memory requirements and resolution time. An independent test of the grid was performed for all geometric shapes by selecting one of the specific properties: the liquid mass fraction and the grid element numbers. Gradually, the element number increased from small to larger, and the liquid mass fraction was examined to reach stability that did not lead to variance calculations. According to the results, the optimal number for the mesh is 2330000, as shown in **Fig**. **(11)**. Less than this number of elements were tested. Still, the accuracy of the solution was insufficient. Also, a larger number of elements was tested, and the difference was found to be very slightly relative to the time taken. Therefore, this number of elements was adopted to reach good accuracy in the solution. **Fig. (12)** shows all the details of the mesh. The model was analyzed as shown in **Fig. (13)**. This will greatly reduce analysis time, improve compatibility between numerical simulation and experimental work, and reduce the error rate.

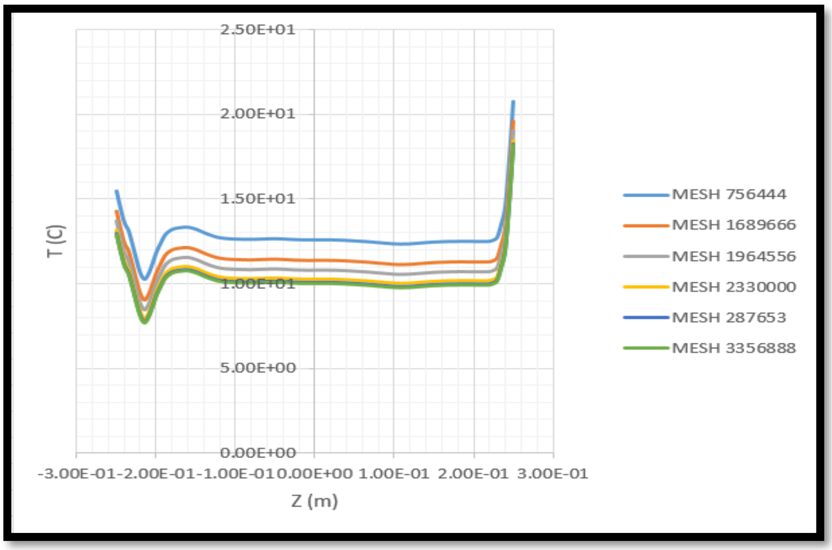
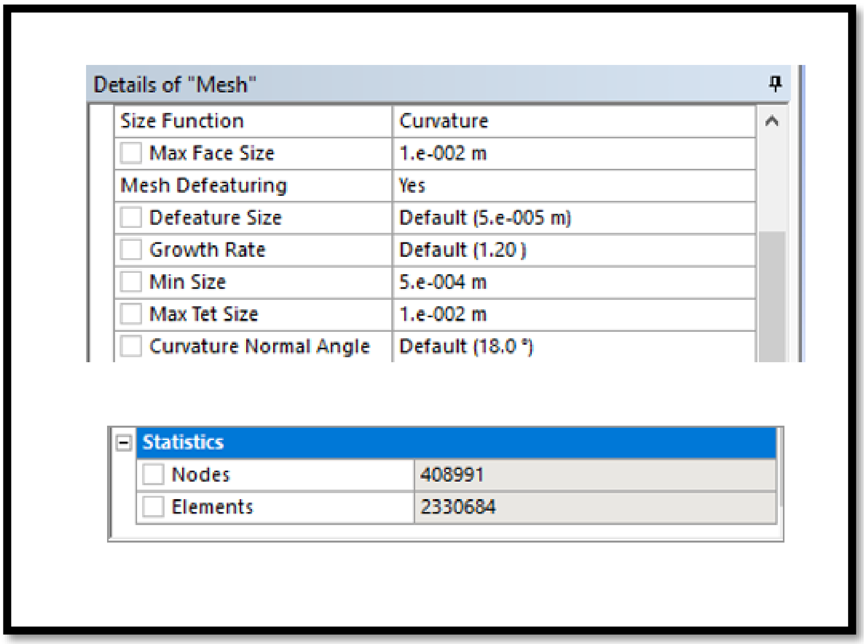


Figure 11. Mesh Independence Test Result.



Details of "Mesh"

Size Function	Curvature
Max Face Size	1.e-002 m
Mesh Defeaturing	Yes
Defeature Size	Default (5.e-005 m)
Growth Rate	Default (1.20)
Min Size	5.e-004 m
Max Tet Size	1.e-002 m
Curvature Normal Angle	Default (18.0 °)

Statistics	
Nodes	408991
Elements	2330684

Figure 12. Details of Mesh .

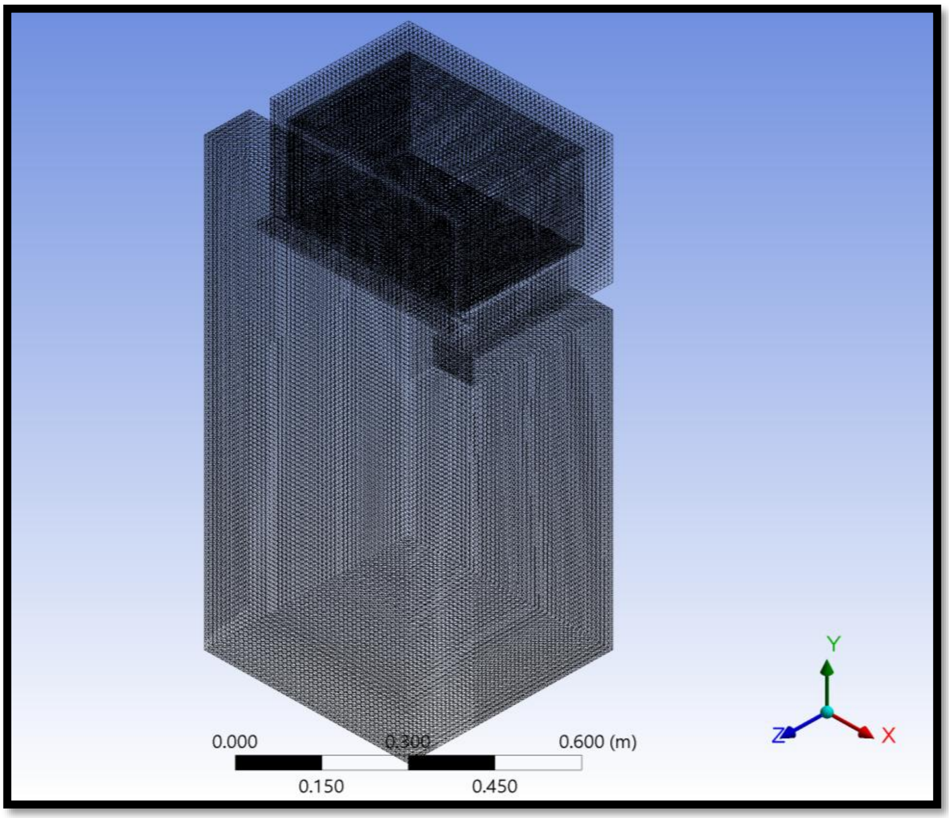


Figure 13. Mesh of the model

5. RESULTS AND DISCUSSIONS

The results of temperature and velocity distribution were obtained in the numerical analysis inside the cavity. The figures showed the theoretical results of the velocity distribution and the temperatures inside the cabin for the three cases and the effect of the variables on the thermal behavior and the velocity distribution.

5.1 Experimental Result

5.1.1 Temperature distribution

In all three cases, as for the analysis of the temperature distribution, it was noted that the layer near the door is the hottest, and it started to cool ging towards the back of the refrigerator. In addition, it was noticed that the lower layer (the place for saving fruits and vegetables) is cooler than the upper layer due to the difference in air density, as the cold air has a higher density than hot air settles at the bottom. The hot air is to the top. **Fig. (14)** shows the practical results of the temperature distribution when the freezer door was closed, divided into layers (parallel to the door), the first is close to the door and it is the hottest, the second is in the middle of the refrigerator cavity and the last is closest to the back of refrigerator.

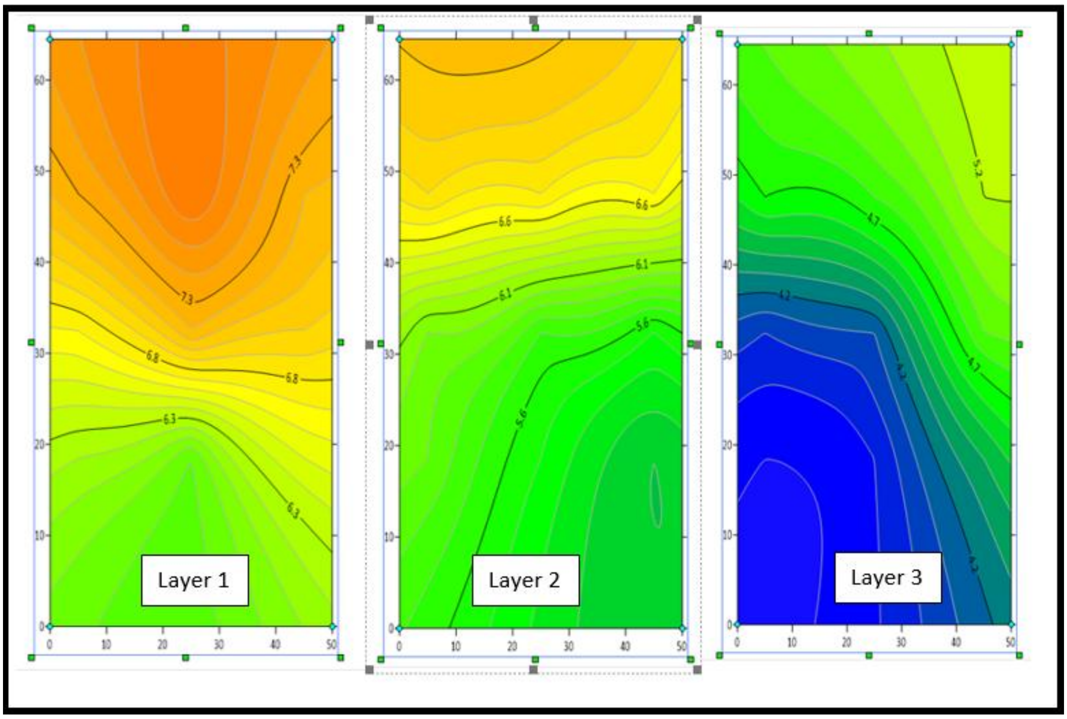


Figure .14 Temperature distribution when the freezer door is closed.

As for the case of removing the freezer door and noticing that the cold air is coming out in front of the freezer and behind it, then the layer near the refrigerator door and from the back of cold air **Fig. (15)**.

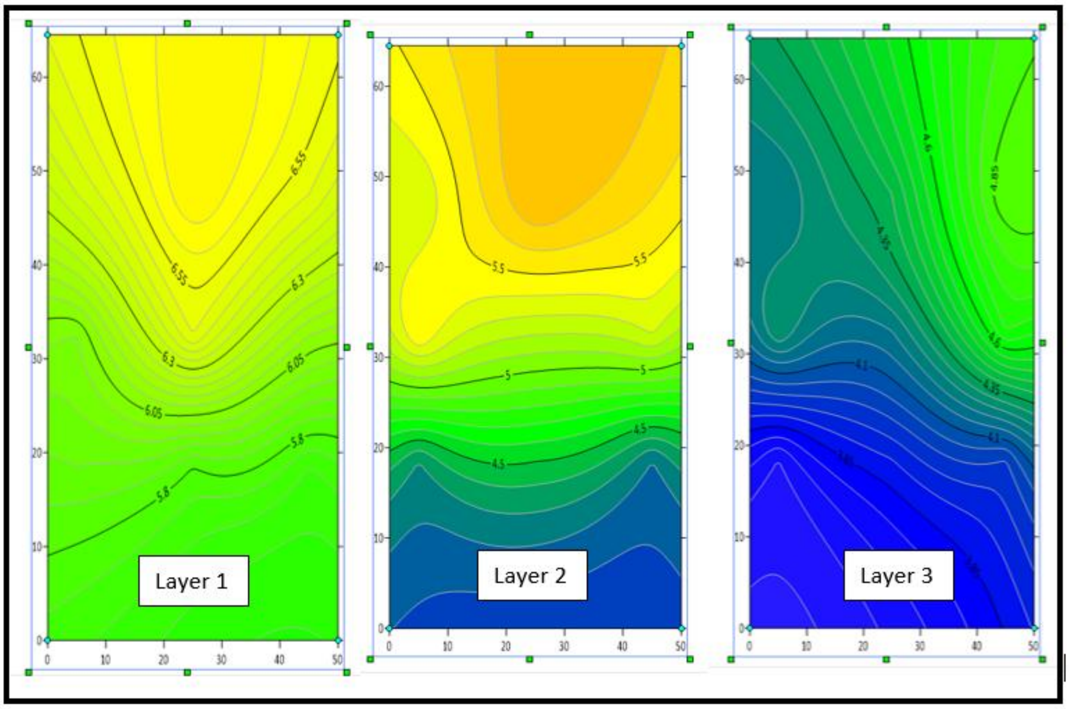


Figure.15 Temperature distribution when removing the freezer door.

As for the last case, with a fan installed in the door of the freeze, the temperatures are shown in **Fig. (16).**

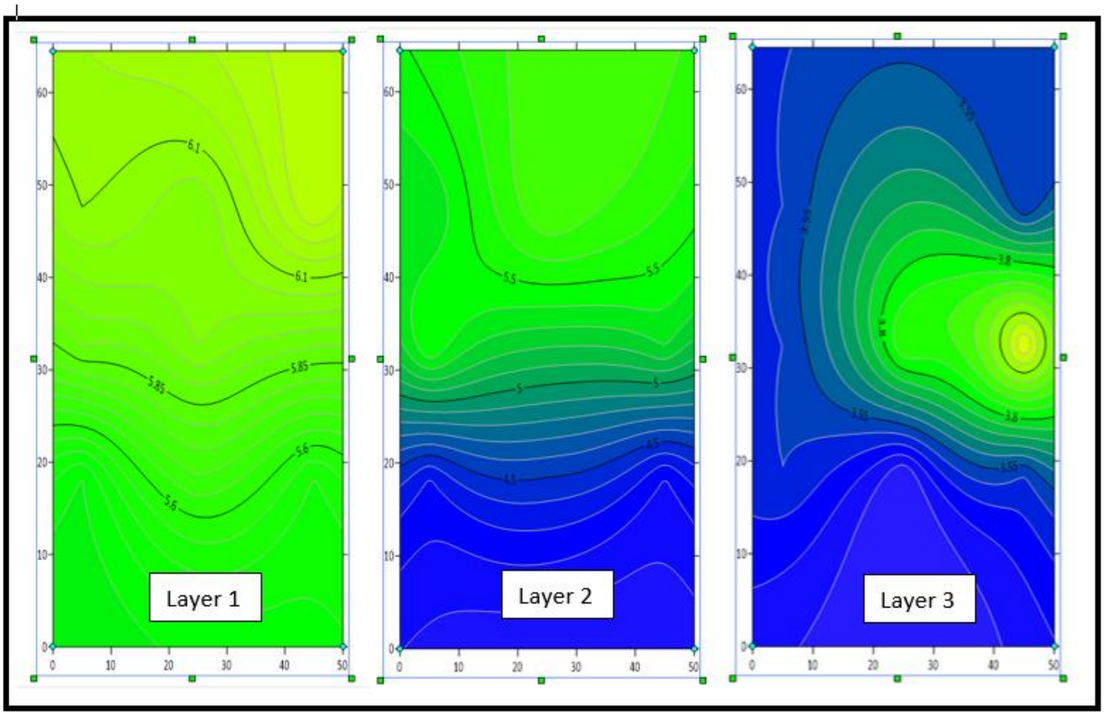


Figure.16 Temperature distribution when with a fan installed in the door of the freeze.

5.2 Theoretical Result

5.2.1 Temperature distribution

A numerical simulation was performed to study the thermal behavior when removing the freezer door and adding a fan, comparing the results to the normal state (the freezer door was closed), and knowing the best condition in terms of temperature uniformity and temperature gradient.

In the first case, where the freezer door is closed, it was noticed that the flow of cold air from the nearby back layer on the back of the refrigerator, the air is moving downward, and the hot air rises to the top in a layer close to the door. Also, the area in front of the freezer door is the hottest **Fig. (17)**.

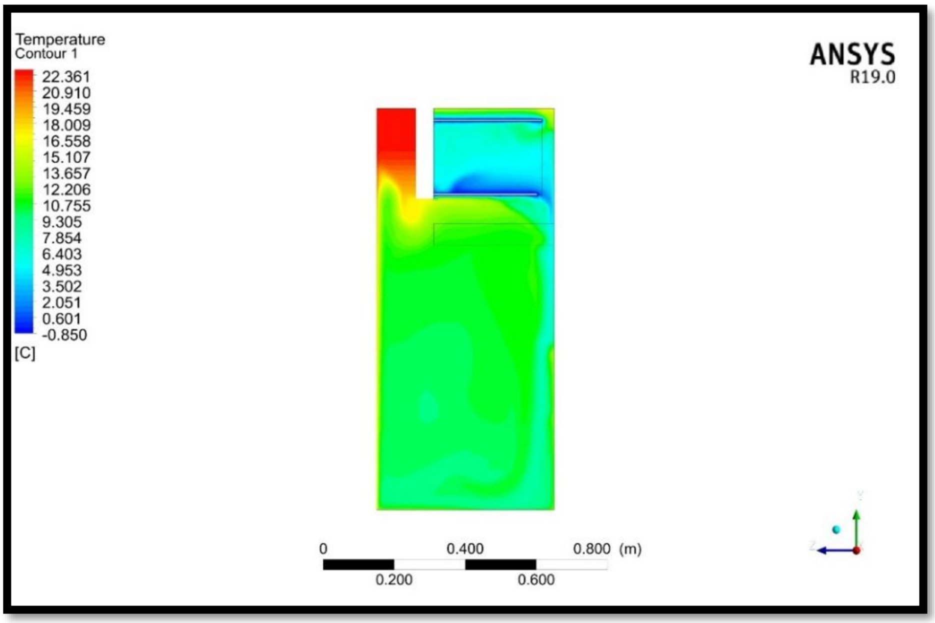


Figure.17. Temperature distribution for the first case.

As for removing the freezer door and noticing that the cold air is coming out in front of the freezer and behind it, then the layer near the refrigerator door and from the back of cold air **Fig. (18)**.

The last case is the best case among all, as the temperatures are more homogeneous. The area near the door is less hot than in other cases. Cold mire spreads more quickly than other cases **Fig. (19)**.

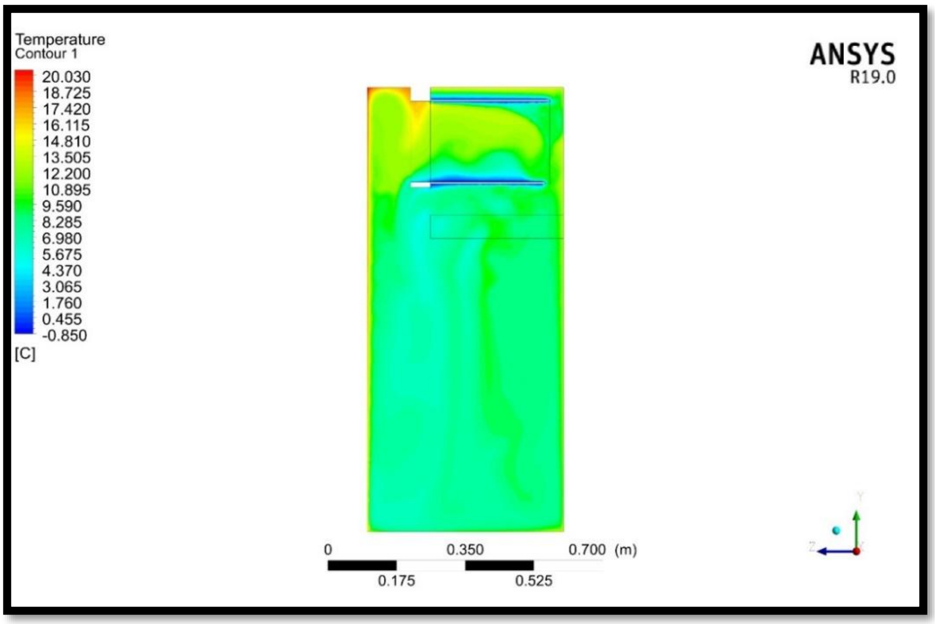


Figure.18 Temperature distribution for the second case.

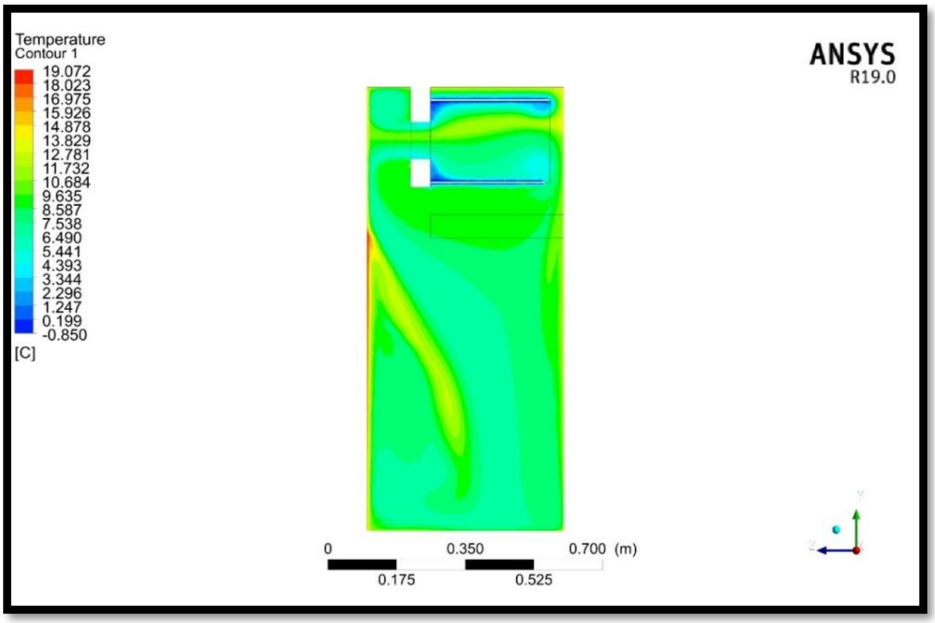


Figure .19 Temperature distribution for the third case.

5.2.2 Velocity distribution:

As for the distribution of speed, it was noticed that the speed increases towards the back of the refrigerator. This is because the density of cold air differs from that of hot air. Cold air is heavier than hot air as it heads downward and hot air rises upward. Therefore, the speed distribution depends on the temperature distribution inside the cabin.

In the case of the freezer, we note that the highest value of the speed is in the layer near the back of the refrigerator, as shown in **Fig. (20).**

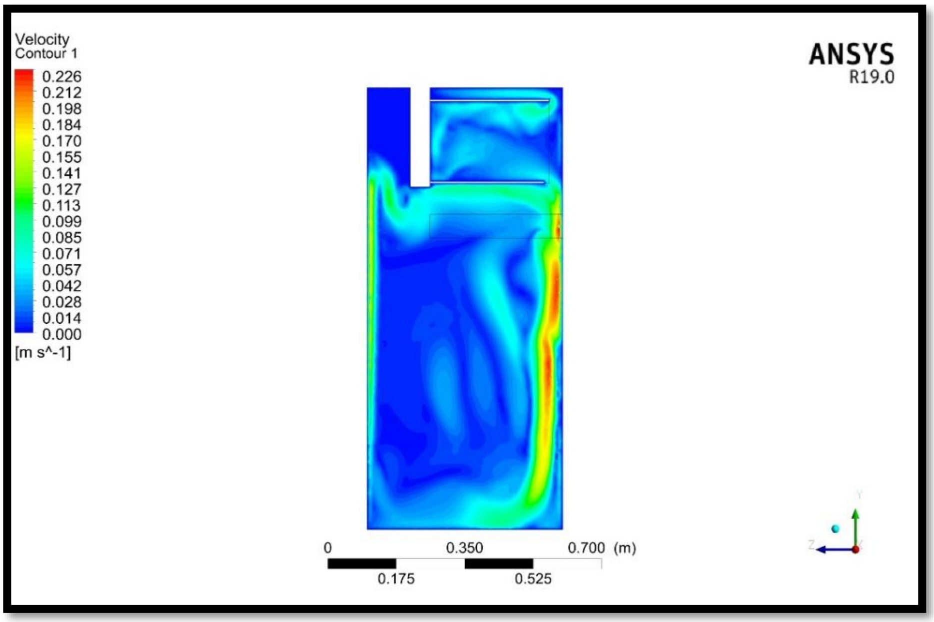


Figure. 20. Velocity distribution for the first case.

If the freezer door is removed, the speed in the center is higher on the sides due to the cold air coming out of the freezer from the front near the door and the backside close to the back of the refrigerator, as shown in **Fig. (21).**

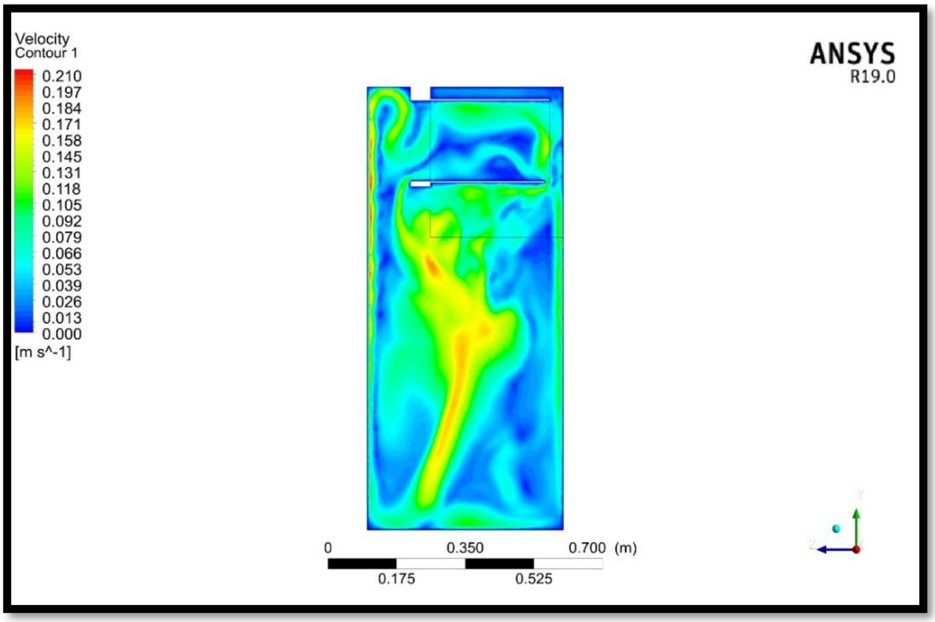


Figure. 21 Velocity distribution for the second case.

As for the last case, when the was fan installed on the door of the freeze in the case. It was noted that the speed is almost non-existent compared to the speed of the fan, as shown in **Fig. (22).**

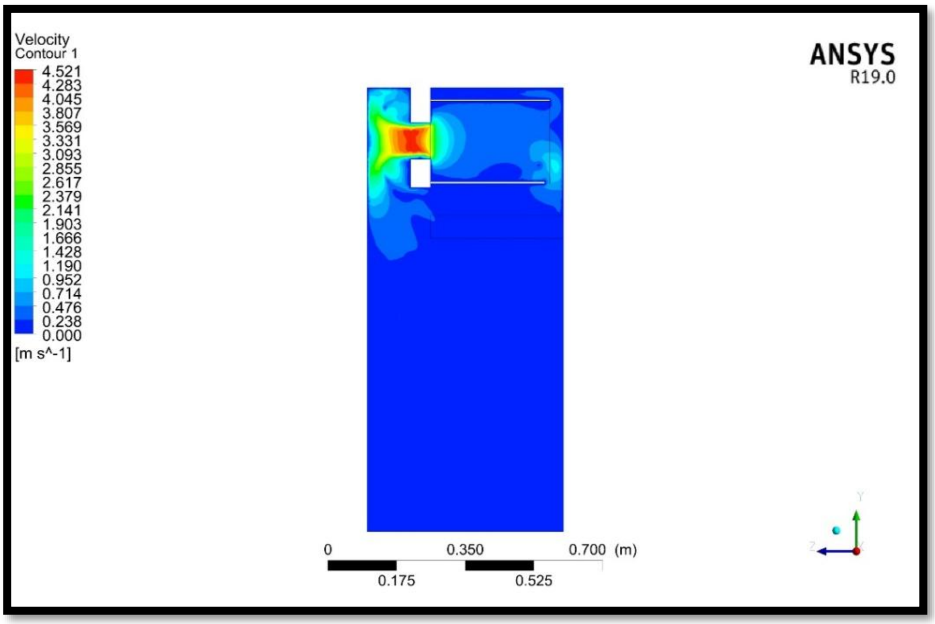


Figure. 22 Velocity distribution for the third case.

The best condition for the performance of the refrigerator out of these three cases is the last case with the fan installed on the freezer door, as it is the best in terms of temperature distribution and velocity distribution. In this case, the refrigerator returns to its stable state after using it faster than in other cases. However, this case requires higher electrical energy than the other two cases due to the presence of the fan.

6. CONCLUSIONS

1. The area near the bottom of the refrigerator is the coldest place
2. The temperature increases in the upper area inside the cavity
3. The temperature inside the refrigerator is more homogeneous with the fan inside the compartment
4. The layer parallel to the refrigerator door is the hottest layer inside the refrigerator compartment
5. With a promoter, the temperature distribution inside the refrigerator is the best among the cases, but you should pay attention to the increase in power due to the presence of the fan.
6. Cold air is heavier than hot air due to the difference in density, so it settles in the lower direction, and the hot air is up.

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