CFD analysis of natural convection heat transfer in a static domestic refrigerator

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Abstract. Refrigerating compartment with and without shelves is designed for analyzing the air flow and temperature distributions by using the Simulation software Ansys work bench 14. Comparing the results of the air and temperature distributions inside the refrigerating compartment with and without shelves. Here shelves considered as obstacles and the refrigerator without freezer compartment is considered as a 2D rectangular enclosure one side is assumed as evaporator wall (cold wall) and other side as Door (warm wall). Inside the refrigerator cabin air flow takes by natural convection. Temperature distributions is observed in the compartment without shelves and with shelves and same is compared. In the natural convection heat transfer happens between the internal walls of the refrigerator and air by radiation, conduction and convection. Air flows downward near the cold wall and moves upward near warm wall due to the density variation. As a result, temperature stratification was observed in the refrigerating compartment. Evaporator wall maintains the colder region and door wall has the higher temperature.

1. Introduction
This study is to analysis the air, temperature distribution and heat transfer which happens inside the refrigerating compartment is modelled with and without shelves (obstacles) of natural convection type domestic refrigerator. There are natural and forced type convection systems are available in the domestic refrigerators. The natural convection type refrigeration system is taken for our simulation. This type of refrigerator, inside the compartment air flow happens because of the air density variations. Refrigerator compartment model designed using Pro E and analysed using Ansys 14.0 work bench software. This study is used to find the temperature at different points in order to maintain a correct temperature for food stuffs by consuming least amount of electricity, this will improve Coefficient of Performance of the system. Optimization of this system design is to improve the performance and it needs better understanding of natural convection heat transfer. Variations of air flow and temperature deviations inside the refrigerating compartment are the most important factors which affects the performance of the refrigerator. This simulation work is carried out by using the predetermined values which done by experimentally and same has performed by the following boundary conditions are steady state and the flow is laminar in natural convection. The model is air-
filled, two dimensional (2D) vertical walls with isothermal boundaries it is heated the wall from below and cooled from above. With the continuation of above introduction, some literature review are follows. C. Balaji et al., studied is to develop the comprehension correlations the natural convection and radiation in surface for square cavity, this study has extensive numerical approach. Convective heat transfer has reduced because of the surface radiation and the same will contribute for overall heat transfer. Christian J.L. Hermes et al., carried the experimental work to simplify the vapor compression refrigeration system model with ON OFF control. For development and validation of the model, controlling and measuring the operating conditions of the system is necessary.

J K Gupta et al., made a comprehensive study of domestic frost-free refrigerator of thermo – fluidic model. Here computational and experimental work is compared to validate the results. Freezer and refrigerating compartment analysed by both simulation and experiment work, as a result predicted temperature as higher value than the experimental observations. And of these results and heat transfer is analysed and some alterations in the design is suggested. S.J. James et al., worked on the review paper to compare the working performance of domestic refrigerator. The aim of this review paper is to reduce the food waste by protecting it with the proper temperature. Especially milk, sea food and vegetables etc have to maintain proper temperature in order to improve its shelf life. T. G Karayiannis et al., studied numerical investigation of convective heat transfer for the rectangular enclosures. O. Laguerre et al., studied the natural convection for closed system experimentally between cold wall and warm walls. In this investigation temperature profile for the central zone of the refrigerator model is investigated. S Ben Amara et al., studied the natural convection heat transfer for without ventilated domestic refrigerators. In the simulation results shows the temperature stratification observed, warm air goes to top and cold air flow bottom of the compartment. Obstacles have slowed down the air circulation in the central zone. D Remy et al., investigated the rectangular cavity by natural convection of heat, moisture. At bottom humidification is observed the thermal stratification and air flow in the cavity. Here the steady state, temperature and humidity fields on the symmetry planes. D Flick et al., studied the natural convection for evaporation and condensation phenomena without fan. Here the numerical results were compared with the experimental values, it is well predicted that simulation under estimates the experimental values. O Laguerre et al., analysed the natural convection heat transfer in domestic refrigerator (unventilated refrigerators). This model is used to quantify by convection, conduction and heat radiation between the vertical plates and air. Evelyne Derens el al., investigated the refrigerating compartment in three sections top, middle and bottom of the system. Temperature is recorded using a data logger. It was found that some researchers found that the temperature is difficult to state and to operate their refrigerator. And the analysis shown that mean temperature of the refrigerator is observed in middle and bottom of the refrigerator. In 1999, 36% of families don’t know about the refrigerator and the food preservative system. Atmospheric temperature is more than the refrigerator temperature and it is affected by the several factors. Ozgur et al., studied the natural convection heat transfer in the domestic refrigerator. And the simulation of fluid flow and temperature distribution of the refrigerator for commercial use. In this analysis, have studied the radiation mode heat transfer. Air flow and temperature inside the refrigerating compartment is extended the analysis which decreased the order modelling method.

As a overall energy can represented by spatial mode by 95%. By considering the radiation effect there is no significant changes in the temperature distribution but heat rates affected much. N.J Smale et al., investigated the reviews of air flow in the numerical models of the refrigerated food applications. Air flow pattern governed directly in order to maintain the temperature homogeneity for the commercial refrigeration system. This paper comparing the numerical and CFD analysed refrigeration system in order to predict the air flow. In the refrigerated model air flow and temperature distribution is for food preservation is found that to reduce the ventilation and temperature heterogeneity in order to improve the efficiency of the system. As a suggestion by this researcher this kind of simulation and experimental work carried out in this area will increase drastically in future. Scope of the present
work, based on the above introduction and the literature survey, it has been observed that temperature distribution and air flow with in the refrigerating cabin are the most important factor which is the reason for system efficiency. Air flow and temperature distribution of static type refrigerator works based on the air density variations. Various environmental issues affect the heat transfer under natural convection phenomena inside the refrigerating compartment. Simulation is carried to explore the correct and actual air flow and temperature distribution of the system in order to improve the performance of the system.

2. Modelling
Model developed using the Pro-E designing software. Model of the domestic static refrigerator (without fan) with and without shelves has developed. Single-door appliance (without freezer) was used and the model of the refrigerating compartment has the combination of four vertical walls, top and bottom walls. Top and bottom walls are assumed as adiabatic and other four sides wall is assumed to be isothermal wall. Heat exchanges based on the free heat transfer between the internal walls and air, radiation between the evaporator and isothermal walls and conduction with in the walls. All the walls inside the refrigerating compartment have to maintain the low temperature than the atmospheric temperature and several parameters will affect the same.

**Figure 1.** Front side of modelled refrigerator compartment

**Figure 2.** Back side view of modelled refrigerator compartment
In the empty modelled refrigerating compartment (without shelves) as shown in the above figure 3. In order to approximate the transfer of heat inside the refrigerating compartment has the simplest approach. Air circulation which is near to the cold wall flows in downward direction and the warm air near to the other walls moves upward direction. Considering the empty refrigerating compartment as 2D, and the heat transfer between cold wall (low temperature region) and warm wall $T_w$ (high temperature region). Homogeneous temperature is maintained in the vertical wall and horizontal wall is considered as adiabatic.

Rayleigh number, $Ra_L = (g\beta\Delta T L^3)/\alpha v$.

**Table 1. Properties of the material**

| Material properties       |                |
|---------------------------|----------------|
| Density                   | 1000 kg/m$^3$  |
| Specific heat             | 1.103e4 J/kg K |
| Thermal conductivity      | 15.309 W/mK    |
| Viscosity                 | 0.001 kg/m-s   |
| Absorption co efficient   | 0.2 m$^{-1}$   |
| Thermal expansion         | 1e-5 K$^{-1}$  |

Modelled refrigerating compartment is analysed based on the theory of natural convection. Inside the compartment working fluid to maintain the pre-set temperature is air. Natural convection takes place between air and vertical walls which is evaporator and the side walls in our design. And the following assumption is made that is the exchange between the evaporator and air and it is similar for the vertical walls. Near the cold wall it is considered as the cold wall and other isothermal walls are taken as the
warm wall. Frost-free refrigerator is considered for the analysis therefore evaporator is not exposed directly in the refrigerating compartment. Instead, air is allowed to flow over the cold wall, so cooling and dehumidification happen simultaneously.

3. CFD Methodology

In our modelled refrigerating compartment has single compartment with the dimension of 100 cm of height, 50 cm of depth and 50 cm of width (100 x 50 x 50 cm) and which it replicates the compartment of actual refrigerator. By neglecting the radiation effect while considered in boundary conditions for the analysis. Following assumptions have to made for the analysis, there should be no mass flow rate across the boundaries and for velocities no slip condition is assumed in between the walls. To maintain the constant transfer of heat the air flow is assumed to be a steady state and flow is laminar. The Rayleigh number for this condition is less than $10^9$.

**Table 2. Dimensions of the refrigerator model**

| Sl. No. | CONTENT                         | Dimension       |
|---------|---------------------------------|-----------------|
| 1       | External dimensions             | 110x60x60       |
| 2       | Internal dimensions             | 100x50x50       |
| 3       | Number of shelves               | 2               |
| 4       | Thickness of glass shelf        | 5 mm            |
| 5       | Conductivity of glass shelf     | 0.75 Wm$^{-1}$K$^{-1}$ |

**Table 3. Boundary conditions for Simulations**

|                     | Relaxation factor | Type of discretization |
|---------------------|-------------------|------------------------|
| Pressure            | 0.3               | Presto                 |
| Density             | 1                 | -                      |
| Gravity forces      | 1                 | -                      |
| Momentum            | 0.7               | Second order upwind    |
| Energy              | 1                 | Second order upwind    |
| Radiation           | 1                 | -                      |
| Pressure-velocity   | -                 | Simple                 |
4. Simulation

Ansys 14.0 workbench software is used for simulation. Refrigerator is assumed as a 2D rectangular cabin and left side wall is assumed as a cold wall and right-side wall is assumed as a warm wall (Door). Both cold wall and warm wall has the different constant temperatures. Top and bottom wall is assumed as adiabatic. In the solution method pressure velocity coupling scheme is set as simple. Cold wall temperature is set as -1.2°C and warm wall temperature is 6.7°C. Geometry is developed in ansys 14.0 and fine mesh is used 4800 nodes for empty refrigerator cavity and 4100 nodes for refrigerator with shelves is used for calculation.

Figure 6 shows the temperatures of evaporator wall (cold wall), warm wall (door), and air (working fluid) at top, middle and bottom of compressor ON and OFF cycle. For our case predicted temperatures are taken from average values of it. This is to assume the constant cold wall, warm wall and air temperatures.

5. Results and Discussions

Simulation results which take into account heat transfer by natural convection between sides of the compartment and the air flow in the refrigerating compartment. Temperature distributions obtained from simulation for the refrigerating cabin with and without shelves shown in figures. Considering only the empty cavity without freezer compartment observed the thermal stratification at bottom and top of the refrigerating compartment. In bottom presence of obstacles have lower the temperature and at top of the compartment has the slightly higher temperature when compared with the case of refrigerator compartment without shelves. These obstacles reduce down the air flow at the middle of the compartment and the same have influenced the air circulation in the boundary layers that is evaporator and isothermal walls. Thermal stratification was observed in each gap of the shelves. The air temperatures increase with increasing numbers of obstacles.

![Figure 4. Pressure variations in refrigerator compartment without shelves.](image1)

![Figure 5. Pressure variations in refrigerator compartment with shelves.](image2)

Pressure inside the cabin, temperature distribution based on the density variations. Due to this flow of air takes place. The above figure shows that pressure variations inside the empty cabin and cabin with shelves and it describes the bottom of the cabin has low pressure and top of the cabin has high...
pressure. This air density variation happens because of temperature and this contributes to air circulation, cold air is heavier than hot air. Velocity variation inside the refrigerator cabin with shelf. Due to the obstacles (shelf) present near the cabin increase the pressure of the air. From the bottom of the cabin pressure of the air flow is increasing. In top of the cabin with shelf pressure is increased than the cabin without shelf.

![Figure 6](image6.png) **Figure 6.** Temperature distributions at different points in refrigerator without shelves.

![Figure 7](image7.png) **Figure 7.** Temperature distributions at different points in refrigerator with shelves.

![Figure 8](image8.png) **Figure 8.** Air flow due to density variation for the refrigerator without shelves.

![Figure 9](image9.png) **Figure 9.** Air flow due to density variation for the refrigerator with shelves.

6. **CONCLUSION:**

Simulation study of air flow, temperature distribution was carried out within the model of the refrigeration system as similar to that of a domestic refrigerator without a fan. Refrigerating compartment with and without shelves is modelled. CFD work carried for the following types of
refrigerating compartment, that is, an empty refrigerator, an empty refrigerator fitted with glass shelves (shelves considered as the obstacles). Results shows that at top and bottom maintained warm region and colder region respectively. The obstacles increase the heat transfer in the model of refrigerating compartment. Obstacles improves the air flow near the wall and thus heat exchange of the natural convection is thus improved. Low temperature air stratification was observed near all measured points with the presence of block (shelves) and this slows down direction the air flow in the middle zone of the refrigerator and mildly influence the main air circulation along the walls.

Table 4. Final temperature predicted in the wall

| Sl.No. | PROPERTIES         | TEMPERATURE |
|--------|--------------------|-------------|
| 1      | Cold wall          | -1.2°C      |
| 2      | Warm wall          | 6.7°C       |
| 3      | Working fluid (air)| 6.3°C       |

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