CFD analysis of forced convection heat transfer in a domestic refrigerator

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ABSTRACT

The function of a domestic refrigerator is to preserve the quality of food products. Quality of food directly depends on temperature and air distribution inside the storage chambers. Unsuitable storing temperature will cause food to deteriorate ahead of time. Therefore temperature distributions and airflow distribution inside the food chambers are crucial for keeping food fresh. In this project the air flow and temperature distribution by forced convection heat transfer in separately modeled freezer and refrigerating compartment of frost-free domestic refrigerator is studied. The freezer and refrigerating compartments is studied for two configurations using shelves and without shelves. The simulations are carried out using ANSYS 14.0 work bench computational fluid dynamics software. The heat transfer between the freezer and refrigerating compartment is neglected and laminar air flow conditions were assumed. Simulation results show temperature stratification in the refrigerating compartment cold and warm zone were top and bottom respectively, in freezer compartment warm and cold zone were top and bottom for both configurations.

Comparison of temperature profiles with and without shelves for both the freezer and refrigerating compartment were done. The air temperature distribution is low almost everywhere in the model containing with shelves. Thus the presence of the shelves enables to maintain different temperature in both freezer and refrigerating compartment.

Keywords: domestic refrigerator, airflow distribution, laminar airflow, temperature distribution, heat transfer

1. INTRODUCTION

The frost-free refrigerator is a refrigerator in which the evaporator is not directly exposed to the refrigerating compartments. Air is made to flow over the evaporator so that it can be simultaneously cooled and dehumidified. The cold and dry air is then blown into the compartments. The air mass takes heat and moisture from the products being refrigerated and surroundings and becomes relatively warm and humid in this process. This warm and humid air stream is again made to flow over the evaporator coils where it again becomes cold and dry by rejecting sensible and latent heat to the refrigerant flowing through the evaporator.

Forced convection heat transfer phenomena inside the cabins are relevant to a wide range of industrial processes or environmental situations. In common practice refrigeration equipments loaded by food products: domestic refrigerator, cheese ripening room, cold room, insulated container etc. Knowledge of air temperature and velocity profiles in a refrigerator is important for food quality control. Knowledge of the thickness of thermal and hydrodynamic boundary layers near the evaporator and the other walls is also important. If the product is too close to the evaporator wall freezing can occur and if it is too close to the other walls there may be health risks. In practice, food products stored in a domestic refrigerator have different forms, dimensions and occupied volumes.

Through this we aim to develop a CFD model of domestic refrigerator for prediction of temperature and velocity fields in freezer and refrigerating compartments and compare and analysis the air flow and temperature distribution inside the freezer and refrigerating compartments with and without shelves.

2. MODELING AND CFD ANALYSIS

The physical model: CFD simulation carried out for a domestic frost-free refrigerator. Freezer and refrigerating compartments is modeled separately and analyze the air flow and temperature distribution with and without shelves. The refrigerator considered here is a 230 liters of domestic frost-free refrigerator in which the evaporator is not directly exposed to the refrigerating compartments. Air is first made to flow over the evaporator so that it can be simultaneously cooled and dehumidified. This cold and dry air is then blown into the compartments. This cold air takes heat and moisture from the products being refrigerated and surroundings and becomes warm and humid in this process. This warm air again made to flow over the evaporator. In convectional refrigerators defrosting is done by manually switching off the refrigerator and allowing the frozen layer to melt on account of heat transfer from the surroundings. In frost-free refrigerators this is done automatically by a combination of defrost heater timer thermostat control. Air first flows inside the freezer and refrigerating compartments (fresh food) and extracts heat from the refrigerated items kept at those locations. The air stream then flows over the evaporator (placed at the back of the freezer) where it is cooled and dehumidified. Subsequently the fan blows the cold air into the freezer inlet from which a portion flows into the freezer while the rest enters the refrigerating compartment. Here the freezer and refrigerating compartment is assumed as separate units.

Assumptions:

- Heat transfer between freezer and fresh food compartments is neglected.
- The condenser and evaporator coils are considered as isothermal walls because of the nearly isothermal phase change processes associated with these components.
- Uniform velocity and temperature profiles are assumed at the inlet.

- A steady state case is being analyzed. In reality there is a continuous on and off cycling for compressor which brings transient nature to the problem.
- The refrigerator is analyzed in an unloaded condition and effects of air leakage or frosting and the associated mass transfer mechanisms are not considered.
- Boussinesq assumption is employed for flow modeling inside the refrigerating compartment which is governed by mixed convection.
- Radiation heat transfer within the refrigerator is not considered. In the refrigerating compartment, none of the walls are in direct contact with evaporator.
- The flow is assumed to be laminar in both the compartments.
- Fluid flow is taken to be incompressible.

Freezer Compartment: Table 1 shows the dimensions of freezer compartment and Figure 1 shows schematic model of freezer compartment. The cold air enters into the compartment through inner inlet ports. A part of the air which comes out of inner inlet ports goes into the portion above the shelf and the remaining air enters directly into the area below the shelf through the gap between the back wall and shelf. Temperature maintained at freezer compartment is -18°C.

Refrigerating Compartment: Figure 2 shows a schematic model of refrigerating compartment. Here inlets located at the top of the compartment. The cold air after getting in to the front inlet flows downwards and confronts the chiller wall and eventually re-circulates inside the compartment. This air after coming back from the chiller mixes with the air blown through the back inlet port. The mixed air descends due to buoyancy circulates through the shelves and finally exits through the door shelves.

Table.1.Dimensions of model freezer compartment

Content	Dimensions
Height	370 mm
Width	410 mm
Depth	400 mm

Table.2.Dimensions of model refrigerating compartment

Content	Dimensions
Height	811 mm
Width	410 mm
Depth	510 cm

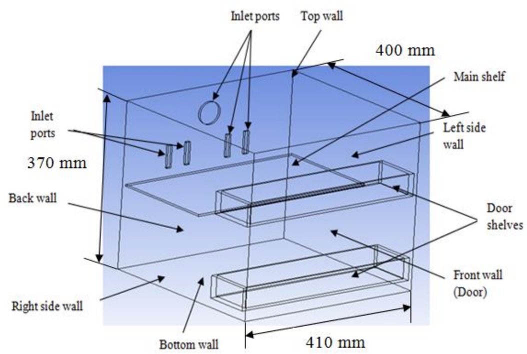

Figure.1.Model of freezer compartment

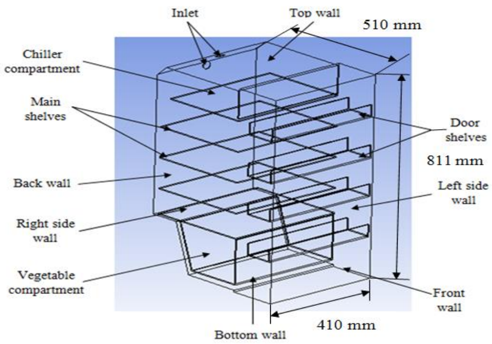

Figure.2.Model of refrigerating compartment

Computational fluid dynamics model: Computational Fluid Dynamics (CFD) is a simulation tool for the modeling of fluid flow problems based on the solution of the governing flow equations. The computational domain of freezer and refrigerating compartments modeled as separate units. Figure 3 and figure 4 shows the discretized model of freezer and refrigerating compartment. Mesh generated using software ANSYS 14.0. The computational domain is subdivided into elements to create the 'mesh' for computation. This stage of the process is also very important to obtain the reliability of the solution is dependent on the dimensions of such elements (the solution is 'grid dependent'). Number of nodes in the element is increased to obtain accurate solution this is achieved by using discretization scheme. This process is necessarily iterative and requires the solution of a huge number of equations at each step. Calculations continue until a specified accuracy is achieved usually quantified by evaluating the residuals in the calculation of the balance of one or more properties. At this point the solution is said to converge. The properties of the fluids and of the solids involved in the simulation must also be specified as well as the boundary conditions at each interface and the initial conditions for all the variables are considered.

Boundary conditions: The boundary condition parameters for freezer and refrigerating compartments are summarized in table 3 and table 4 respectively. Bottom wall of freezer and top wall of refrigerating compartment is assumed as adiabatic Heat exchange between the air and the inner cavity wall is purely conductive on the modeling scale because of velocity of air is zero at the surface. Non- slip conditions apply for all the solid surfaces.

Table.3.Boundary conditions - Freezer compartment

Boundary	Temperature	Velocity
Inlet	251.7 K	2.1 m/s
Top wall	Convective T_∞= 302 K, h_o = 0.27 $Wm^{-2}K^{-1}$	No slip
Left side wall	Convective T_∞= 302 K, h_o = 0.37 $Wm^{-2}K^{-1}$	No slip
Right side wall	Convective T_∞= 302 K, h_o = 0.37 $Wm^{-2}K^{-1}$	No slip
Bottom wall	Adiabatic	No slip
Back wall	Convective T_∞= 251 K, h_o = 11.11$Wm^{-2}K^{-1}$	No slip
Front wall	Convective T_∞= 302 K, h_o = 0.59 $Wm^{-2}K^{-1}$	No slip

Table.4.Boundary conditions - Refrigerating compartment

Boundary	Temperature	Velocity
Top inlet	253 k	1.45 m/s
Back inlet	253 k	1.3 m/s
Top wall	Adiabatic	No slip
Left side wall	Convective t_∞= 302 k,h_o = 0.37 $wm^{-2}k^{-1}$	No slip
Right side wall	Convective t_∞= 302 k, h_o = 0.37 $wm^{-2}k^{-1}$	No slip
Bottom	Convective t_∞= 302 k, h_o = 0.37 $wm^{-2}k^{-1}$	No slip
Back wall	Convective t_∞= 302 k, h_o = 0.37 $wm^{-2}k^{-1}$	No slip
Front wall	Convective t_∞= 302 k, h_o = 0.37 $wm^{-2}k^{-1}$	No slip

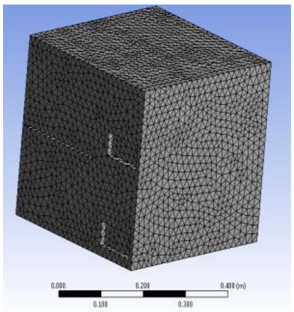

Figure.3.Mesh model of freezer compartment

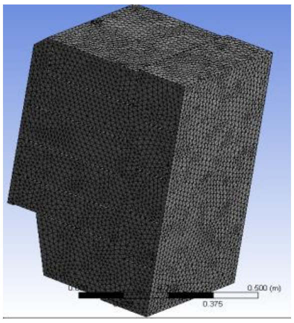

Figure.4.Mesh model of refrigerating compartment

Table.5.Operating conditions of air

Material properties	
Density	1.225 kg/m^3
Specific heat	1006.43 J/kg K
Thermal conductivity	0.0242 W/m k
Viscosity	1.7894 x 10^{-5} kg/m-s
Absorption co efficient	0.2 m^{-1}
Thermal expansion	1e-5 K^{-1}

Table.6.Resolution parameters used in simulation

Content	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
Pressure-velocity	-	Simple

Table 5 and table 6 shows the operating conditions of air and resolution parameters used in simulation. These are the conditions used for simulation. An unstructured grid system with hexahedral elements is used to discretize the computational domain. The values of pressure at the cell faces are interpolated using the PRESTO scheme, which uses the discrete continuity balance for a staggered control volume centered on the cell face to compute the staggered pressure and the pressure velocity coupling is achieved by using SIMPLE.

3. RESULTS AND DISCUSSION

CFD results are obtained in order to study the temperature and velocity fields inside the domestic frost-free refrigerator. This results concern simulations which shows heat transfer by convection between the internal walls of freezer and refrigerating compartments.

Variations of temperature fields in freezer compartment: The temperature fields obtained from simulations for the two configurations of freezer compartment with and without shelves as shown in figure 5 and figure 6. For

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both the cases thermal stratification is observed with the cold zone at the bottom and the warm zone at the top. In addition a cold zone is also observed along the back wall. This is related to cold air coming from the evaporator.

Figure 7 shows the comparison of freezer compartment with and without shelves. The temperature fields in freezer compartment 1°C local temperature rise by the presence of obstacles (with shelves). Temperatures of freezer at bottom with and without shelves having 252.5K and 253.5K respectively. Slight temperature variations obtained for both the configurations. Local temperature rise at top of compartment.

Variations of velocity fields in freezer compartment: Figure 8 and figure 9 shows the air velocity vector of freezer compartment for both configurations without shelves and with shelves. In figure 8 large portion of air swirling around the compartment. Uniform temperature is maintained at the compartment with no shelves. Velocity is higher at top of the compartment warm stream present in the compartment makes the inlet cold stream lighter. Thus the warm stream moves upward and mixes with cold stream and flows from top to bottom.

Air flows inside the freezer compartment: Inlet stream enters the compartment at top with high velocity from back wall to front wall. Near front wall (door wall), cold stream flows downwards. Figure 9 shows the velocity vectors with shelves, inlet cold stream first flows over the top while a small portion of air comes down through the clearance between main shelf and the back wall. Large portion of air flows over the top from back to front. From front wall cold stream comes through the door shelves. Air velocity at the center of the cavity is very low (<0.5 m/s). Figure 10 shows the air then flows upwards along the door and the side walls while its velocity decreases progressively and becomes stagnant at the top of the compartment. Figure 8 shows the velocity vectors of freezer compartment without shelves. The air temperature field show with cold air located at the bottom and warm air at top of the compartment.

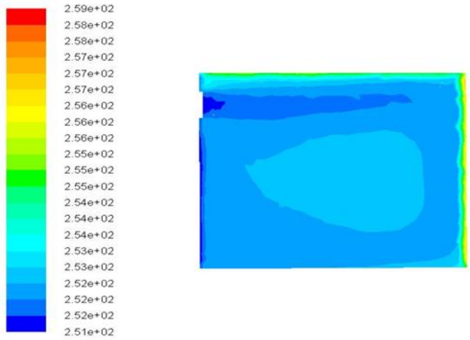

Figure 1.Temperature variations of freezer compartment (without shelves) at x = 200mm

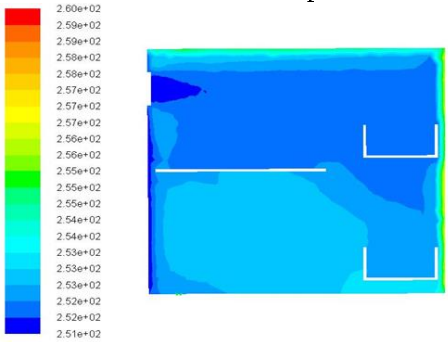

Figure.2.Temperature variations of freezer compartment (with shelves) at x = 200mm

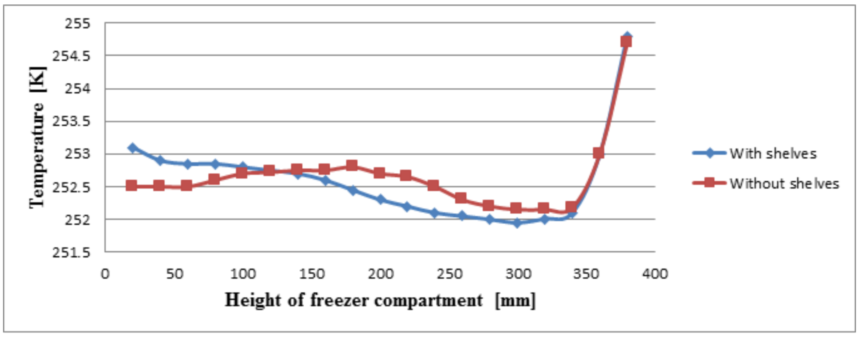

Figure.3.Comparison of temperature distribution in freezer compartment with and without shelves at x = 270mm and z = 150mm

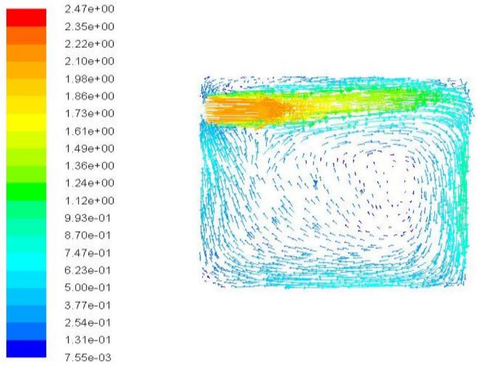

Figure.3.Velocity vectors of freezer compartment (without shelves) at x = 200mm

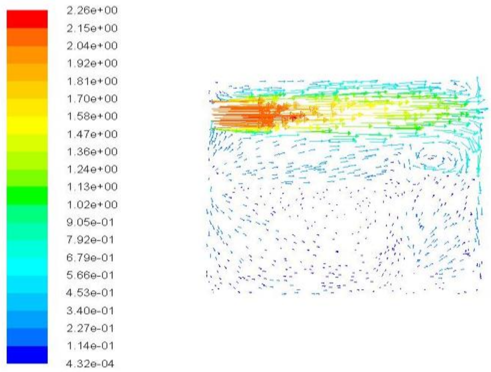

Figure.4.Velocity vectors of freezer compartment (with shelves) at x = 200mm

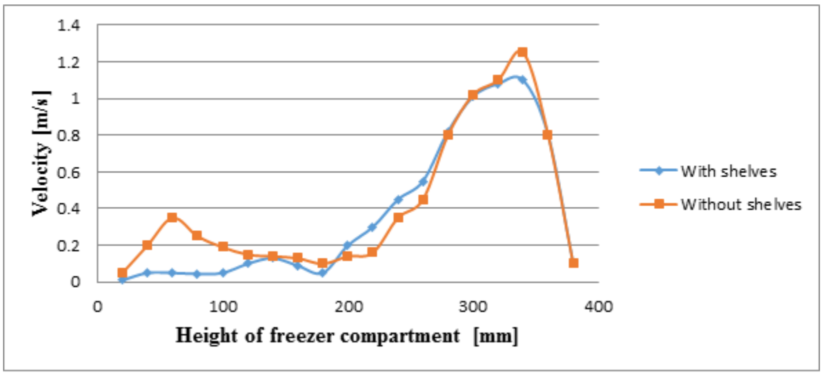

Figure.10.Comparison of velocity variations in freezer compartment with and without shelves at x = 205 mm and z = 255 mm

Variations of velocity fields in refrigerating compartment: Three dimensional flows in refrigerating compartment. Figure 11 and 12 shows the velocity vectors in the refrigerating compartment without and with shelves. In figure 12 air flows from the front inlet first enters into the chiller compartment. Though the air is cold a gravitational stability makes it to settle down on the chiller compartment. The air get heat from the surroundings becomes lighter. This hot air flows back and mixed with the cold air stream from the inlet located at back. Cold air flows down due to buoyancy effects. A small portion of this cold air enters the first shelf and settles down. This cold air again become lighter and re circulates as it mixes with the inlet. Air flows down from back wall and the shelves as same happens in all shelves. Warm air stream rises from the bottom of the compartment. The temperature rises from the bottom. Figure 11 shows the velocity vector for refrigerator compartment without shelves. Cold air inlet from the back wall of the compartment flows over the top from back to front wall (near door). Cold air mixes with the warm air present in the compartment and becomes lighter it flows upward and re circulates. Refrigerating compartment without shelves uniform temperature is obtained.

Variations of temperature fields in refrigerating compartment: Figure 13 and 14 shows the temperature distributions of refrigerating compartment. Figure 13 shows compartment having shelves (main shelves and door shelves). Temperature in the chiller compartment is the lowest and the temperature increases as one move along the downward direction. Cold air from the chiller compartment flows down to the shelves. Maximum temperature is obtained at the vegetable box 13°C.

Figure 13 shows the temperature variations of compartment without shelves. Air temperature fields obtained by simulation between internal walls of the refrigerating compartment. It was observed that overall the temperature field is similar to that present, a cold zone at the top and a warm zone at the bottom. In fact for an empty refrigerator, the maximum temperature rises from 8 °C to 10 °C.

Figure 14 and figure 15, shows the graph of comparing the refrigerating compartment with and without shelves of temperature and velocity variations. The obstacles (shelves and/or products) slow down the air circulation in the central zone of the refrigerator and mildly influence the main air circulation along the walls. The heat exchange between the top wall and the other walls tends to reduce the top wall temperature and consequently reduces air temperature near this wall.

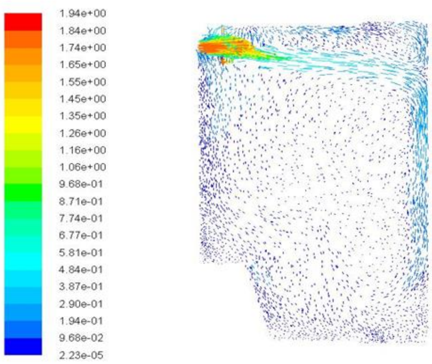

Figure.11.Velocity vectors of refrigerating compartment (without shelves) at x = 270 mm

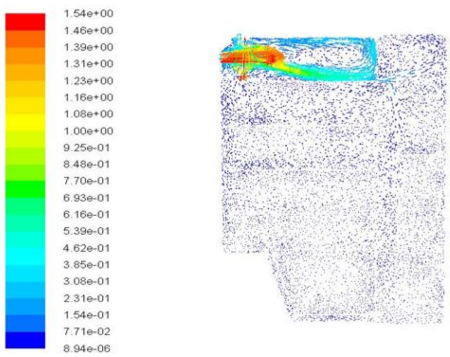

Figure.12.Velocity vectors of refrigerating compartment (with shelves) at x = 270 mm

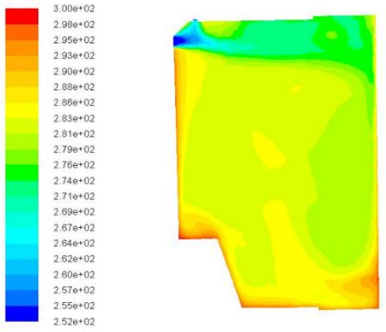

Figure.13.Temperature variations of refrigerating compartment (without shelves) at x = 270 mm

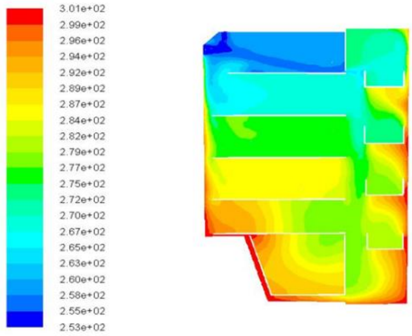

Figure.14.Temperature variations of refrigerating compartment (with shelves) at x = 270 mm

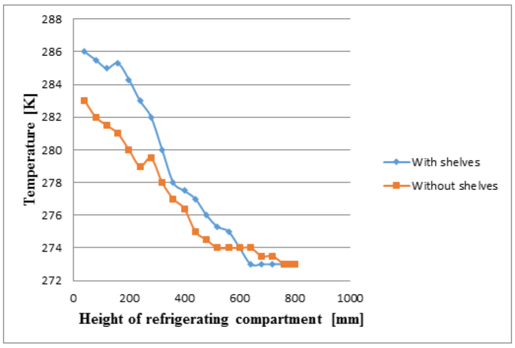

Figure.15.Comparison of temperature variations in refrigerating compartment with and without shelves at x = 205 mm and z = 255 mm

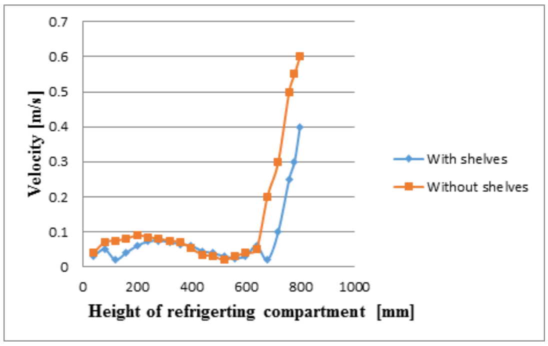

Figure 16.Comparison of velocity variations in refrigerating compartment with and without shelves at x = 205 mm and z = 255 mm

4. CONCLUSION

CFD simulation of air flow and heat transfer is carried out within the freezer and refrigerating compartment of a domestic frost-free refrigerator. Two configurations are studied in both the compartments with and without shelves. Temperature distributions in the freezer model confirm the theory that there is stratification, a warm zone (higher temperature) at the top and a cold zone at the bottom. Temperature distributions in the refrigerating model a warm zone (higher temperature) at the bottom and a cold zone at the top.

In both freezer and refrigerating compartment large portion of air first flows over the top and small portion comes down through the gap between main shelves and back wall. The obstacles slow down the air circulation in the central zone of the compartments. Temperature fields for both the configurations (with/without shelves) for this domestic frost-free refrigerator.

1. The average temperature maintained in the freezer and refrigerating compartment is about -10°C and 6°C respectively.
2. In refrigerating,

Temperatures in chiller compartment - 0°C to 3°C.
Temperatures in Shelves - 3°C to 10°C
Temperatures in vegetable compartment - 10°C to 13°C

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