Chapter 1
Optimization for Position of Heat Loop in Refrigerator Using Steady-State Thermal Analysis

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Abstract Heat loop is an integral part of the household refrigerator, which helps to avoid external condensation on the refrigerator but also increases its energy consumption. Hence, heat loop position inside foam needs to be carefully chosen to provide an optimum trade-off between the robustness of refrigerator to external condensation and minimum energy consumption. The present study aims to develop a simulation methodology for the selection of heat loop position which gives minimum energy consumption and maximum robustness for external condensation. Optimization problem definition discussed in the study led to the creation of full factorial design of experiment (DoE) setup which is solved using the finite element methods. The output from full factorial design of experiment is utilized to perform sensitivity analysis and trade-off analysis to find the optimum heat loop position. The work thus helps to have a systematic and optimum selection of input parameters so as to predict and design the refrigerator with desired attributes.

Keywords Refrigerator · External condensation · Heat gain · Energy · Optimization · Sensitivity

Nomenclature

E	Energy consumption (dimensionless since this is considered as ratio in current study)
R	Robustness to external condensation (dimensionless)
T_{ambient}	Ambient temperature of air (°C)
T_{dp}	Dew point temperature (°C)
RH	Relative humidity (dimensionless)
T_{H}	Temperature of refrigerant in heat loop (°C)
T_{I}	Inside temperature in refrigerator (°C)

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T_A	External temperature on refrigerator surfaces (°C)
x, y	Decision variables representing heat loop coordinates (position) (m)
U_x	Upper bound for x-values (m)
U_y	Upper bound for y-values (m)
L_x	Lower bound for x-values (m)
L_y	Lower bound for y-values (m)
q	Heat flux (W)
h	Convection coefficient (W/m^2−°C)
A	Surface area (m^2)
$T_{surface}$	Surface temperature (°C)

1.1 Introduction

A refrigerator is a household appliance that comprises a compartment which is thermally insulated and transfers heat from the items placed inside the compartment to the external environment [1]. This ensures that the temperature of items placed in the refrigerator is maintained below the external ambient temperature [1]. The foam which is popular insulation acts as a thermal barrier to heat flow due to very low thermal conductivity which is in the range of 0.01–0.05 W/m-K [2]. Cooling effect inside the refrigerator is provided by the continuous flow of refrigerant in the refrigerator tubes. Refrigerant follows vapor compression cycle to absorb the heat from refrigerator space (evaporator) and dissipate the heat to the atmosphere using a heat exchanger (condenser) [3]. Generally, the refrigerator comprises two basic compartments such as freezer and refrigeration section. Flow and compression of refrigerant and operation of auxiliary components like motor, fan, and lighting require energy that is supplied in the form of electrical energy. Energy consumption is an important attribute and sales feature in the cost competitive appliances industry [4]. Use of finite element analysis (FEA) to predict and optimize the energy consumption of the refrigerator is widespread in the appliances industry [4].

As a known fact, dew point temperature is the temperature at which water vapor in the air at constant pressure begins to condense into water [5]. Further, the rate of condensation is equal to the rate of evaporation of water vapor at the dew point temperature. When the ambient temperature is equal to or below the dew point, condensation occurs. This means that water vapor in the air gets converted to water and appears as dew drops on surfaces [5]. Since the refrigerator has a larger temperature difference between the inner surface and the ambient, there is a possibility that the external surface temperature of the refrigerator may drop below ambient air temperature. Freezer section in the refrigerator is affected more than the refrigeration section as the freezer section has to be maintained at a lower temperature with approximately −18 °C, whereas the refrigeration section is maintained at 5 °C. Since the temperature difference between ambient and freezer section is higher as compared to the refrigeration section, utmost care has to be taken while designing. In such a scenario, ambient air flowing over the refrigerator external surfaces gets cooled. If

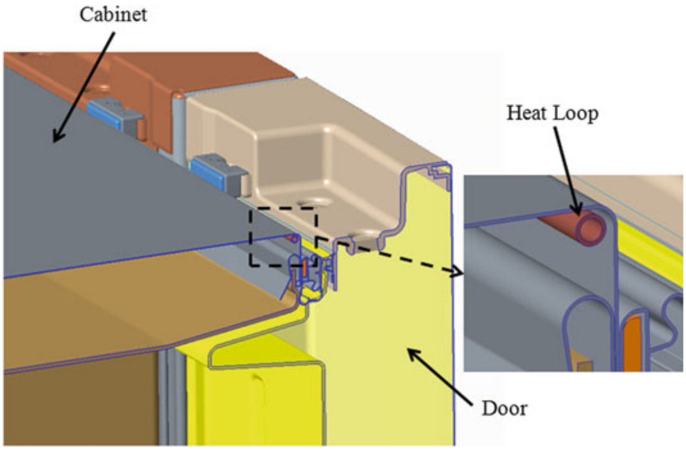


Fig. 1.1 Heat loop position

the temperature of air falls below dew point temperature, it will result in condensation of water vapor on the refrigerator surface. This leads to accumulation of a pool of water droplets on the refrigerator surface and is commonly termed as external condensation in the appliances industry. External condensation hampers perceived the quality of refrigerator and impacts aesthetics. Heat loop in the refrigerator plays a vital role to avoid external condensation.

Refrigerator normally has compressor and condenser at the rear side. These components are at significantly higher temperatures as compared to ambient. Hence, the external surfaces of refrigerator adjoining to these components (rear surfaces) are hotter than ambient air. Front flange is the outside surface of the refrigerator cabinet which is adjoining to the gasket. Since it is close to gasket interface and far from rear surfaces of the cabinet, the front flange is prone to condensation. Heat loop is a tube made of steel or copper and contains warm refrigerant that exits from the condenser. Heat loop is routed behind the front flange. Hence, it allows the front flange portion of the refrigerator to be warm. Heating the flange is considered necessary to prevent condensation in high humidity environment [4]. Figure 1.1 shows the position of heat loop in the refrigerator. It is an in the foamed part where foam helps to maintain its position and shape. Heat loop thus increases the robustness of refrigerator to external condensation. A lot of effort has gone into heat loop joint technique with condenser, whereas the impact of heat loop position on refrigerator energy consumption is still an un-researched area [4].

Heat loop acts as heat producing source inside the insulation and thus allows the flow of some heat into the refrigerator interior area. It thus increases the temperature of the refrigerator interior area and compels the refrigerator to consume more energy to maintain the cooler temperature [4]. Thus, the heat loop tube helps to avoid external condensation but at the same time increases energy consumption. Amount of heat leak to the refrigerator interior area depends on the heat loop position inside the foam. This demands a detailed study for heat loop position inside the foam and analysis to obtain an optimum trade-off between external condensation and energy consumption. Thus, various heat loop positions have to be analyzed, and the optimum position needs to be selected. The work thus intends to study the impact of variation in heat loop position on robustness to external condensation and energy consumption.

1.2 Methodology

This section presents the strategy adopted to achieve the optimization of heat loop position. Schematic of the proposed strategy is shown in Fig. 1.2. Proposed strategy includes two distinct methodologies named as Simulator and Optimizer integrated to achieve an optimum position of heat loop. The Simulator comprises FEA model, and Optimizer comprises design of experiments (DoE)-based optimization technique.

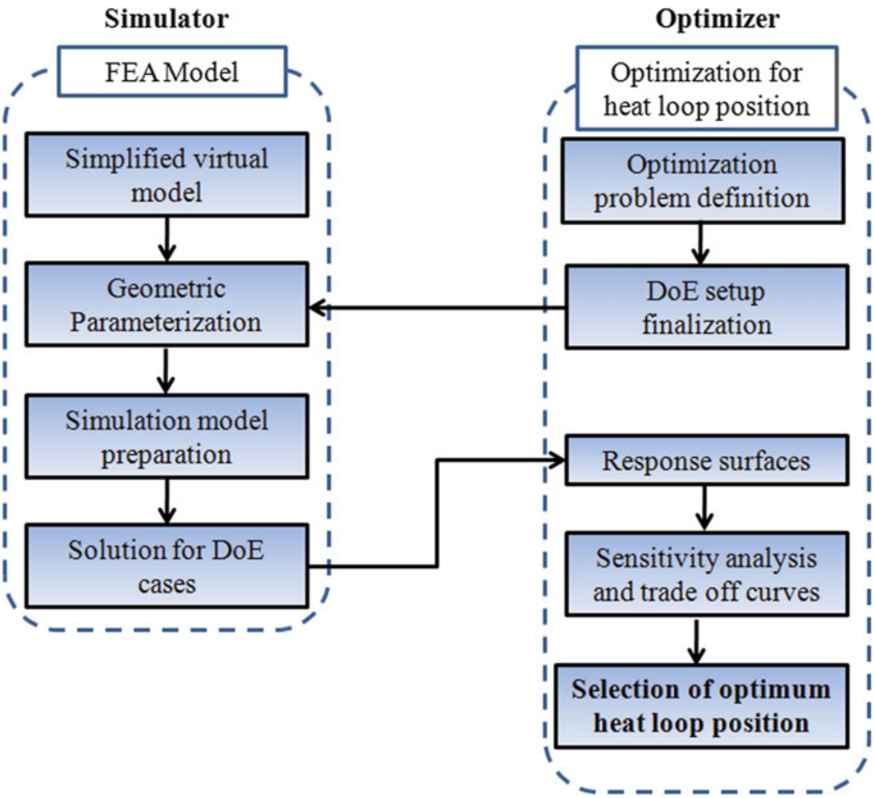


Fig. 1.2 Schematic for proposed strategy

The study is performed using steady-state thermal analysis. The building of the FEA model starts with the simplification of the 3D CAD model. In the present work, the heat loop region is considered. As shown, geometric parameterization is the next step in the FEA model. Herein, the decision variables which are chosen for DoE setup are parameterized in the simulation tool. By parameterization, we mean that the chosen decision variables along with their levels should be defined in the simulation environment so that they can be dynamically varied by the simulation solver to generate DoE results. This step requires the input of detailed DoE setup which comes from the Optimizer methodology.

Geometric parameterization from Simulator and DoE setup finalization from Optimizer work in parallel with each other. Optimizer starts with the definition of the optimization problem which includes the objective function, constraints, and decision variables. The range of decision variables is a vital part that has to be considered. Once the optimization problem is defined, we can now define the DoE setup. DoE setup contains the number of cases to be run and details of each case. This input needs to be passed on to geometric parameterization. Simulation model with boundary conditions, loads, and mesh details needs to be defined in simulation software. Next step consists of solving the FEA model to generate results for DoE cases.

Some common surfaces (response surfaces) should be chosen in the solved FEA model to generate results for energy consumption and robustness to external condensation. These results can be then further analyzed using statistical or mathematical tools such as sensitivity analysis and trade-off plots. Sensitivity analysis helps us to understand the effect of each decision variable. Trade-off plots help us overlap the energy consumption and external condensation results in order to analyze the optimum heat loop position. The above-proposed strategy provides a systematic way of performing DoE-based optimization work.

1.3 Modeling Strategy

1.3.1 Assumptions

1. The refrigerant temperature that has just exited the condenser is assumed in the range of 35–45 °C.
2. Freezer section temperature is assumed as −18 °C.
3. The ambient temperature of outside air is assumed in the range of 25–40 °C.
4. Considering the worst humidity values of coastal belts and high rainfall zones, the relative humidity of 80% is assumed in the study.
5. Dew point temperature is calculated using the ambient air temperature of 32 °C by approximation given below in Eq. 1.1 [6]:

$$T_{\mathrm{dp}} = T_{\mathrm{ambient}} - \left(\frac{100 - \mathrm{RH}}{5}\right) \tag{1.1}$$

1.3.2 Modeling Approach

A sectional simulation model of depth 10 mm in the heat loop region is considered as shown in Fig. 1.3. Length and width of the section are chosen so as to adequately capture the heat loop region along with gasket interface. The sectional model considered has dimensions of 150 × 100 × 10 mm. Figure 1.3 shows the detail of the simulation model considered. External condensation situation is more likely to occur on freezer doors. Hence, it is advisable to consider the heat loop in freezer door region for analysis. Also, heat loop is present behind the front flange of the cabinet, and hence, its impact is also limited on to the front flange region. Generally, dimensions and boundary conditions in the heat loop region are uniform across the profile of the cabinet and door. Hence, energy consumption value obtained for small depth section can easily be extrapolated for a total profile of cabinet and door. Also, the temperature gradient plot obtained for small depth sectional models can be used to understand temperature distribution across the profile.

As shown in Fig. 1.3, parts considered for analysis are cabinet assembly, door assembly, gasket, trapped air and heat loop along with the refrigerant. Cabinet assembly and door assembly each consists of steel wrapper, plastic liner, and foam. Foam is constructed using volume extraction between wrapper and liner in CAD software. Similarly, trapped air inside gasket and refrigerant inside heat loop are also constructed using volume extraction. In order to avoid the complexity of contact

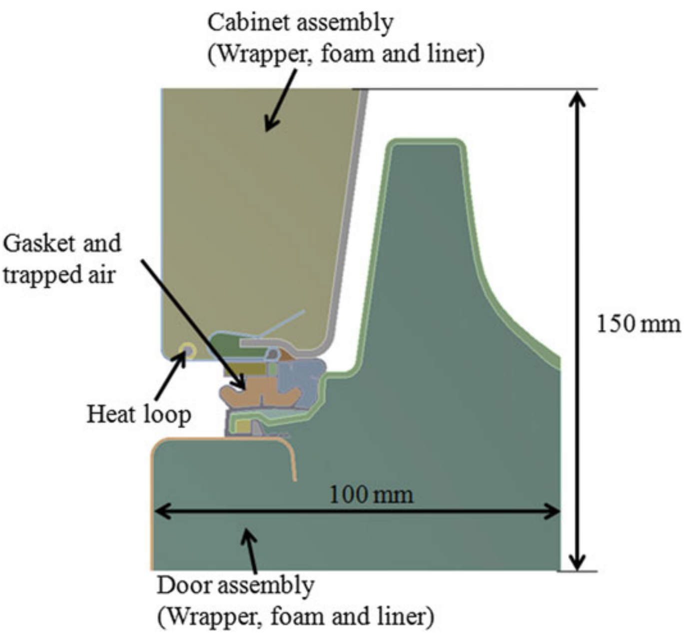


Fig. 1.3 Details of the simulation model

algorithms, multibody single-part approach is followed using ANSYS software. In this approach, we merge all the bodies inside a single part. Bodies inside the part can be applied different material properties and mesh properties. Material properties are determined using experimental investigations.

With the single-part multibody approach, care is taken to ensure mesh connectivity across bodies. Mesh connectivity is thoroughly checked while meshing the part. All the bodies are meshed with solid elements. Mesh used consists of linear tetrahedral elements with nodal degrees of freedom (DoF) of 1. Soft element sizing of 2×10^{-3} m is applied for all bodies to adequately capture intricate shapes and contours. Figure 1.4 shows the meshed model used in the analysis.

Mesh size suitable for the model is determined by the grid independence test. This test is performed by successively reducing the mesh size until we see a negligible divergence between successive iterations. Allowable or targeted divergence value in this test is taken as 0.5%. Results for this test are mentioned in Table 1.1. The table shows that, a mesh size of 2 mm, the divergence between successive mesh sizes is 0.32%. Thus, we can say that results are independent of mesh size at 2 mm element size. Hence, a mesh size of 2 mm is used in the analysis. Actual heat gain values cannot be disclosed here. Hence, the values in the table are in relative terms.

Boundary conditions used in the FEA model are shown in Fig. 1.5. The refrigerant that exits from the condenser is at a fixed temperature, T_{H} °C. Hence, a fixed temperature boundary condition of T_{H} °C is applied to the refrigerant body. T_{H} varies in the range of 35–45 °C. All the nodes of the refrigerant body are maintained at a fixed temperature during runtime on account of this boundary condition. External surfaces of the cabinet and door that are exposed to ambient air are applied with convection boundary condition with an ambient temperature of T_{A} °C and convection coefficient that is experimentally determined. Inside surfaces of the refrigerator that are exposed to cool air are applied with convection boundary condition with an inside temperature

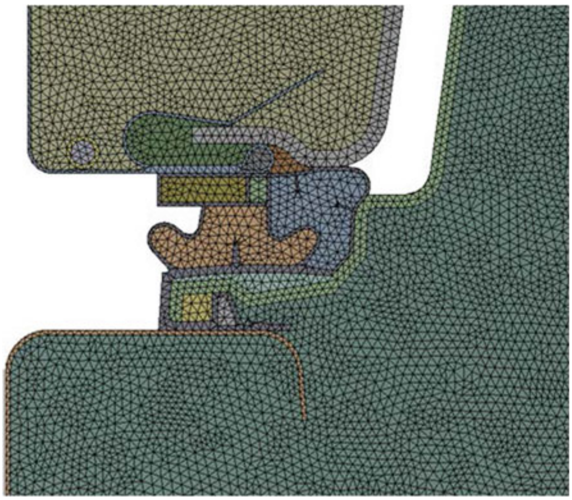


Fig. 1.4 Mesh details

Table 1.1 Grid independence test

Mesh size ($\times 10^{-3}$ m)	Energy consumption (relative terms)	% Divergence
10	1	–
8	0.985	1.5%
6	0.992	0.72%
4	0.985	0.61%
2	0.981	0.32%

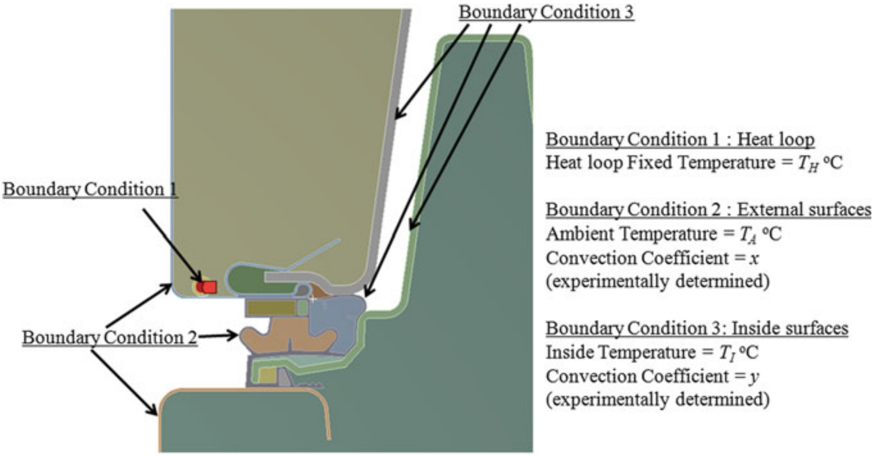


Fig. 1.5 Boundary conditions

of T_{I} °C and convection coefficient which is experimentally determined. T_{A} varies in the range of 25–40 °C, while T_{I} is assumed as −18 °C. Convection coefficients cannot be disclosed since these values are company proprietary and confidential.

1.4 Optimization Problem

Efforts to increase robustness to avoid external condensation leads to an increase in energy consumption. Thus, there must be a trade-off between these two. This trade-off is considered as an optimization problem. The objective of this optimization problem is to minimize energy consumption. Let us denote the energy consumption value of the refrigerator as E.

The implicit constraint for the problem is to avoid external condensation on the refrigerator. In quantifiable terms, this constraint can be stated as temperatures on exterior faces of the refrigerator should be greater than dew point temperature. In order to simplify the interpretation of constraint, Let us convert the minimum temperature on external faces of a refrigerator to a parameter called robustness to external

Table 1.2 Scale for robustness to external condensation

Minimum temperature (°C)		Robustness to external condensation (R)
Lower bound	Upper bound	
27.00	27.99	−1
28.00	28.00	0
28.01	28.99	1
29.00	29.99	2
30.00	30.99	3
31.00	31.99	4

condensation. Let us denote this parameter as R. With the current ambient temperature and relative humidity assumptions, dew point temperature of 28 °C is obtained. Hence, any temperature above 28 °C indicates that the model is robust to prevent external condensation on the external flange. Further, higher is temperature, as compared to the dew point, more robust, is the model. Considering this, we define robustness scale, where the temperature of 28 °C corresponds to $R = 0$. Table 1.2 defines the robustness scale. Thus, as per the below scale, any positive robustness score ($R \geq 1$) indicates that there is no condensation on the external flange. Zero or negative score ($R \leq 0$) indicates there is an external condensation in the model. Thus, the implicit constraint for the optimization problem is $R \geq 1$.

The explicit constraint for this optimization problem would define the maximum allowable range for decision variables. Let us discuss details for the choice of decision variables as given in Sect. 1.4.1.

1.4.1 Choice of Decision Variables

Decision variables for the problem comprise of x- and y-coordinates of heat loop position with respect to the coordinate axes defined subsequently. Quantifiable and measurable decision variables in order to define the heat loop position are chosen. A coordinate system (X, Y) is chosen as shown in Fig. 1.6 where X-axis is taken as inside wall of cabinet side face and Y-axis is taken as inside wall of the front flange of the cabinet. In this way, x-coordinate represents lateral (sidewise) position of heat loop from side face, while y-coordinate represents the depth-wise position of heat loop from the front flange.

Next step is deciding bounds for decision variables. It is advisable to consider the heat loop as close as possible to the front flange to avoid external condensation. $y = 0$ m represents that heat loop is just below the flange which is the most favorable position to avoid external condensation. As y increases, heat loop moves further away from front flange resulting in lesser heating of front flange. If it crosses an allowable distance, it will become ineffective in heating the flange. Considering this aspect,

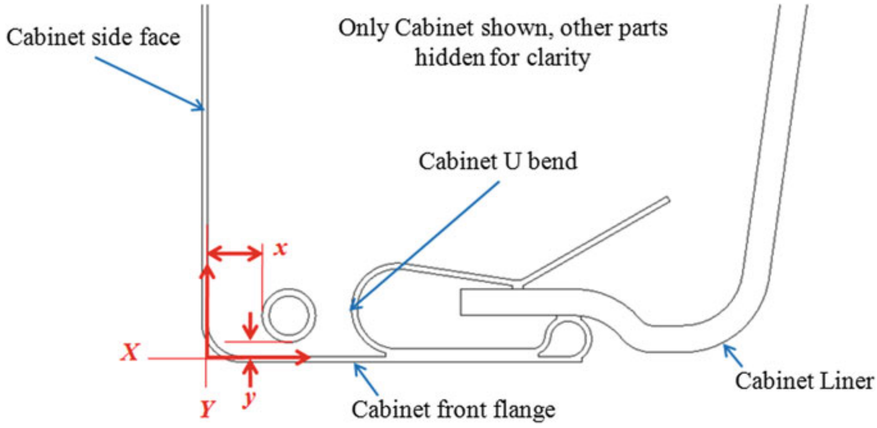


Fig. 1.6 Coordinate axes definition

the upper limit is 4×10^{-3} m for y. As a parametric study, values for y considered in the study are from 0 to (4×10^{-3}) m with a step size of 1×10^{-3} m.

For x-position, heat loop in contact with U-bend of the cabinet should be avoided. This is because U-bend of the cabinet is in direct contact with refrigerator interior liner. Also, there is a 2×10^{-3} m fillet distance between the coordinate axes (between the front flange and side face). Hence, x-values should start from $x = 2 \times 10^{-3}$ m. Values till $x = 6 \times 10^{-3}$ m are considered. This is because, beyond 6×10^{-3} m, heat loop comes in the close vicinity of U-bend. Thus, values from $x = (2\text{–}6) \times 10^{-3}$ m with the step of 1×10^{-3} m are considered. In this way, we will have full factorials DoE with two factors (x and y) each having five levels. These decision variables should be reflected in the simulation model as parameters in ANSYS tool [7].

1.4.2 Formulation of the Optimization Problem

Considering the above discussion, the optimization problem is defined by Eqs. 1.2, 1.3a, and b. Equation 1.2 represents the objective function, while Eq. 1.3a and b represent implicit constraint and explicit constraint, respectively.

$$\text{Objective: Minimize } E = f(x, y) \tag{1.2}$$

Subject to:

$$R = g(x, y) \geq 1 \tag{1.3a}$$

$$L_x \leq x \leq U_x$$

$$L_y \leq y \leq U_y \tag{1.3b}$$

In Eq. 1.3b, L_x and U_x are lower and upper bounds for variable x. L_y and U_y are lower and upper bounds for variable y. The functions $f(x, y)$ and $g(x, y)$ for E (energy consumption) and R (robustness to external condensation), respectively, cannot be analytically defined. This is because E and temperature R are outputs of 3D conduction and convection effects which cannot be manually evaluated. Geometry also consists of complex contours. Hence, problem solving using finite element analysis with the help of ANSYS as a tool for analyzing these two functions is considered to be appropriate.

Reason for choosing a full factorial DoE is twofold. The first reason is that since this is a decision-making point in the project, it is best to extract maximum information about levels and all interactions of the factors before taking a final decision about the values of x and y. Partial factor or screening DoEs are conducted during initial stages to eliminate weak or unimportant factors. In other words, when factors are large and the goal is to narrow down to few important factors, the partial factorial DoE is preferred. Here, only two factors are present, and the goal of DoE is not to eliminate the factor but to determine the most favorable levels for factors to satisfy optimization requirement (objective function). Hence, a full factorial approach is selected for DoE. For a full factorial DoE with n levels and k factors, a number of iterations (cases) m can be determined using Eq. 1.4.

$$m = n^k \tag{1.4}$$

Hence, DoE with m cases needs to be performed for optimization work. Consider, $n = 5$ and $k = 2$ for the present study; then, a number of cases m are 25. Parametric modeling in ANSYS modeling interface which is the Design Modeler is used to complete this task. Boolean operations are set parametrically in Design Modeler to achieve different heat loop positions. DoE setup is obtained by setting up all combinations of variables x and y in the ranges specified in the above optimum optimization problem.

1.5 Solution Strategy

Model is solved using the physics of steady-state thermal analysis. Instantaneous heat flow and energy consumption are efficiently predicted by the solver. Governing equation of the analysis is as depicted in Eq. 1.5 below [8].

$$[K(T)]\{T\} = \{Q(T)\} \tag{1.5}$$

In Eq. 1.5, K stands for the thermal conductivity of the materials involved. K can be constant or temperature dependent. Q matrix is for boundary conditions and loads applied in the model. Solver solves for nodal temperatures using Eq. 1.5. This is basically a conduction-based equation based on Fourier's law. Heat flux, fixed temperature imposition, and convection are treated as boundary conditions represented by $\{Q\}$ in the above equation. In the present analysis, convection on external and inside surfaces of the refrigerator is considered. Further, a fixed temperature boundary condition is considered on the heat loop. Convection boundary condition incorporates heat flow dependant on the temperature differential between the surface and ambient temperature with the help of Eq. 1.6 below [8].

$$q = hA(T_{\text{surface}} - T_{\text{ambient}}) \tag{1.6}$$

The solver uses implicit iterative algorithms to solve Eq. 1.5. Loads are applied incrementally through substeps. Each substep is started by randomly assuming temperature at nodes and calculating the internal load based on assumption. Difference between internal and external load is then computed. Based on this result, the next iteration is chosen by the solver so that this difference is reduced sequentially. When this difference falls below convergence criteria (tolerance), load substep is said to be converged and next load substep is taken up for solving [7].

1.6 Results and Discussion

1.6.1 Results and Post-processing

Response surfaces chosen for post-processing are shown in Fig. 1.7. Since the cabinet front flange is prone to condensation, cabinet front flange is chosen as response surface for external condensation. Further, in order to evaluate E (energy consumption), all the inside surfaces of the refrigerator (surfaces of liners and gasket) are chosen as response surfaces, and heat gain for the model is evaluated by running a post-processing script on these response surfaces.

Sample results for one of the heat loop positions are shown in Fig. 1.8. Temperature scale and exact temperature values are not shown for the purpose of confidentiality.

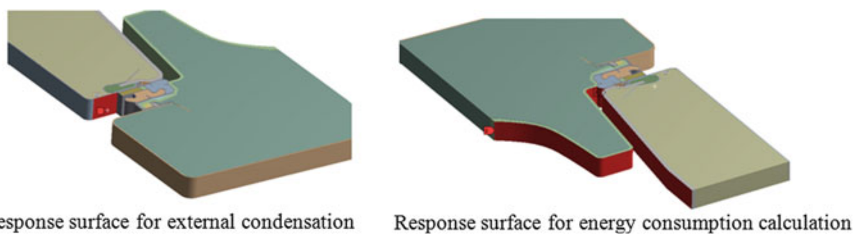
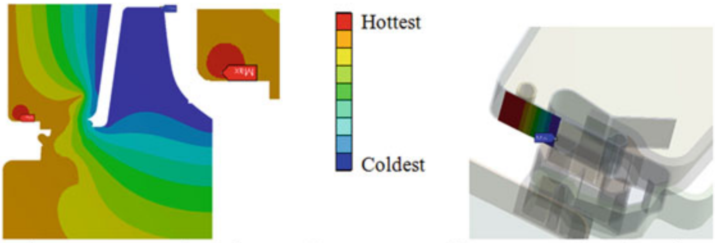


Fig. 1.7 Response surfaces



Overall temperature gradient plot   Temperature gradient on external condensation response surface

Fig. 1.8 Sample output plots

Note that, in the below temperature gradient plots, red color shows hottest zones, while blue color shows coldest zones.

The minimum temperature on external condensation response surfaces is obtained by analyzing temperature gradient plots. This data is converted to *R* (robustness to external condensation) using Table 1.1.

Since our study is based on comparative assessment and selection, we treat *E* value for DoE case 1 as a reference and express *E* values for other cases as ratios with respect to reference *E* value. *E* value for DoE case 1 is then considered as unity to allow comparison with other values. With these considerations, consolidated data is populated in Table 1.3 as shown.

1.6.2 Sensitivity Analysis of Factors

In order to evaluate the sensitivity for each factor on respective outputs, multiple variable regression analysis is conducted. *P* values and coefficients of both factors for each of the two outputs are studied to determine the dominant factor in the analysis. An approximate equation is built between decision variables and output. Equations 1.7 and 1.8 below show the approximate relations obtained between decision variables and outputs. Values of variables x and y should be used in ($\times 10^{-3}$ m) or mm format to use the below equations.

$$R = 1.44 + 0.4x - 1.1y \tag{1.7}$$

$$E = 0.978 + 0.002x - 0.0117y \tag{1.8}$$

As shown above Eqs. 1.7 and 1.8, it is said that both external condensation and energy consumption are strongly dependant on decision variable y. In other words, y is the dominant factor in DoE. This is also reflected in significantly lower *P* values obtained for y as compared to x.

Table 1.3 Post-processed DoE results

Case No.	Heat loop x-coordinate ($\times 10^{-3}$ m)	Heat loop y-coordinate ($\times 10^{-3}$ m)	R	E
1	2	0	3	1 (reference)
2		1	1	0.958
3		2	−1	0.952
4		3	−1	0.949
5		4	−1	0.948
6	3	0	4	1.001
7		1	1	0.957
8		2	−1	0.951
9		3	−1	0.949
10		4	−1	0.947
11	4	0	4	1.008
12		1	1	0.955
13		2	1	0.953
14		3	−1	0.950
15		4	−1	0.948
16	5	0	4	1.006
17		1	1	0.958
18		2	1	0.956
19		3	−1	0.953
20		4	−1	0.951
21	6	0	5	1.011
22		1	2	0.968
23		2	1	0.963
24		3	1	0.957
25		4	1	0.957

1.6.3 Trade-off Plots and Selection of Optimum Position

In order to select the optimum position of heat loop, we need to create trade-off plots between E and R. Using Eqs. 1.2, 1.3a, and b, an optimum x and y position can then be selected. The optimization problem is to minimize E with the implicit constraint of $R \geq 1$. Five trade-off plots are generated keeping x as constant with varying y-coordinates. Consider Fig. 1.9a, the plot for $x = 2 \times 10^{-3}$ m which is L_x. An optimum point is obtained in the plot by selecting the point with minimum energy consumption (E) and robustness to external condensation (R) ≥ 1. This point is highlighted by a green balloon in the plot. A similar exercise is repeated for $x =$

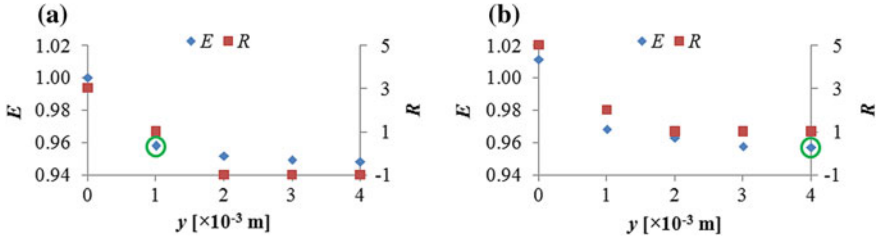
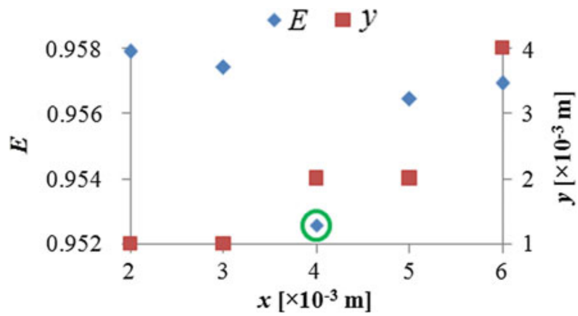


Fig. 1.9 **a** Trade-off plot at $x = 2 \times 10^{-3}$ m, **b** trade-off plot at $x = 6 \times 10^{-3}$ m

Fig. 1.10 Selection of most optimum heat loop position



(3, 4 and 5) $\times 10^{-3}$ m by generating respective trade-off plots. In this way, optimum points at each x-position are obtained. Position (x, y) data for each optimum point is recorded. Figure 1.9b shows the trade-off plot for $x = 6 \times 10^{-3}$ m which is U_x.

Next, five optimum points with varying x are plotted against E to select least energy consumption (E_m) out of the above-mentioned optimum points as shown in Fig. 1.10. This position is highlighted by a green balloon in Fig. 1.10. The heat loop position thus obtained is the final solution of the optimization problem. Thus, the heat loop position is one with least E and also satisfies the constraint of $R \geq 1$. After plotting the data in Figs. 1.9 and 1.10, we note that most optimum heat loop position is at $x = 4 \times 10^{-3}$ m with $y = 2 \times 10^{-3}$ m.

1.7 Conclusion

Heat loop placement provides a unique challenge of satisfying contradictory requirements which are minimizing energy consumption and maximizing the robustness of refrigerator to external condensation. This challenge was solved by building a comprehensive methodology for optimum selection of heat loop. This methodology comprises framing an optimization problem and solving the problem using DoE-based optimization approach. Full factorial DoE was executed using steady-state thermal FEA model built in software ANSYS. An efficient modeling approach for FEA was developed which can be utilized across different types of refrigerators like a single door, top mount, bottom mount, multidoor bottom mount, and side-by-side refrigerators. Appropriate response surfaces were plotted and chosen to compare DoE cases. Sensitivity analysis was conducted to identify a dominant factor which was found to be depth-wise position of heat loop. Due to rigorous analysis, trade-off plots helped to select the most optimum heat loop position. From the trade-off analysis, the optimum position of heat loop for the present study was found to be $x = 4 \times 10^{-3}$ m (lateral position) and $y = 2 \times 10^{-3}$ m (depth-wise position).

This work would be helpful in providing a systematic and efficient methodology for the selection of heat loop position for complex designs of future refrigerators. The proposed methodology can be effectively utilized in the early design phase of a refrigerator to cut down design time and expensive experimental efforts. Physical testing can be completely eliminated in the early design phase and replaced by virtual experiments using simulation. This work also promotes the rigorous use of simulation for design evaluation.

As a future scope, refrigerant fluid flow in heat loop and its effect on energy consumption and external condensation are planned to be studied using computational fluid dynamics. Incorporation of transient effects to study the impact on the energy rating of the refrigerator can also improvise the analysis.

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