Simulation Based Design for Refrigerator Development

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Abstract
The simulation based design (SBD) is one of the new approaches to shorten development periods, reduce cost of development and avoid failures. This approach emphasizes an in-depth analytical understanding of target products or services in the upstream of a design process by using the simulation technology. This short communication presents some cases of simulation in the development of refrigerator as examples of BSD approach.
Keywords Function S-rough sets, Structure of function S-rough sets, Relation theorem, Function transfer Rough law mining

1 Introduction

Manufactures of refrigerators are forced to shorten development periods, reduce cost of development and avoid the failures and incidents. For those purposes, they are now trying to introduce new technologies and processes such as CAD/CAM/CAE, digital engineering, or concurrent engineering instead of traditional ones.

The simulation based design (SBD) is one of the new approaches to meet those purposes. According to Bossak[1], its concept is “simulation of the entire life cycle of the product, from concept development to detailed design, prototyping, testing, manufacturing operations, maintenance and disposal” and it consists of “modeling methods and computational tools, virtual reality environment, an infrastructure for collaborative engineering and integration technologies and tools.” The concept of SBD is almost the same as those of the analysis-leads or analysis led design (ALD, the terminology of ISI and Yamaguchi Univ.) and the Simulation Driven Product Development^{TM} (SDPD, the terminology of Fluent). Either word emphasizes a radical front-loading of design, i.e., an in-depth consideration in the upstream of a design process.

An ordinary design process consists of the requirement definition, conceptual design, project design, and detail design phases. Manufacturing and testing start almost as soon as the detailed design starts. Some researchers argue that a sufficient analytical understanding of a target product/service is required in the upstream of design, i.e., the requirement definition and conceptual design phases and it results in decrease in the cost of development[2]. In the other words, a poor understanding of target products/services will bring some serious problems in the downstream of the design process, cause many trials and errors in the manufacturing and testing process, and significantly increase cost and time to market. Therefore, the necessity for the analytical understanding in the upstream of a problem-solving process has been mentioned since a long time ago[3-4]. Nowadays, a progress of information technology allows manufacturers to use computer simulations as a tool for the analytical understanding of target products/services; hence new approaches of design such as SBD, ALD, and SDPD TM are proposed.

2 Simulation Methods in Refrigerator Development

Concept of SBD has become important among the refrigerator manufacturers, although SBD is not perfectly deployed in the design and manufacturing process. In this industry two types of simulation are mainly used for design process. One is cycle simulation, which is the system simulation of a refrigerating cycle, and the other is computational fluid dynamics (CFD). This short communication treats the latter.

(a) Dynamic and Changing. Process knowledge should be updated along with the emergence of new techniques and new methods.

CFD simulation applied for designing refrigerators are as follows: Cortella et al. applied a FEM (finite element method) code to carry out unsteady 2-dimensional simulation of a refrigerated display cabinet[5]. Chang et al. applied a CFD code with a $k-\varepsilon$ turbulent flow model to refrigerators equipped with freezing cabinets at the top[6]. Afonso and Matos used a commercial CFD code, Fluent TM to study the effect of radiation shields around a condenser and compressor[7]. Gupta et al. used the CFD model to study effects of various operating and design parameters on the refrigerator performance[8]. Haldar et al. applied their developed code to simulate free convection inside a freezer[9].

The author of this short communication has also carried out CFD analyses in the upstream of the refrigerator development. Some CFD analyses carried out by the author are presented in the following sections as examples of BSD.

3 Realization of Thermal Uniformity Inside Refrigerators

Fig.1 shows a household refrigerator with a conventional air-supply system. The fan supplies the air cooled by an evaporator to the fresh food cabinet, the vegetable cabinet and the freezing cabinet. In the fresh food cabinet, the cooled air is supplied from openings in the rear panel. Temperature of the supplied air is set at a sufficiently low temperature to cool the freezing cabinet. Thus the flow rate of the supplied air to the fresh food cabinet is suppressed to prevent freezing and drying foods, and increasing the heat gain from outside the refrigerator. However, the suppression of the flow rate causes rises in temperature in the door pockets and the upper shelf. Besides this problem, the conventional air-supply system can not increase cooling rate because of the suppression of the flow rate.

To meet the requirements for keeping food fresh, a new air-supply system for improving the thermal uniformity and the cooling rate inside the fresh food cabinet was developed by adding a blower and jet slots to a conventional cooled air supply system[10]. In the design process of this new air-supply system, CFD is applied to study air distribution inside refrigerators.

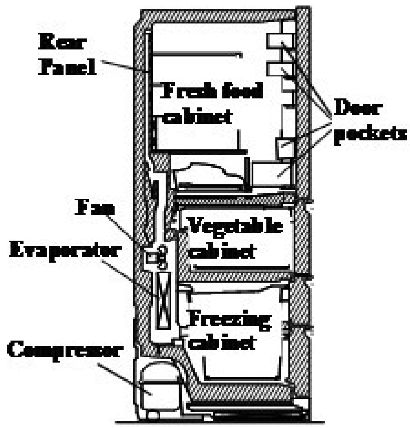


Fig.1 Cross section of the refrigerator

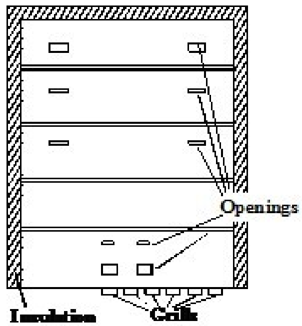
3.1 Design of the Air-supply System

Fig.2 shows the schematics of the fresh food cabinets with a conventional air supply-system and our developed system. The volume of each cabinet is 0.24 m^3. Each air-supply system has ten openings and six grills. The openings supply cooled air at 0.17 m^3 min^{-1} and -10°C to keep the cabinet temperature below 5°C, and the grills returns the air to an evaporator. The flow rate of the supplied air to the cabinet is suppressed to prevent freezing and drying foods, and increasing the heat gain. A thermal sensor is set on the rear panel of each cabinet. When the sensor detects that the surrounding temperature is lower than the preset one, air-supply is stopped.

System A is the conventional air-supply system. The temperatures in the door pockets and the upper shelf will rise, because of the distances between those places and the supply openings.

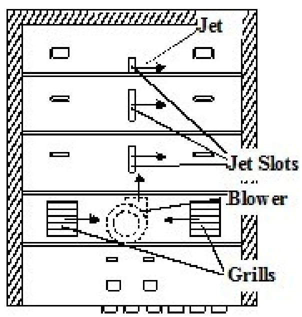
System B is the new air-supply system. One blower, three jet slots and two return grills are added to system A to improve the thermal uniformity and the cooling rate. The flow rate of the air jetted by the additional blower is 0.3 m^3 min^{-1}. The total opening area of the jet slots is one sixth of that of the supply openings. The velocity of the jets is thus ten times higher than that of the cooled air. The jet stirs the air inside the cabinet and improves thermal uniformity. The jet also improves the heat transfer on the surface of foods and cools it rapidly.

The blower collects the air inside the cabinet through the grills and jets air from the slots. The air does not pass through the evaporator. The air is thus at about the same temperature as the average temperature inside a cabinet and does not freeze foods.



(a)

(a)System A



(b)

(b)System B

Fig.2 Layouts of air supply systems

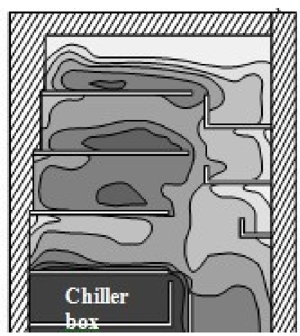
It takes much time to repeat the measurements for studying the air distribution inside the cabinet with the new system. In order to cut down the development period, we applied CFD simulations to the study on the air distribution inside the cabinet.

3.2 Simulation Results

Fig.3 shows the simulated thermal distribution for each air-supply system. Regarding system A, there are high temperature regions above the top shelf and the top door pocket, and there is also a low temperature region in the center of each shelf.

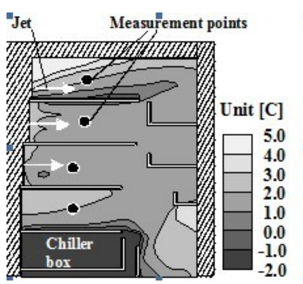
In system B, the air is kept at about 2°C in most of the area, because the jetted air sufficiently stirs the air inside the cabinet. The heat gains of system B increases by 5% compared to system A because of the decrease in temperature of the regions that are not sufficiently cooled by system A. However, the standard deviation of the temperature for the fresh-food cabinet with system B is about half of that of system A.

Simulation results are validated by comparing with the measurement after the



(a)

(a)System A



(b)

(b)System B

Fig.3 Thermal distributions in the central cross section

simulation. The difference between the temperatures at the points indicated by circles in Fig. 3 is 0.5°C in the simulation and it is 0.3°C in the measurement.

It is concluded from these simulation results that system B improves thermal uniformity. After these simulations, the project design and detail design were carried out and the refrigerators with this new air-supply system were released to the market.

4 Thermal-bridge Problem

In order to decrease heat exchange between the inside and outside of refrigerators, insulating walls are applied. However, supporting elements of the insulating walls (frames and reinforcements) often act as thermal bridges and increase heat gain or loss. Boughton et al. have shown that heat loss through thermal bridges accounted for about 30% of a refrigerators overall heat loss[11].

Applying CFD and a heat-flow visualization technique to the upstream stage of the refrigerator design will help to know and solve the thermal-bridge problems. Below is an example of the thermal-bridge problems[12].

4.1 Thermal-bridge Problem Around Gaskets

Fig.5 shows a cross section of the region where the insulating wall and door of a refrigerator contact through a gasket. The wall and door consist of polyurethane foam insulators and reinforcements. The foam of the insulators is filled with isobutane. The wall and door are 100.0-mm-thick, and are separated by a 4.0-mm-wide gasket. The left side of the insulation is the inside of the refrigerator and the right side is the outside. The inside and outside air are at temperatures of 273 and 303K respectively. The heat transfer coefficients on both surfaces are set to 10.0 W m^{-2} K. The upper side of the wall and lower side of the door are set to be adiabatic boundaries.

Two cases of steady-state simulations were carried out. The region shown in Fig.4 is divided into ten thousand of 1.0 mm^2 control volumes. The inner reinforcements were made of steel sheets in case (a) and of ABS resin in case (b). The thermal properties of the material used in this region are listed in Table 1.

4.2 Simulation Results

Fig.5 (a) and (b) shows the distributions of heat-flow intensity in cases (a) and (b) respectively. The respective heat flow intensities are 1.8 MW m^{-3} and 64 kW m^{-3} at the marked points in Fig.5 (a) and (b); this indicates that the steel inner reinforcements conduct heat about 28 times as large as ABS reinforcements.

5 Radical Change in the Layout of Cabinets

The design for environment (DfE), i.e., environmentally conscious design is an important issue for manufacturers. They pay attention to the energy efficiency of their products to decrease CO2 emission resulting from their energy consumption. In the field of the household refrigerators, manufacturers develop high performance insulation walls, compressors, heat exchangers, and control devices to improve the energy efficiency of their products. Moreover, they try to change

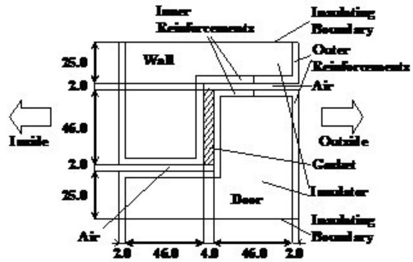


Fig.4 Cross-sectional view of the region where an insulating wall is connected with an insulating door. Unit: mm

the refrigerants to natural ones to keep the ozone layer.

However, the improvement of energy efficiency will reach the limit if the shapes of the refrigerators are fixed. Manufacturers should try to change the shape of the refrigerators to improve the energy efficiency.

The current mainstream refrigerators shown in Fig.1 are called “bottom freezer type” because of the location of the freezing cabinet. The layout of each cabinet is decided based on the usability or ergonomics. This layout has not changed for many years. However, there are two following problems in this type of refrigerator from the view point of thermal engineering.

- Nearness of the compressor and freezing cabinet causes temperature rise in the freezing cabinet because of heat gain from the compressor.
- Placing the compressor in the limited space decreases the heat transfer from the compressor.

These problems decrease refrigerators’ energy efficiency. One of the solutions of these problems is change in the shape of the refrigerators. The effects of change in the layout of cabinets were studied by CFD[13].

Table 1 Conditions of the heat gain calculation

	Conductivity [W m^1 K]	Density [kg m^{-3}]	Specific heat [J kg^{-1} K^{-1}]
Air	0.026	1.205	1006
Gasket	0.16	1230	1.42
	Inner reinforcements		
(steel)	43	7880	473
(ABS resin)	0.22	1040	1000
Insulator	0.03	100	836
Outer reinforcement (steel)	43	7800	473

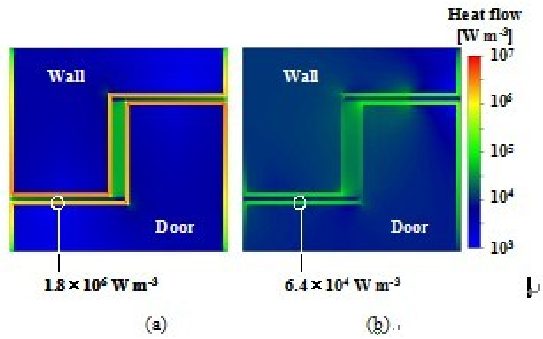


Fig.5 Distributions of heat-flow intensities for the region shown in Fig.4

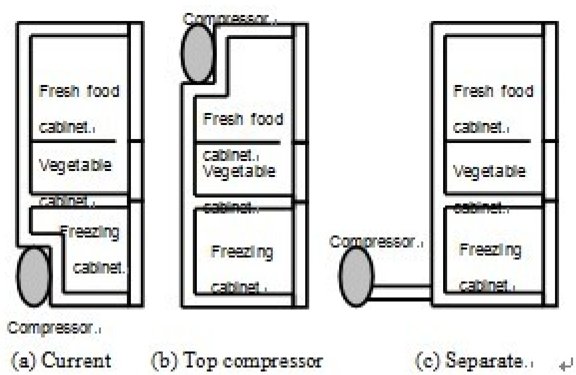


Fig.6 Layouts of cabinets and compressors

5.1 Alternative Layouts of Cabinets

Some alternative shapes of refrigerators have been already proposed as shown in Fig.6. The "top compressor type" refrigerators are the ones that have the compressor at the top. They increase the heat transfer from the compressor. The "separate type" refrigerators are the ones that the compressors are separated from the refrigerators' cabinets. This type of refrigerator not only increases the heat transfer from the compressor but also prevent the freezing cabinet from gaining the compressor's heat.

The heat gains of the cabinets of the ordinary and alternative types from the ambient air were calculated by CFD on the conditions listed in Table 2.

5.2 Simulation Results

The result is shown in Fig.7. The heat gains of the alternative types are smaller than that of the current one. This tells that the energy efficiency of the alternative types will be improved.

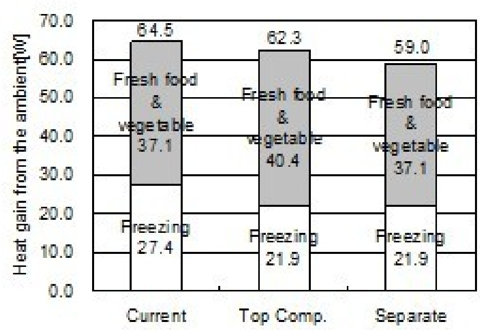


Fig.7 Heat gain of cabinets from the ambient air

Table 2 Thermal property of materials

	Fresh food & vegetable cabinets	Freezing cabinet
Size		
Width [m]	0.65	0.65
Depth [m]	0.65	0.65
Height [m]	1.35	0.45
Insulation Wall		
Thickness [m]	0.04	0.06
Thickness [m]	0.04	0.06
Conductivity[W m^1 K^{-1}]	0.02	0.02
Heat transfer		
Inside[W m^{-2} K^{-1}]	10.0	10.0
Outside[W m^{-2} K^{-1}]	5.0	
Temperature		
Cabinet [°C]	5.0	-18.0
Ambient [°C]	30.0	
Compressor [°C]	50.0	

However, there are some problems in the serviceability or usability dimension. The top compressor type doesn't allow users to put something on the ceiling and the location of the compressor makes it difficult to maintain the compressor. Moreover, the separate type needs an excess area and time to set it up. This indicates that it is not only the engineering performance that decides the value of a product/service. A design of a product/service should be carried out in view of performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality [14]. This is why an in-depth consideration by using simulation is required in the upstream of a design process.

6 Conclusion

Three examples of SBD in the refrigerator development are presented in this short communication. AS shown in each example, by using CFD simulations, we can study the performance of target products analytically in the upstream of the design process, avoid to repeat the measurements and test in the downstream, and cut down the development period and cost.

Acknowledgements

The research is supported by National Natural Science Foundation of China(No. 11171065).

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