A New Control System of a Household Refrigerator-Freezer

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ABSTRACT

This paper will present the structure of the new system, the control scheme and its performance test results. In this new system, the damper in the conventional refrigerator is replaced by an additional cooling fan. Thus, it uses two cooling fans: one (F-fan) is to provide cooled air for freezing compartment (F-compartment) and the other (R-fan) is for refrigerating compartment (R-compartment), respectively. The F-fan and the R-fan are controlled independently by thermo-sensors installed in the F and R-compartments.

Experimental results show improved performance of the new refrigerator over the conventional refrigerator. Among them is the lower fluctuation of the R-compartment temperature, which has a significant effect in lowering the refrigerating temperature and storing foods fresh longer. It can quickly response to the load change in the R-compartment. The air-defrosting by the use of the R-fan was proved to be an efficient method in saving the energy consumption during the defrosting cycle.

INTRODUCTION

Household refrigerator-freezer systems can be classified as direct and indirect cooling systems. The direct cooling system utilizes natural convection to cool food storage volume. It has inherent advantages of high energy efficiency and simple structure. This cooling type is used in small size refrigerator and still widely used in European market for bigger size. As the refrigerator becomes bigger, the direct cooling system encounters with a problem in controlling temperatures in the F and R-compartments as mentioned by Onishi.

By that reason, large size refrigerators over 200 liters usually adopt the indirect cooling system. The indirect cooling system has a cooling fan to circulate cold air through an evaporator and refrigerator-freezer compartments. In this cooling system, the cooling fan and the compressor are typically controlled by a temperature controller installed in the F-compartment. A damper controls R-compartment temperature by regulating cold air flow rate.

A limitation in this type refrigerator comes from the fact that the temperature of the R-compartment depends entirely on the F-compartment temperature. If the R-compartment is excessively loaded, the temperature in the R-compartment rises too high while the temperature in the F-compartment is still below its preset temperature. However, the compressor would not restart because the control operation is based on the F-compartment temperature. As a result, the R-compartment often fails to maintain its temperature range. Hence, the F-compartment based control has to sacrifice the refrigerating performance to some extent, while it gives good performance in frozen food storage. Some refrigerators are designed to be controlled by the R-compartment temperature in order to improve refrigerating performance, but at the sacrifice of the freezing performance.

The new control system development was intended to achieve more improved refrigerating performance without any degradation of the freezing performance. This purpose was obtained by the use of two independently operating cooling fans.

DESIGN OF NEW REFRIGERATOR WITH TWO COOLING FANS

The conventional indirection cooling system refrigerator has a cooling fan that blows cold air into food storing compartments; usually F and R-compartments. The fan is always running during the compressor is active. As shown in Fig. 1, the cold air is distributed into F and R-compartments. The system control is based on the F-compartment temperature. A thermo-sensor installed in the F-compartment switches the compressor and the cooling fan ON and OFF based on the F-compartment temperature. Cold air flow rate into the compartment is regulated by a thermo-damper, which has its own temperature detecting device.

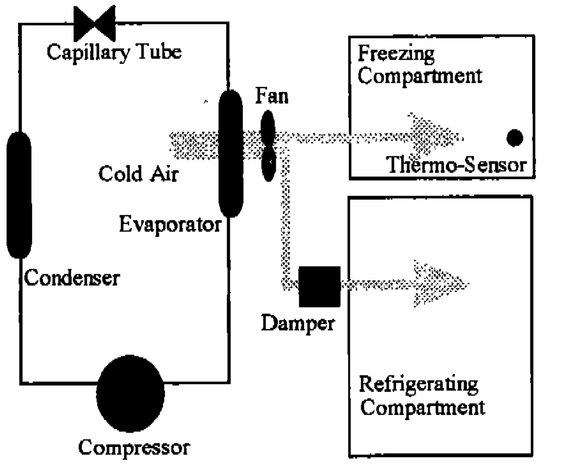

Fig. 1 Schmatic of the conventional refrigerator with one cooling fan

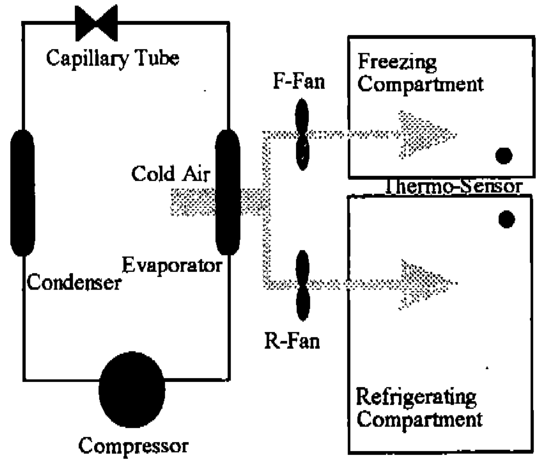

Fig. 2 Schamatic of the new refrigerator with two cooling fans

The damper, located at the end of the duct, is fully opened initially at the start of the compressor and the cooling fan. As the R-compartment temperature decreases, the damper becomes closed and reduces flow rate into the R-compartment. When a preset temperature of the R-compartment is reached, the damper closes completely. As the F-compartment temperature falls below a preset temperature, the compressor and the cooling fan stop. The temperatures in the F and R-compartments increase due to the heat leakage through the insulation wall. Thus the control of the R-compartments is inevitably depends upon the F-compartment condition in the conventional refrigerator.

Fig. 2 shows the schematic diagram of the new refrigerator. Instead of having a damper regulating cold air flow rate into the R-compartment, the new system adopts an additional cooling fan. These two cooling fans operate independently each other. One cooling fan (F-fan) feeds cold air into the F-compartments and the other fan (R-fan) provides cold air into the R-compartment respectively. The flow passage is also separated so that the air blown by the F-fan and R-fan can not be mixed.

The compressor and the F-fan operation depend on the F-compartment temperature as they do in the conventional refrigerator. However, the control method of the temperature in the R-compartment makes a significant difference between them. While the conventional refrigerator relies on the F-compartment temperature for the temperature control, the new refrigerator uses thermo-sensors installed in both of the F and R-compartments.

The thermo-sensor installed in the R-compartment detects the temperature variation in this compartment and gives control signal to the R-fan. As the R-compartment temperature rises, the R-fan starts to blow cold air into the R-compartment. This R-fan operates independently regardless of the compressor ON/OFF status. The evaporator temperature remains still around -15 °C even when the compressor is not running. Usually the R-compartment is need to be at 3 °C that is considerably high compared with the evaporator temperature during the compressor stopping period. Thus circulating the air in the R-compartment through the evaporator can provide air which is cold enough to compensate the heat leakage.

Advantages of the two fan cooling system can be estimated as follows;

1) Small temperature fluctuation in the R-compartment
2) Ability of quick response to the load change in the R-compartment
3) Energy saving effect by the use of air-defrosting

These characteristics will be discussed in the following sections with experimental results.

CONTROL CHARACTERISTICS

Experiments have been performed to investigate the performance of the new refrigerator in comparison with the conventional refrigerator. Both of these refrigerators are 500 liter capacity size. Two refrigerators were installed in a test room; base area of 3000 mm × 4200 mm and height of 2200 mm. The test room was conditioned at a room temperature of 30 °C and a relative humidity of 60 % during the experiments. Thermocouples used in the temperature measurements are T type with a diameter of 0.3 mm. Temperature measurement data were acquired at every 30 second by a data acquisition unit, which is composed of a remote scanner and a data recorder (Yokogawa HR-2500E). A workstation (Sun, SPARC Station LX) read and stored the data from the data acquisition unit through a GPIB communication port.

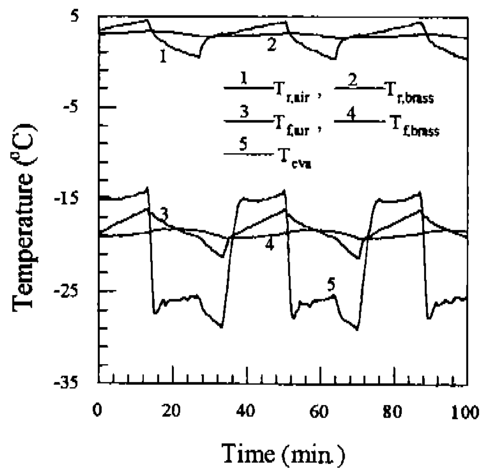

Fig. 3 Control characteristics of the conventional refrigerator

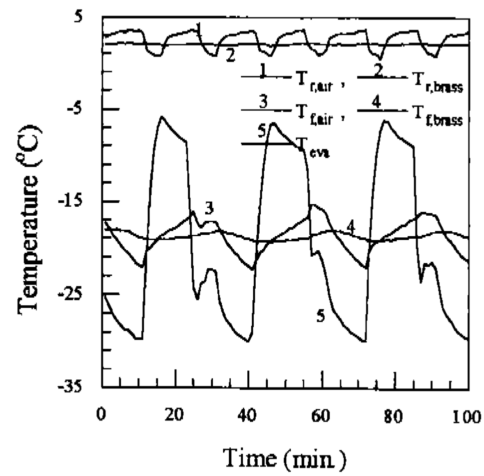

Fig. 4 Control characteristics of the new refrigerator

Control characteristics

The control characteristics of the conventional and the new system refrigerators are shown in Fig. 3 and Fig. 4. The temperature variations during the control operation were measured at five measuring positions. For the F and R-compartment temperatures, air ($T_{f,air}$, $T_{r,air}$) and brass cylinder($T_{f,brass}$, $T_{r,brass}$) temperatures were measured at position halfway between the rear internal wall and the internal wall of the closed door, and one third of the compartment height from the bottom of the compartments. The brass cylinder has thermal capacity equivalent to 20 g of water, and the size is 26 mm in diameter and 48 mm in height. An evaporator surface temperature (T_{eva}) was also measured at the entrance of refrigerant flow.

As can be seen in Fig. 3, the air temperatures in the refrigerating ($T_{r,air}$) and freezing ($T_{r,air}$) compartments, start to decrease as the compressor starts. In this conventional refrigerator, the cooling of the R-compartment can be achieved only during the ON time of the compressor, which is activated by the F-compartment temperature. The temperatures of the brass cylinders show smaller variation and time delays behind the air temperatures because of their thermal capacities. During the test, $T_{f,brass}$ was set to be -18 °C for both of the conventional and new refrigerators. $T_{r,brass}$ was set to be 3 °C for the conventional refrigerator and 2 °C for the new refrigerator, respectively. The evaporator temperature shows large fluctuation as the compressor starts and stops. It rises up to -15 °C when the compressor is OFF and reaches -28 °C when the compressor is ON.

Compared with the conventional refrigerator, the control characteristics of the new refrigerator look more complicate as can be seen in Fig. 4. That is because of the independent R-fan operation. The R-fan starts and stops to keep the R-compartment temperature, $T_{r,brass}$, to a preset level regardless of the compressor running status. The result shows that evaporator temperature, T_{eva} ,is greatly influenced by the R-fan operation. When the R-fan is running, the evaporator temperature rises due to heat exchange with the relatively warm air from the R-compartment, and the $T_{r,air}$ decreases. At this time, $T_{f,air}$ rises because of the increased evaporator temperature. The evaporator temperature of the new refrigerator in Fig. 4 shows higher temperature than that of the conventional refrigerator shown in Fig. 3 when the compressor is OFF.

This results from the heat transferred to the warm air from the R-compartment blown by the R-fan.

Small temperature fluctuation

The function of the R-compartment is to keep food fresh as long as possible. In this point of view, the lower the food storing temperature becomes, the longer the freshness lasts. While pure water will freeze at 0 °C, most food starts to freeze at -1 ~ -2 °C. That is a limitation of lowering the refrigerating temperature. Thus, the R-compartment temperature should be kept above zero during control operation in order to prevent the food from being frozen. In addition to the storing temperature, temperature fluctuation should be minimized to reduce thermal shock to the food.

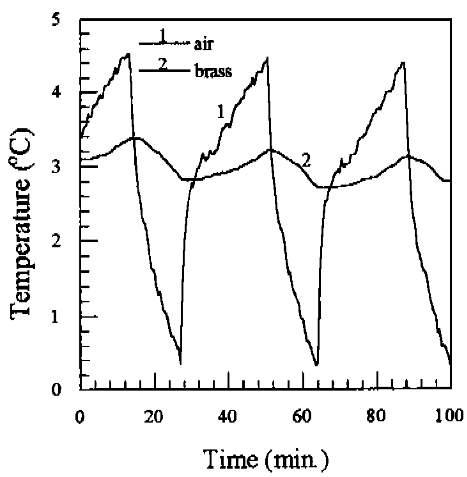

Fig. 5 Refrigerating compartment temperature, Conventional refrigerator

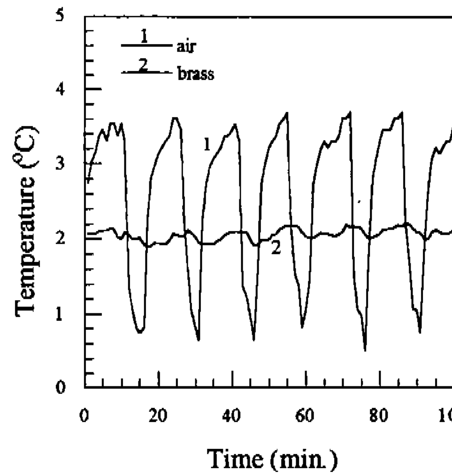

Fig. 6 Refrigerating compartment temperature, New refrigerator

Figures 5 and 6 show the refrigerating temperatures during control operation of the refrigerators. These are just magnified views of $T_{r,air}$ and $T_{r,brass}$ in the Fig. 3 and Fig. 4. In the new refrigerator, the frequent chopping of the cold air supply by the use of the R-fan reduces the temperature fluctuations in the R-compartment. Compared with the conventional refrigerator shown in Fig. 5, the new refrigerator shows much smaller fluctuations in both of the $T_{r,air}$ and $T_{r,brass}$ in the R-compartment. In the conventional refrigerator, the big temperature fluctuation during the control operation restricts lowering the R-compartment temperature, $T_{r,brass}$, which is set to 3 °C. In the new refrigerator, we can set the compartment temperature at 2 °C which is lower than in the conventional refrigerator. Thus it can store food cooler and keep the freshness longer with the new refrigerator.

Quick refrigeration

There is a quick refrigeration mode in the new refrigerator, which is possible with the help of the independent R-fan operation. In the quick refrigeration mode, the compressor and the R-fan are running regardless of the F-compartment condition. An experiment on the refrigerating speed has been performed. During the control operation, 100 g of water at 25 °C contained in a beaker was put into the R-compartment to test the cooling speed. For the new refrigerator, quick refrigeration mode was activated just after the water was placed in the R-compartment. However the conventional refrigerator does not have the quick refrigeration function because its control depends on F-compartment temperature. Five minutes after the compressor resumes, the water was placed in the R-compartment in case of the conventional refrigerator.

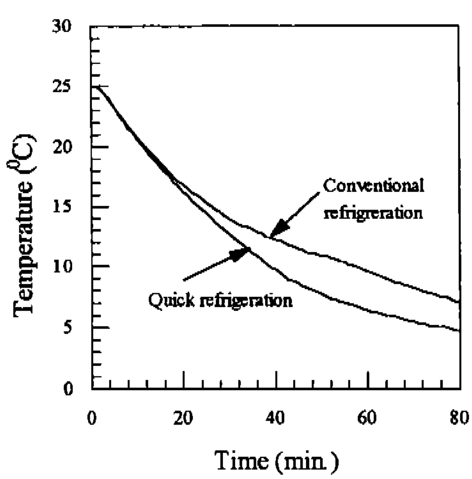

Fig. 7 Comparison of the refrigerating speed of 100 g water in the R-compartment

The result can be seen in Fig. 7 as the temperature change of the cooling water. It shows the water in the new refrigerator cools faster than in the conventional one. To cool the water from 25 °C to 10 °C, it takes 58 minutes in the conventional refrigerator, but only 37 minutes in the new refrigerator.

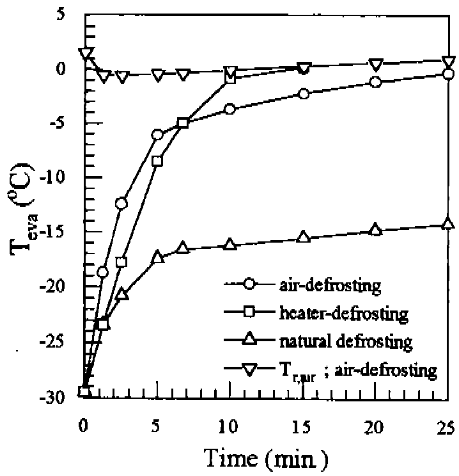

Fig. 8 Evaporator surface temperature during the defrosting cycle and air temperature in the R-compartment

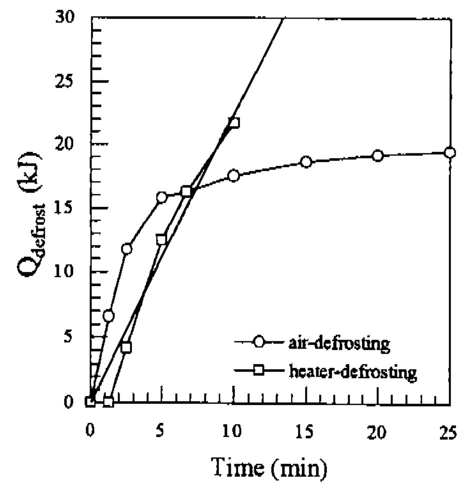

Fig. 9 Heat exchanged during the defrosting cycle ; air-defrosting and heater-defrosting

DEFROSTING BY WARM AIR CIRCULATION

In indirect cooling refrigerator, moisture contained in the air tends to condense and accumulate on the evaporator surface. The frost accumulation increases resistance to heat transfer and reduces air flow rate by blocking air passages. Thus we need to remove the frost periodically. Usually the frost is removed by applying heat by means of glass enclosed heater or cal-rod, which is a metal jacketed electric resistance. The portion of defrosting in energy consumption takes about 6 ~ 7 % of the total energy consumed in a household refrigerator-freezer. Considering the refrigerating energy to compensate the temperature increase during the defrosting cycle, this portion should be doubled approximately.

An efficient method of defrosting, air-defrosting, can be introduced by using the R-fan, in which the relatively warm air in the R-compartment is circulated to warm up the frost on the evaporator during the defrosting cycle. The compressor and F-fan are OFF during the defrosting cycle. The heat exchange rate depends on the temperature difference between the warm air and the evaporator temperature. Thus, air-defrosting must be a powerful method at the initial stage of the defrosting cycle, in which the temperature difference is large. Though air-defrosting is not enough to melt the frost completely, combined use of it with the defrost heater showed significant energy saving effect.

Experiments

The effect of air-defrosting was investigated with an experiment using the new refrigerator. The defrosting experiments have been performed with three methods including heater-defrosting, air-defrosting and natural defrosting. The capacity of the heater enclosed by a glass tube is 195 watt. The air flow by the R-fan is 14 m^3/hr. Evaporator surface temperatures were measured during the defrosting cycle at five locations; top-right, top-left, bottom-right, bottom-left and center. Before the start of defrosting, the refrigerator had been in steady control operation. Frosting was induced in the same experimental conditions for all cases, to ensure constancy of the frost deposited. An accumulation of 255 g frost was generated.

The measured evaporator temperatures for each defrosting method were shown in Fig. 8. Since the evaporator temperature shows slight variation depending on the measurement positions, average value of the temperatures at the five positions is plotted in the Fig. 8. In the air-defrosting, the evaporator temperature shows rapid increase at the initial stage of the defrosting. Then, the increasing rate slows down as it approaches the air temperature of the R-compartment.

When the compressor stops, hot refrigerant from the condenser leaks through the capillary tube. This hot gas leakage suddenly warms up the evaporator even though no external heat is applied (natural defrosting). In the evaluation of the heat applied in defrosting (air-defrosting, heater-defrosting), the heating by the hot refrigerant should be subtracted. The net amount of heat used in defrosting is obtained by measuring the temperature of the evaporator.

$$Q_{defrost} = C_{eva}(\Delta T_{defrost} - \Delta T_{natural})$$

It is assumed that the frost temperature is equal to the evaporator temperature. The frost evaporated directly to the air is neglected so that all the heat transferred to the frost is used to warm up the evaporator and the frost. The net heat during defrosting process is obtained applying the above equation, where C_{eva} is the thermal capacity of the evaporator including the frost accumulated on it.

Results

The results are shown in Fig. 9 for the heater-defrosting and air-defrosting. Air-defrosting shows higher defrosting rate than heater-defrosting at the beginning of defrosting. It is attributed to the low evaporator temperature causing high convective heat transfer from the air to the evaporator. As the defrosting proceeds, the evaporator temperature rises quickly so that the air-defrosting becomes less efficient compared with the heater-defrosting which has almost constant defrosting rate.

One critical factor to be considered in the defrosting cycle of the household refrigerator-freezer is the F-compartment temperature. If the defrosting takes too long, F-compartment fails to keep food frozen because of the temperature rise resulted from the heat leakage through the insulating wall. That restricts the use of the air-defrosting only. In order to solve this problem, it was tried to use the air-defrosting followed by the heater-defrosting. That is to run the R-fan for the first 10 minutes of the defrosting cycle; after that the defrost heater is powered until the defrosting cycle finishes. From the experimental data in Fig. 9, 10 minutes of air-defrosting has the same effect as 7.5 minutes of heater-defrosting in the refrigerator used in this experiment.

Usually one defrosting cycle for the test refrigerator takes about 25 minutes with the heater-defrosting. Hence about 25 % of the energy required for a defrosting cycle will be saved even if considering the power consumed by the R-fan. Moreover, it shows an additional effect of cooling the R-compartment during defrosting cycle as shown in Fig. 8.

CONCLUSIONS

The performance of the newly developed household refrigerator-freezer was presented. The new refrigerator adopts two cooling fans for the control of the freezing and R-compartment independently. Experimental work shows the new refrigerator demonstrates its advantages as follows;

1. Smaller temperature fluctuation and lower average temperature in the R-compartment which have significant effect in improving food freshness
2. Faster refrigerating speed and quick response to the load change in the R-compartment
3. Energy saving by the use of the air-defrosting and maintaining the R-compartment cool during the defrosting cycle.

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