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Thermal Performance of a Compact Evaporator Coil in Household Refrigerator-Freezers

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A high-efficiency evaporator coil, which is placed horizontally between refrigerator and freezer compartments, for household auto-defrost refrigerator-freezers has been developed. Several experiments were performed to investigate the thermal performance of the newly developed compact evaporator coil in a 248*l* auto-defrost refrigerator-freezer and the results are compared with those of the conventional evaporator. The energy efficiency of the system with newly designed evaporator can be improved by 7%, and the size and material of the evaporator can be reduced by 7% and 40%, respectively, compared with the conventional one.

Key Words: Auto-Defrost Refrigerator-Freezer, Evaporator, Condenser, Compressor, Cooling Speed, Freezer Compartment, Refrigerator (Fresh-food) Compartment

1. Introduction

Refrigerator-freezer is a major household appliance designed for preserving foods through refrigerating and freezing. The mechanical system used for the objective is a vapor compression refrigeration system, which usually consists of compressor, condenser, evaporator and expansion device. With the increasing market demand for energy saving of the household appliances, research and development of an energy-efficient refrigeration system has attracted many investigators (Turiel and Levine, 1989; Nowotny, 1991; Turiel et al., 1991 and Granryd, 1992). To achieve a substantial improvement in the overall thermal efficiency of the system, the performance of the components constituting the refrigeration system should all be improved simultaneously; reduction of thermal resistances of both evaporator and condenser is necessary in addition to higher compressor efficiency, improved characteristic of the expansion device, and better insulation of the enclosure.

As a first step toward the eventual goal, the present study is focused on the evaporator for the refrigeration system. Since the heat transfer surface of the refrigerator evaporator is subjected to frosting of moisture contained in air, melting of the frost through heating, and being wetted with water, the selection of surface geometries requires consideration of other problems beyond the performance of dry surface. Further, a household refrigerator-freezer is periodically on-off controlled and the heat capacity of the evaporator besides the thermal resistance influences the performance of the system. Aoki and Hattori (1988) investigated on the heat exchanger performance with frosting based on a uniform frosting model. Rite and Crawford (1991a) evaluated the effect of frost on the air-side heat transfer coefficient and pressure drop of a domestic refrigerator-freezer evaporator coil with interference fit fins, while a constant airflow was maintained. They (1991b) also performed a series of experiments to investigate the effect of various parameters on the rate of frost formation on an evaporator coil. Ding and Chen (1992) studied the influences of the weight of evaporator on the thermal characteristic of a household refrigerator-freezer. They showed that large evaporator resulted in slow temperature change during pull down operation and decreasing energy consumption because the on-off cycle

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became larger and the intermittent energy losses decreased. James and Evans (1992) investigated the temperature performance of domestic refrigerator-freezers and Jakobsen (1995) developed simulation models of the dynamic behavior of the refrigerator and validated against measurements on a 325 *l* refrigerator. Lee et al. (1997) developed numerical model for analyzing frost formation phenomena on a cold flat plate and compared the results with experiments.

This paper investigates the thermal performance of an auto-defrost refrigerator-freezer with newly designed compact evaporator. New-augmented fin surface has been developed and a series of tests is performed to compare the thermal performance with the conventional system.

2. Experiments

2.1 Experimental apparatus

The schematic diagram of experimental system is shown in Fig. 1. The system is an auto-defrost refrigerator-freezer composed of a compressor, a condenser, an evaporator and a capillary tube. The evaporator is situated horizontally between the refrigerator and freezer compartments. The system uses a liquid-suction heat exchanger (lshx) by soldering the capillary tube to the suction line for some length, which subcools the refrigerants in the capillary tube by the suction vapor coming from the evaporator. The volume of refrigerator-freezer is 248 *l* (refrigerator and freezer volumes

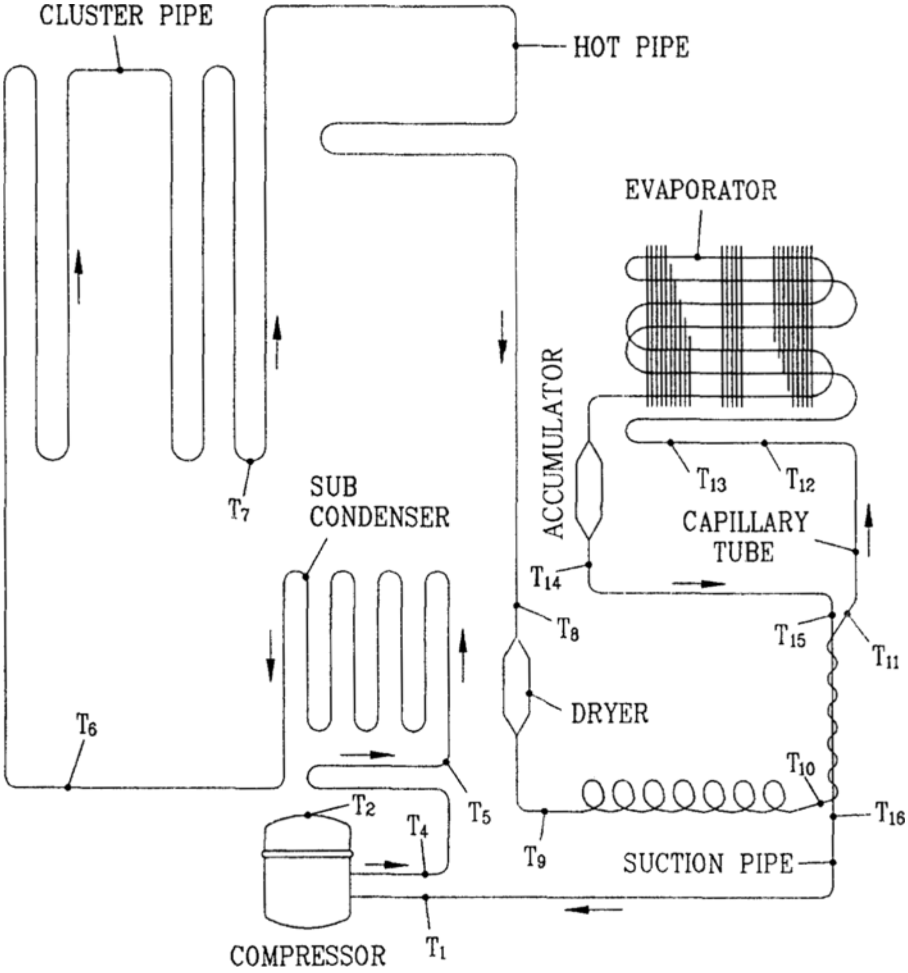
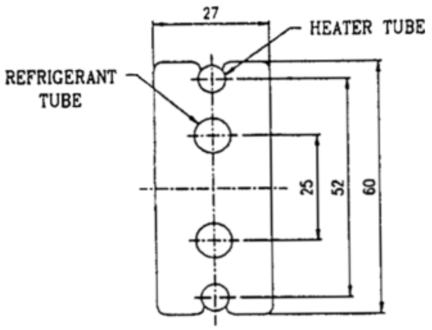
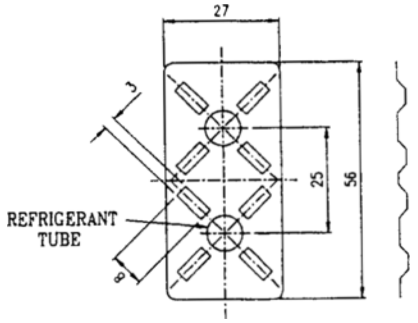


Fig. 1 Schematic diagram of experimental system.

of 187 and 61*l*, respectively) and the system is classified by "four-star"; temperatures in the refrigerator and freezer compartments are not higher than 3 and -18°C, respectively, for standard cycle(N-N operation mode). The refrigerant is R-12 and the amount of charge is 155g. Hybrid recorder and digital power meter are attached to the system in order to measure the temperatures and power consumption, respectively. Constant temperature and humidity chamber is also provided to maintain uniform ambient conditions.



(a) Conventional type(EP-1)



(b) Newly designed type(EP-2)

Fig. 2 Schematics of evaporator fins.

Figure 2 shows the schematic of the conventional and newly designed compact fins for evaporator. As shown in the figure, the conventional evaporator has the heater tube embedded at the top and bottom portion of the fin. A heater cord is also provided under the bottom surface of the evaporator to prevent defrosted water from refreezing. These result in an increase of the volume, complicated manufacturing process and thermal degradation of the evaporator. Newly designed evaporator coil removes a sheathed heater from the evaporator. Instead it has a heating plate consisting of a cord heater at the bottom surface of the evaporator and has new-augmented heat transfer surface. The detailed specifications for conventional evaporator(EP-1) and newly designed evaporator (EP-2) are presented in Table 1. Evaporator size and weight for EP-2 are 420×56×210 mm(93% of EP-1) and 580g(59% of EP-1), respectively. The air-side heat transfer area for EP-2 is 0.96 m^2 which is 14% smaller than that of EP-1.However, the air inlet frontal area per unit width for EP-2 is 38.4 mm, which is 7% greater than EP-1, so that air-side friction loss through the evaporator coil with frost accumulation can be decreased.

2.2 Experimental procedure

Thermal performance tests for a 248 *l* auto

Table 1 Specifications for conventional evaporator(EP-1) and newly designed evaporator(EP-2).

Items		EP-1	EP-2	EP-2/EP-1
Evaporator	Size(W×H×D, mm)	420×60×210	420×56×210	93(%)
	Weight(g)	981	580	59(%)
	Air-side heat transfer area(m^2)	1.11	0.96	86(%)
	Air-inlet frontal area per unit width(mm)	36.05	38.4	107(%)
Fin	Surface geometry	Plane	Augmented	-
	Size(W×H×t, mm)	27×60×0.2	27×56×0.1	46(%)
	Fin material	Aluminum	Aluminum	-
Refrigerant tube	Outer diameter(mm)	8.8	8.8	-
Heater tube	Outer diameter(mm)	6.35	-	-

Table 2 Locations of measurement points used in the test unit

Channel	Location
T1	Compressor inlet
T2	Compressor dome surface
T3	Ambient temperature
T4	Compressor outlet
T5	Subcondenser inlet
T6	Cluster pipe inlet
T7	Hot pipe inlet
T8	Hot pipe outlet
T9	Capillary tube inlet
T10	Capillary tube(inlet of lshx)
T11	Capillary tube(outlet of lshx)
T12	Capillary tube outlet
T13	Evaporator inlet
T14	Evaporator outlet
T15	Suction pipe(inlet of lshx)
T16	Suction pipe(outlet of lshx)
T17	Refrigerator compartment
T18	Freezer compartment

defrost refrigerator-freezer with the existing evaporator(EP-1) and the new-compact evaporator (EP-2) have been conducted under various test conditions. Eighteen T-type thermocouples are mounted on the surface of the key-points of the tested refrigerator-freezer. The locations of measurement points are listed in Table 2.

2.2.1 No load pull down test

The test is carried out at ambient temperature of 30±1℃ and relative humidity of 75±5%. The temperature controller of the freezer compartment is taken apart and the defrost timer is also separated from the defrost circuit. The cooling speed is measured by the time it takes until the average temperature of refrigerator compartment reaches 5℃ and of freezer compartment -15℃ with no load in a refrigerator-freezer with all the doors closed.

2.2.2 On-off cycle test

Ambient temperature and relative humidity for this test are maintained at 30±1℃ and 75±5%, respectively. Defrost timer is placed at normal position where the manufacturer specifies for normal use and the temperature controller is adjusted to one of the three(W-W, N-N and C-C) modes which make the average temperature for the refrigerator compartment 6±2℃, 3±2℃, and -2±2℃, respectively. With no load inside the refrigerator-freezer and all the doors closed, the operation rate(% on time) which is the percentage of compressor run-time is measured after reaching the normal mode. Energy consumption test is also carried out at the ambient temperature of 30±1℃ and the relative humidity of 75±5%.

2.2.3 Residual defrost test

Defrost test for an intermittent operation has been conducted at ambient temperature 35±1℃ and relative humidity, 85±5% with placing all the accessories at where they are supposed to be. Chemical test packages are filled in the freezer compartment and the refrigerator temperature controller is adjusted to N-N mode so that the temperature of water placed in the refrigerator compartment is 3℃. When the temperatures of the refrigerator and freezer compartments reaches 3℃ and −18℃, respectively, the refrigerator is forced to go into the defrosting cycle by adjusting the defrost timer, and the water in the refrigerator is replaced with 30℃ water. After 2 hours, the cabinet doors opening/closing procedure was carried out for 14 hours(freezer cabinet once every 28 minutes and refrigerator cabinet once every 7 minutes). The door opening time and angle are 10 seconds and 90°, respectively and the door is fully open for at least 5 seconds. If the refrigerator goes into a defrosting cycle during the test, the door opening/closing procedure is continued for the remaining time after the defrosting is over. Temperature behavior for the refrigerator and freezer compartments are measured during the test.

3. Results and discussion

The results of pull down, on-off cycle and residual defrost tests for the system with newly designed evaporator(EP-2) are depicted in Figs. 3~6. In Table 3, energy consumption, cooling speed, and on time ratio of the compressor for 248

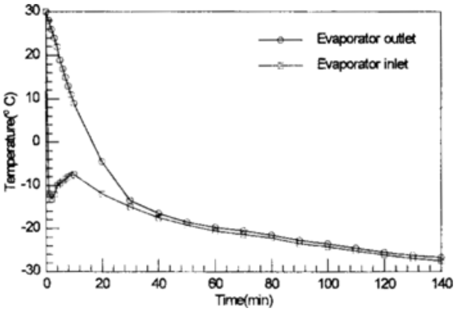


Fig. 3 Temperature profiles at evaporator inlet and outlet during pull down test.

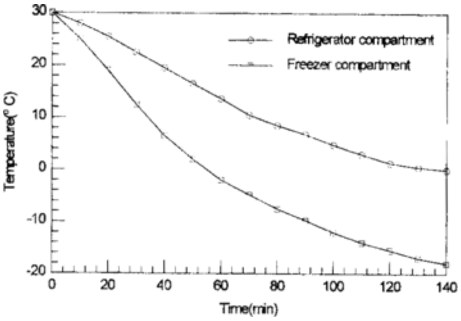


Fig. 4 Temperature profiles of the refrigerator and freezer compartments during pull down test.

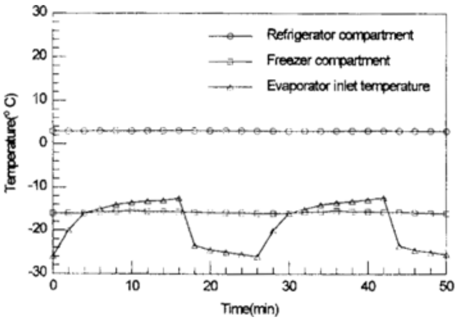


Fig. 5 Temperature distribution for on-off cycle test (N-N operation mode).

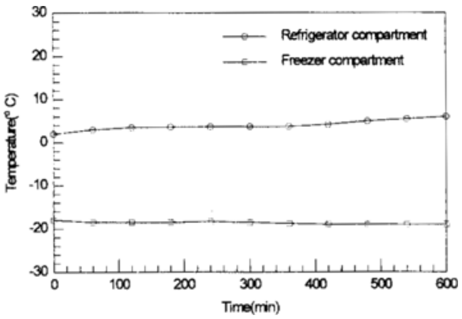


Fig. 6 Temperature profiles of the refrigerator and freezer compartments for residual defrost test.

l auto-defrost refrigerator-freezer with EP-2 are presented, compared with those of conventional evaporator(EP-1). Figure 3 shows the evaporator inlet and outlet temperature for no load pull down test. The outlet temperature of the evaporator decreases monotonically with time, whereas the inlet temperature falls suddenly to -13℃, about 3 minutes after startup of the system, increases for some time(3 to 10 minutes after startup), and then decreases to a certain value which is 2℃ lower than outlet temperature. These results can be explained as it follows. Before switching on the system, the high and low side pressures equalize through the open capillary tube and the refrigerant in the system at startup is saturated at 30℃.The refrigerant is rapidly drained from the evaporator just after the system is switched on since the pumping capacity of the compressor is greater than the flow capacity of the capillary tube and therefore the suction pressure drops suddenly from the equilibrium pressure. The starvation of the evaporator and the sudden drop in the suction pressure cause the evaporator temperature to go down rapidly. However, the heat capacity(thermal mass) of the evaporator and the increasing refrigerant flow rate through the capillary tube result in the increase of the evaporator temperature from 3 minutes till 10 minutes after startup. The lshx also affects the evaporator inlet temperature because the refrigerant in the capillary tube section of lshx is cooled by the cold suction gas.

In Fig. 4, the average temperature profiles of the refrigerator and freezer compartments during pull down test are depicted. The cooling speeds of refrigerator-freezer with EP-1 and EP-2 are presented in Table 3. It is observed from the table that the cooling speeds are improved by 3% for the refrigerator compartment and 2% for the freezer compartment by adoption of the newly designed evaporator, EP-2.

Figure 5 shows the temperature distribution for a standard on-off cycle(N-N operation mode)

Table 3 Summary of test results.

Items		EP-1	EP-2	EP-2/EP-1
Cooling speed (min)	Refrigerator (30 → 5°C)	119.0	116.5	98 (%)
	Freezer (30 → −15°C)	96.7	94.0	97 (%)
On time ratio (%)	C-C Operation mode	56.9	45.4	80 (%)
	N-N Operation mode	42.4	38.9	92 (%)
	W-W Operation mode	35.5	33.7	95 (%)
Energy consumption (kWh/month)		38.4	35.9	93 (%)

test. The operation rate of the compressor can be calculated from the figure and the results for three test modes are presented with those for the conventional system in Table 3. As shown in the table, the operation rate for the system with EP-2 was 5～20% lower than that for EP-1 and energy consumption was decreased by 7% using the newly designed evaporator. Such results may partially be explained if we note the frontal area and weight of evaporator. The weight of EP-2 is 59% of EP-1 and therefore the heat capacity of EP-2 is smaller than that of EP-1. This results in decreasing the compressor on-time ratio and increasing energy consumption because compressor on-off cycle period becomes smaller and the cyclic losses increase. However, newly designed evaporator, EP-2 has augmented heat transfer surface and the larger air inlet frontal area (the air inlet area of EP-2 is 7% larger than that of EP-1). The augmented surface could enhance air-side heat transfer. The larger air inlet area of evaporator causes pressure drop of EP-2 to be less than that of EP-1 and therefore increases the thermal performance of the system when the same amount of frost accumulates on the evaporator surface (Rite and Crawford, 1991a). Even though smaller weight evaporator increases energy consumption of the system (Ding and Chen, 1992), the overall performance of the system with newly designed evaporator, EP-2 is better than that of conventional one, EP-1. Therefore we may conclude that the thermal performance of the system rather depends on air-flow rate through the evaporator when the frost accumulates on the evaporator surface. Figure 6 presents temperature profiles for the refrigerator and freezer compartments during residual defrost test. The temperature of the freezer compartment remains nearly constant whereas the refrigerator temperature increases slowly with time.

4. Conclusions

A high-efficiency compact evaporator for household auto-defrost refrigerator- freezers has been developed and a series of tests was performed to investigate the thermal performance of the system. By comparing the test results with the conventional system, the following conclusions can be drawn:

(1) Thermal performance of the system with newly designed evaporator was better than that of conventional system.

(2) Cooling speeds were improved by 2% for the refrigerator compartment and by 3% for freezer compartment, respectively.

(3) Energy efficiency was improved by 7%, and compressor on-time ratio was decreased by 5 to 20%.

(4) Thermal performance of the system rather depends on air-flow rate through evaporator when the frost accumulates on the evaporator surface.

(5) The size and material of the evaporator can be reduced by 7% and 40%, respectively, compared with the conventional one.

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