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J. K. Park
LG Electronics

S. T. Park
LG Electronics

T. H. Kwak
LG Electronics

K. S. Im
LG Electronics

DUAL-CONTROLLED INDIRECT COOLING REFRIGERATOR/FREEZER USING TWO CAPILLARY TUBES AND AN AIR FLOW SWITCHING SYSTEM

Jin-Koo Park, Sang-Tae Park, Tae-Hee Kwak and Keum-Sik Im
HVAC Team, Living system research laboratory
LG Electronics, Seoul, KOREA

ABSTRACT

The dual-controlled refrigeration system is devised to enhance the energy efficiency and basic performance of an indirect cooling household refrigerator/freezer. In order to alternately serve the fresh food and freezer compartment with a conventional simple refrigeration cycle, two capillary tubes and on/off valves are adopted. The air flow switching system, which is composed of two fans and dampers, is used to provide air flow for each compartment. The motor-driven on/off dampers are employed to switch the circulating path of air flowing through each compartment. The cycle and air flow switching system are controlled on the basis of compartment temperature. In the present investigation, the 510L prototype unit is a modification of a conventional refrigerator/freezer. The cycle matching and performance test is performed at 30℃ ambient temperature. The energy consumption test reveals that compared to the conventional system, the energy consumption of the present refrigeration system is reduced by about 9%. Moreover, the cooling speed test result shows that with the present refrigeration system, the refrigeration and freezing time become about 10 minute shorter than the conventional system. R-12 was used for this research.

1. INTRODUCTION

Most of the currently designed household refrigerator consists of a fresh food compartment and a freezer compartment(hereafter denoted by RF). Generally, an indirect cooling type of refrigeration system with simple vapor compression cycle is employed to a RF. The nominal operating temperature of the fresh food and freezer compartment is 3℃ and -18℃ respectively. It is well known that the efficiency of a vapor compression refrigeration cycle is increased as the evaporation temperature increases. This is attributable primarily to the inherent characteristics of thermodynamic properties of a refrigerant and cycle thermodynamics. From this, it can be stated that if the refrigeration cycle operates independently with two different evaporation temperatures for fresh food and freezer compartment respectively, the cycle efficiency may be increased. Several kinds of advanced cycle to take advantage of the aforementioned characteristics have been devised and investigated in the industry[1,2,3,4]. However, the advanced cycles investigated up to the present have not satisfied at least one of the requirements such as the cost performance, productivity and reliability. Considering the above requirements, we studied a dual-controlled refrigeration system, which consists of the cycle with two capillary tubes and the air flow switching system, which is called SEDS system(Single Evaporator Dual Source Refrigeration system).

Steady state computer simulation technique was developed and utilized to design the SEDS cycle. A simple empirical model was adopted to predict the compression process with a reciprocating compressor. Rigorous experiments were performed on the test unit as follows: first, the baseline test was conducted with a 510*L* RF unit. Second, the refrigeration cycle, air flow system, and control unit were modified to implement the SEDS system. Finally, system matching and optimization test were conducted.

2. SEDS SYSTEM

The SEDS system is a new approach model to enhance the energy efficiency of a RF, in which two capillary tubes and air flow switching system are incorporated. In light of Thermodynamics, the refrigeration cycle of the SEDS system is quite similar to a simple vapor compression cycle except for the capillary tubes and the dampers. A schematic configuration of the SEDS system is shown in Figure 1. At the end of the condenser, two capillary tubes are connected: one is for the cooling of the fresh food compartment(R-captube) and the other is for the freezer compartment(F-captube).

When a fresh food compartment is being cooled, for example, then the shut-off valve connected to the R-captube is opened, while the other connected with F-captube is closed. Consequently, the refrigerant flows into the evaporator passing through the R-captube. At the same time, the air flow switching system controls fan motors and dampers for the circulation of cooled air into the fresh food compartment through the evaporator (for freezer compartment, vice versa).

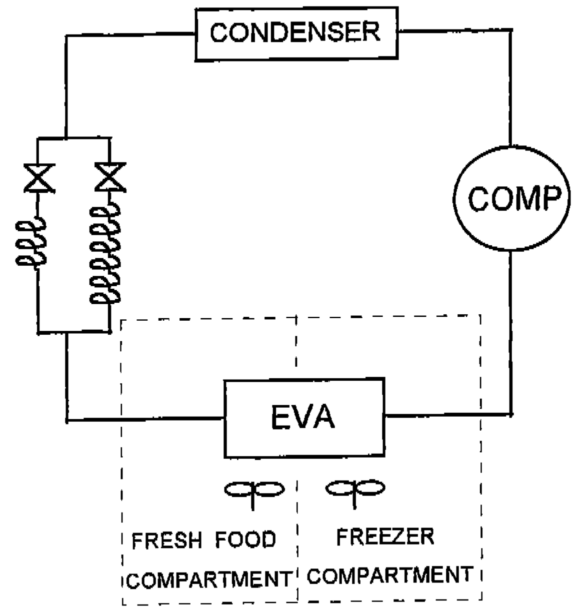

Figure 1. Schematic of the SEDS system

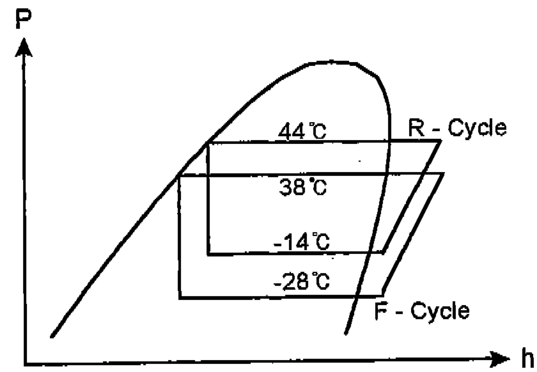

Figure 2. p-h diagram of the SEDS cycle

3. DESIGN OF SEDS CYCLE

Compressor calorimeter test and compressor selection

In order to select the compressor pertinent to the SEDS system, the calorimeter test was performed for the compressor units manufactured in our company. The cycle simulation program was developed to predict the performance and thermodynamic states of the SEDS cycle. It requires the compressor data and the thermodynamic properties as well as the cycle component models such as capillary tube and heat exchanger. The specifics of methodologies are not given here. Through rigorous cycle simulations, a newly developed compressor(hereafter denoted by C-2) was selected.

Cycle design

The two different refrigeration cycles can be implemented to a SEDS cycle with only one evaporator. One of which is utilized to provide cooling for the fresh food compartment and the other for the freezer compartment. In general, the fresh food compartment air temperature is much higher than the freezer one. With to the same trend, the evaporation temperature of the cycle for fresh food compartment (hereafter denoted by R-cycle) is higher than that of the cycle for freezer(hereafter denoted by F-cycle). From this, it can be stated that the efficiency of the SEDS cycle is directly influenced by the evaporation temperature of R-cycle.

For a given ambient condition, the evaporation temperature completely depends on the thermal load transferred into the evaporator by the air flow. The thermal load, Q, can be expressed by the following mathematical equation:

$$Q = UA\,(\Delta T)_{LMTD} \quad (4)$$

where U is the overall heat transfer coefficient, A the heat transfer area, and $(\Delta T)_{LMTD}$ the logarithmic mean temperature difference between the evaporator and the air. Here, U is derived from the following empirical formula:

$$U = a(V_{air})^{\,b} \quad (5)$$

where, a and b are empirically determined constant, and V_{air} the velocity of air flow through the evaporator.

In the present investigation, the same evaporator as used in the original RF unit were used in the unit equipped with SEDS cycle because of the structural limitation of the unit. Moreover, due to the aeroacoustic noise and limited capacity of a fan/motor, the volume flow rate of air was limited to *1.5CMM*.

By performing the iterative cycle simulations for the various evaporating and condensing temperature conditions, We designed both the R- and F-cycle. The results are summarized in Table 1. The thermodynamic state of the SEDS cycle is shown by Figure 2 at a pressure-enthalpy diagram.

4. EXPERIMENT

Baseline test

A baseline test was conducted to the original RF unit. The main purpose of the baseline test was to eventually compare the energy consumption level of the unit to the SEDS system. The 510L, automatic defrost, top-mounted RF unit was adopted (it is marketed for the domestic use in Korea in 1995). The unit was equipped with the reciprocating compressor(hereafter denoted by C-1). The evaporator and condenser were forced-convection cross-flow heat exchangers and both have 10W fans. A suction line heat exchanger, with both capillary tubes soldered to the suction line, was also included. The evaporator was placed in the freezer compartment. The compressor and condenser were located under the cabinet. An electronic controller is used to control the operation of system components such as compressor and fan motor. The freezer air temperature and compressor operation was controlled by a thermistor , while the fresh food air temperature was controlled by thermistor and electronic damper installed in the fresh food compartment.

The baseline unit was placed inside the environmental chamber maintained at 30℃ and the exact location was marked to ensure consistency of the tests over the period of the experiment. In order to measure the energy consumption, the fresh food and freezer compartment temperatures were set to be nominal temperatures using the button placed in the control panel on the freezer door.

SEDS system test

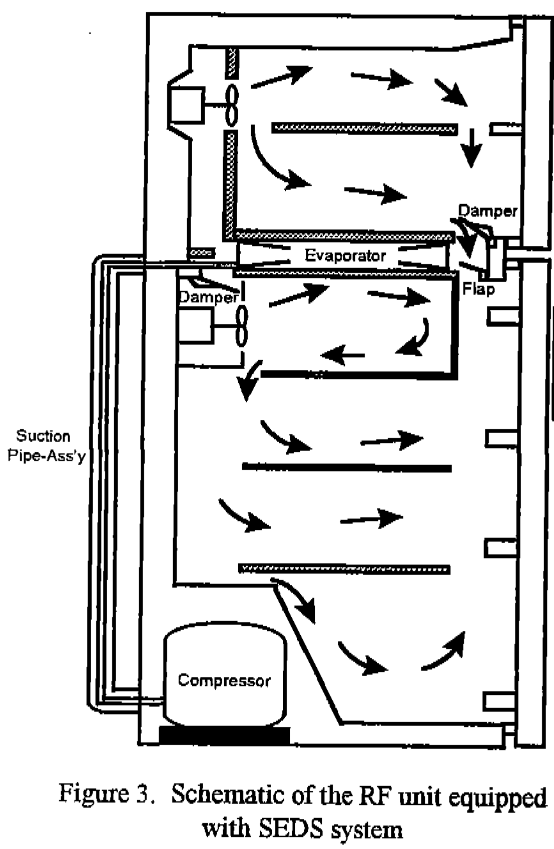

Figure 3. Schematic of the RF unit equipped with SEDS system

After the completion of our baseline test, the RF unit was modified to the SEDS system. At first, the compressor and the evaporator were detached from the suction line heat exchanger. The original compressor(C-1) was replaced with C-2. The evaporator was re-installed inside the barrier between the fresh food and freezer compartment by removing the freezer side of the barrier. Next, two shut-off solenoid valves of 5.5W(R- and F-valve), which are normally closed, were mounted on the one end of capillary tubes. The opposite end of capillary tubes were soldered onto the suction line, these were inserted into the barrier through the hole drilled on the insulation panel behind the unit and connected to the evaporator. Then, the upper side of the evaporator was covered with insulation panels. The two electronic dampers were installed at the inlet of airflow from the freezer(top side of the barrier) and outlet of the airflow to the fresh food compartment(bottom side of the barrier). Additionally, auto flap(PP) was installed at the inlet of airflow from the fresh food compartment. The grill fan was removed from the freezer and the evaporator fan for the fresh food compartment(R-fan) was installed at the back side of inner liner. Figure 3 shows a schematic of the unit equipped with the SEDS system.

The original unit controller was replaced with the newly designed one and it was connected to the main computer placed on the outside of the environmental chamber. The operation of the RF unit was controlled by the main computer. A thermistor to measure the fresh food compartment temperature is mounted on the rear side of inner liner inside the fresh food compartment .

A total of twenty thermocouple sensors were attached at the locations along the tubes of the heat exchanger inlets and outlets to measure temperatures. Two pressure transducers were installed at the outlet of the condenser and the compressor suction line. A sight glass was also installed at the outlet of the condenser to check the state of the cycle. A data acquisition system and Hybrid recorder were used to obtain the real time data.

The cycle matching test was conducted with the refrigerant charge of 170g to check the leakage and the state of the system operation. Next, the test to determine the optimum amount of refrigerant charge was performed by increasing the amount of refrigerant charge by 10g at one time. Finally, with this optimum refrigerant charge, the tests for the energy consumption, cooling speed, and compressor starting characteristic were performed.

5. RESULTS AND DISCUSSIOIN

Figure 4 displays temperature profiles of each compartment and heat exchanger during a period of on and off cycle in the SEDS system. The compressor, fan motor, and shut-off valve were turned off at the same time. The fresh food compartment starts cooling down just after the compressor turns on. The temperature of the fresh food compartment dropped very quickly, while it rises gradually during the subsequent F-cycle. The slope is steady until it reaches the upper limit. During the F-cycle and off time, the heat transfer from the fresh food compartment to the barrier suppresses the rise of fresh food compartment temperature. Consequently, as revealed in Figure 4, the %run time of R-cycle is smaller compared to that of F-cycle. It does not agree with the design results. This discrepancy is partly attributable to the effect of thermal inertia of the insulation materials surrounding the evaporator and the heat transfer between the barrier and fresh food compartment, and partly to the suction of the air from the freezer at the initial stage of the R-cycle. Figure 4 also exhibits the initial fluctuation of evaporation temperature at the initial stage of R-cycle.

The pressure and instantaneous power profiles are shown in Figure 5. The increase of suction and discharge pressure arise after compressor start-up. In particular, it is noteworthy that the discharge pressure drops down to about 8bar at the end of the off period, while it drops down to about 1.5bar in the original RF. The difference is caused by action of the shut-off valve. That is, both of the shut-off valves are closed just after the system is stopped and thus the hot refrigerant in the condenser never comes into the evaporator through the capillary tube.

Results of energy consumption tests are summarized in Table 2. It shows that the energy savings, accounting for the efficiency improvement of the compressor, are about 9%. The shut-off solenoid valves consume 1.8kWh a month. Thus, if latching type valves are employed, the energy efficiency can be improved up to 11.7%. Figure 6 illustrates the contribution of SEDS cycle to the improvement of energy efficiency. The reduction of energy consumption by 6.1kWh(8.5%) results from the change of compressor, from C-1 to C-2. The EER of C-2 is 12. 5% higher than C-1. As mentioned before, when the compressor was stopped, the shut-off valve closed the refrigerant circuit, thus prohibiting the migration of hot refrigerant from the condenser to the evaporator and maintaining the high and low pressure at their pre-stop levels. About 3.6%(2.6kWh) reduction of energy consumption resulted from these effects. Accordingly, the net effect of the SEDS cycle(except that of energy saving valve) is about 5.2%.

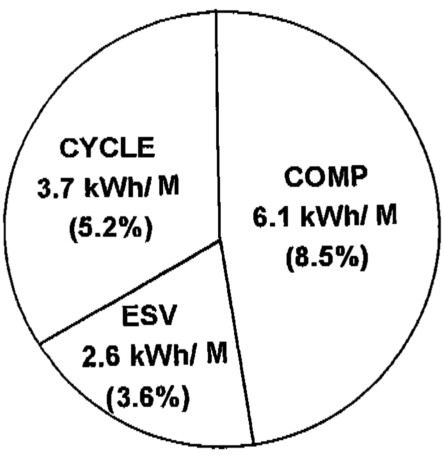

Figure 6. Contribution of the SEDS cycle for the reduction of energy consumption

The RF unit was first left off inside the environmental chamber at 30℃. Once it reached thermal equilibrium state at 30℃, then the unit turns on. For the fresh food and freezer compartment, the elapsed time was measured for the temperature to reach 10℃ and -5℃ respectively. The elapsed time of a SEDS system was about 10min shorter than that of original unit. Table 3. shows the elapsed time of the SEDS system and the original unit.

6. CONCLUSIONS

Experiments were carried out on a household RF unit which was modified to a SEDS system. From the test results and discussion, the following conclusion was obtained:

1) The SEDS system provides energy savings up to 9% compared to the baseline unit. With a latching type shut-off valve, 11.7% of energy saving is anticipated.
2) Part of the 9% reduction in energy consumption(about 3.6%) is attributable to the effect of the energy saving valve.
3) The elapsed time to refrigerate each compartment is reduced about 10 min.
4) The disagreement between the test and design results is mainly due to the effect of thermal inertia of the insulation material surrounding the evaporator and the heat transfer from the fresh food compartment to the barrier.

7. ACKNOWLEDGEMENTS

Thanks are due to Mr. H. Jaster of GE CRD for kind cooperation.

8. REFERENCES

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Table 1. Summary of the design results for SEDS system

	ORIGINAL	SEDS
compressor	*C-1*	*C-2*
evaporation temperature	*-27 ℃*	*R-cycle : -14 ℃* *F-cycle : -28 ℃*
condensing temperature	*42 ℃*	*R-cycle : 44 ℃* *F-cycle : 38 ℃*
volume flow rate of air	*1CMM*	*R-cycle : 1.23CMM* *F-cycle : 1.12CMM*
capillary tube	*3185mm(f0.72)*	*R-cycle : 2476mm(f 0.8)* *F-cycle : 4180mm(f0.72)*
%run time	*46.1%*	*R-cycle : 11.0%* *F-cycle : 28.5%*
energy consumption	*71.5kWh/month*	*55.0kWh/month*

Table 2. Summary of the energy consumption test results

	ORIGINAL	SEDS
%run time	*46.1%*	*R-cycle : 6.1%* *F-cycle : 36.0%*
energy consumption	*71.5kWh/month*	*59.1kWh/month*

Table 3. Test result of refrigeration speed

	ORIGINAL	SEDS
fresh food*(30 ℃ -> 10 ℃)*	*115min*	*102min*
freezer*(30 ℃ -> -5 ℃)*	*77min*	*66min*

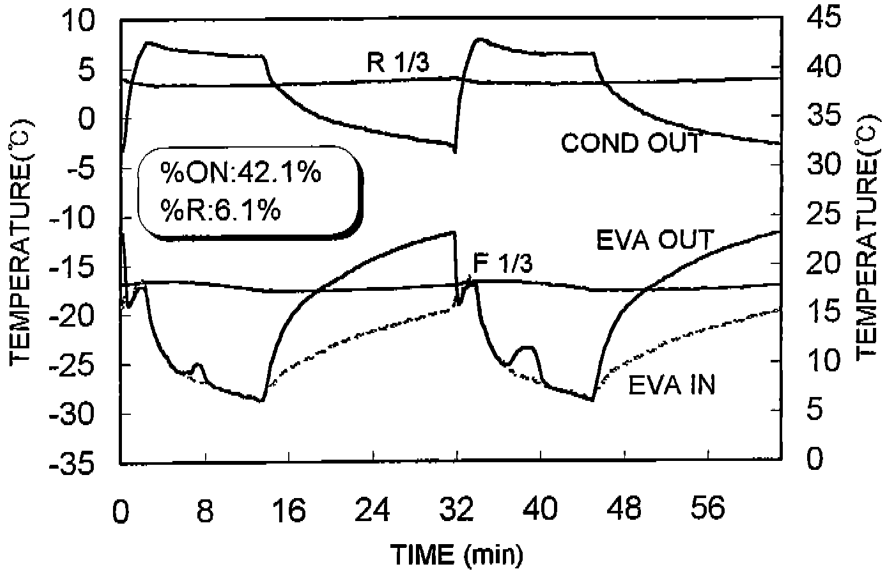

Figure 4. Temperature profiles for the SEDS system

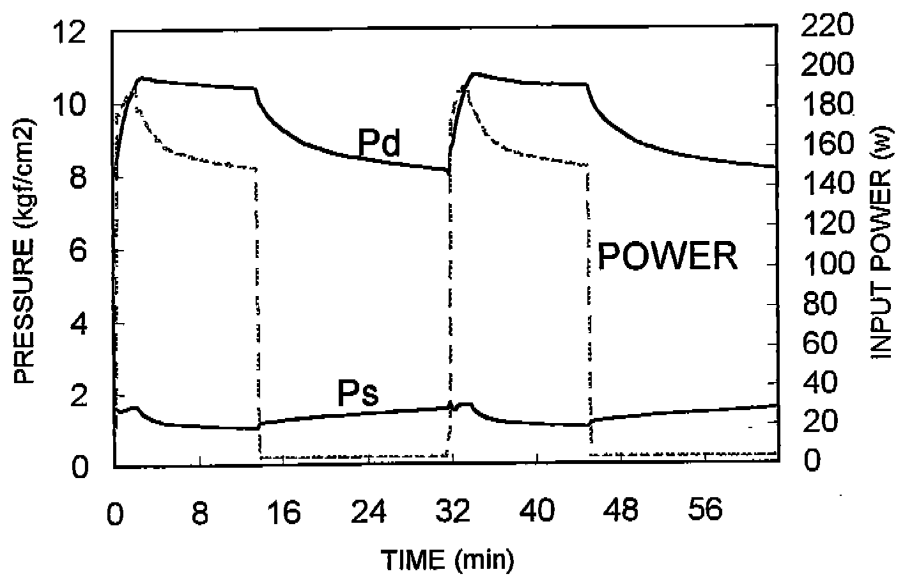

Figure 5. Pressure and power profiles for the SEDS system