2008

Implementation of Inverter-Driven Household Refrigerator/Freezer Using Hydrocarbon Isobutane for Refrigeration

Wenruey Chang
Industrial Technology and Research Institute

Tsongse Shaut
Tatung Corporation

Chiangho Lin
Tatung Corporation

Kueitien Lin
Industrial Technology and Research Institute

Implementation of Inverter-Driven Household Refrigerator/Freezer Using Hydrocarbon Isobutane for Refrigeration

Wen-Ruey Chang[1,]*, Tsong-Se Shaut[2], Chiang-Ho Lin[2], and Kuei-Tien Lin[1]

[1] **Energy and Environment Research Laboratories (EEL), Industrial Technology and Research Institute (ITRI), Chutung, HsinChu, Taiwan.**
[2] **Household Appliance Design Division, Tatung Corporation, Tucheng, Taipei, Taiwan.**
*** Corresponding author. TEL.886-3-5914221, FAX 886-3-5820250,**
E-mail: wrchang@itri.org.tw

ABSTRACT

Hydrocarbon(HC) isobutane(R-600a) is one of the environmental friendly refrigerants to the greenhouse effect, and is applied to household refrigerator/freezer(HRF) with fixed frequency(FF) AC induction compressor successfully around the world. As well, the novel variable frequency(VF) HRF has significant energy-efficiency potential and also has a great benefit of low noise. This paper describes the development of a VF HRF using refrigerant R-600a driven by a variable-speed reciprocating compressor with a brushless DC(BLDC) motor inside. To compare the performance between the refrigerants R-600a and HFC-134a, two inverter-driven HRFs with the same cabinet model are fabricated and studied experimentally. The gross inner volume for this cabinet model is rated 560 liters with a top-mounted freezer of 133 liters. By a steady test of 24 hours, the energy consumption of the R-600a VF HRF is 1.426 kWh/day with 12% lower than that of the HFC-134a VF HRF, which rates 1.620 kWh/day under the same storage temperatures and ambient conditions. To deduce the efficiency improvement of VF BLDC compressors for HFC-134a and R-600a, the data for the FF HRFs of the same model are also provided. The energy-saving potential of HRF with VF BLDC compressor is about 35% for using refrigerants HC R-600a and HFC-134a.

1. INTRODUCTION

Household refrigerator/freezer(HRF) is a daily-necessity domestic appliance and operates practically all the year. According to statistics in Taiwan, the operation of a HRF takes 17% of the total household electric energy consumption. Due to the impact of global warming effect and energy shortage, the minimum energy performance standards (MEPS) of domestic electric appliances have been improving in several countries recently. HRF is usually considered as the high priority of improved MEPS for its annual running and popularity. In the same manner as all the other countries do for energy saving, Taiwan has setup criteria for energy regulation on HRFs since 1996, and has been enhanced successively twice in 2000 and 2003. Compared internationally, the current regulation criteria on HRFs in Taiwan are on the low side; taking example of a fridge with an equivalent inner volume of 600 liters, the energy efficiency regulation in Taiwan is 66% lower than that in USA and 61% lower than that in Korea as reported by Huang(2005). In view of this fact, the Revised MEPS of HRFs announced by the Bureau of Energy, Ministry of Economic Affairs, Taiwan in 2006 is set as high as a 60% uplift after 2010, which is close to the current US regulation criterion as reported by Chang(2008).

Although HFC-134a was ever recommended as a potential replacement for CFC-12 since the last decade and is still popular in several countries, its global warming potentials(GWPs) are extremely high up to 1300. For this reason, the HRF refrigerant replacement for CHC-12 was shifted directly to hydrocarbon(HC) in Europe since 1990's. HC isobutane(R-600a) is one of the environmental friendly refrigerants to the greenhouse effect, and is utilized for HRF products with AC induction compressors successfully around the world. In public literature, there are also many efforts on the studies of thermal performance and energy consumption for HRFs using HC refrigerants. Some focused on the solution of the ozone layer depletion problem and the green house effect without a significant change in energy efficiency, and some proposed energy-saving schemes by novel technologies for HRFs. James et al.(1992) carried out the drop-in test of one CFC-12 domestic refrigerator by propane(R-290). They recommend propane as a potential refrigerant for CFC-12 from the experimental results in energy consumption, lubrication of compressor, as well as the analysis of cost, environmental impact, and safety. Richardson et al.(1995) investigated the performance of HC refrigerants in a hermetic vapor-compression system replaced by propane and propane/isobutane mixtures for CFC-12. They found that the usage of these HC blends for HRF would keep the similar behavior as CFC-12, and the mineral lubricant for compressors was still feasible. Alsaad and Hammad(1998, 1999) studied the performance of a CFC-12 HRF retrofitted with liquid petroleum gas(LPG) and HC mixtures for the refrigeration system, which was lubricated with naphthalene based oil. They found that the COP of the LPG refrigeration system was as high as that of CFC-12, and the long-term test continued for over two years. Granryd(2001) reviewed the safety consideration of HC refrigerants, including some efforts on natural refrigerants in Europe, available safety standards for combustible refrigerants, technical guideline, etc.

Recently, there are still many studies concerning with the refrigerant replacement topics of domestic refrigerators for energy saving and the global warming effect reduction. Tashtoush et al.(2002), Sekhar et al.(2004) and Wongwises et al.(2005) proceeded refrigerant retrofit experiments of HRFs with HC and HFC-134a, and reached similar performance results of CFC-12. Akash et al.(2003) presented the resembling trend of LPG refrigerant for HRF as the previous manuscripts. These surveyed papers here almost focused on the efficient improvement of fixed frequency (FF) HRFs, and the novel variable frequency(VF) technology actualized in the HC refrigeration system is scarce.

For energy-saving improvement of HRF, one novel inverter-control technology with DC compressor has been applied to HFC-134a refrigeration system for over ten years, especially in Asia. In recent five years, almost all the Japanese manufacturers of HRF proposed R-600a VF HRF products in the lead around the world. There are also some studies available on VF HRF for HFC-134a refrigerant in open literature. Liu et al.(2004) studied the effect of door openings of VF and FF HRFs on energy consumption and storage temperature variation experimentally compared with those of closed door conditions. Chang et al.(2004, 2005) presented the implementation on the control methodology of VF HRF with refrigerant HFC-134a, and the energy consumption and corresponding thermal characteristics of cabinets were also included. Under some specified conditions, the VF HRF had over 35% improvement of energy efficiency to that of a FF HRF product. Considering some benefits of R-600a to the global warming effect vs. DC VF technologies to energy saving, this paper proposes the implementation of VF R-600a HRF in replacement for HFC-134a, and provides the performance comparison of VF HRFs between refrigerants R-600a and HFC-134a with the same cabinet model.

2. IMPLEMENTATION of VF HRFs for HC R-600a

Two VF HRF samples are studied experimentally here for refrigerants R-600a and HFC-134a with the same cabinet model, as shown in Figure 1 and Figure 2(a). The outer dimensions of the HRF cabinet are H1800mm×W754mm ×D742mm with inner gross volume of 560 liters. The volumes of the freezer, fresh food, and vegetable/fruit compartments are 133L, 309L, and 118 respectively, for each of which has its individual door. The blowing agent of PU insulation foaming of the studied HRFs is shifted to cyclopentane(CP) in replacement for HCFC-141b. As shown in Figure 1 and 2(b), the top-mounted freezer/evaporator uses an automatic defrost mechanism, which electric heater rates 200W at 110V/60Hz. The air circulation in the HRF cabinet is chilled by the evaporator and driven by a DC fan/motor. The minimum temperature of the evaporator's tube bundle is below -28°C in general. The chilled air flows to the freezer compartment directly and is also divided to the fresh food compartment regulated by a mechanical damper shown in Figure 2(c) to maintain the thermostat. The same type of reciprocating compressor driven by a BLDC motor is applied to the refrigeration system for these two HRFs. The displacement of R-600a VF compressor is larger than that of HFC-134a. The VF controller is combined with a digital signal processing(DSP) micro-processor, sensor-less power electronic circuits, six-step driving transistors for pulse width modulation(PWM) regulation, switching power supply, and some peripheral communication circuits. The auxiliary electrical parts include with the fan/motor, door switch, relay, lamp, damper, defrosting electrical heater etc. The start-up and sequent control commands continue to proceed following the pre-verified ROM built in this VF controller to compensate the thermal load variation. The refrigeration capability of a VF HRF can be adjusted through compressor speed regulation. So the main power turning on/off frequency used in FF HRF can be greatly reduced, and the energy consumption will decrease due to the increase of refrigeration cycling efficiency. The details of the control methodology of VF HRF was proposed by the same research group, Chang et al.(2004, 2005).

Some specification of the R-600a VF HRF is modified to fit the optimized operation, including the condenser, compressor, and charge amount of refrigerant. Table 1 lists some specified parameters of these two VF HRFs. Although VF HRF is the research topics for refrigerant replacement, another FF HRFs for HC R-600a and HFC-134a of the same cabinet model are also provided to give more information, noted by C and D in Table 1. For shortage in paragraph, some results are also listed in the same table for comparison.

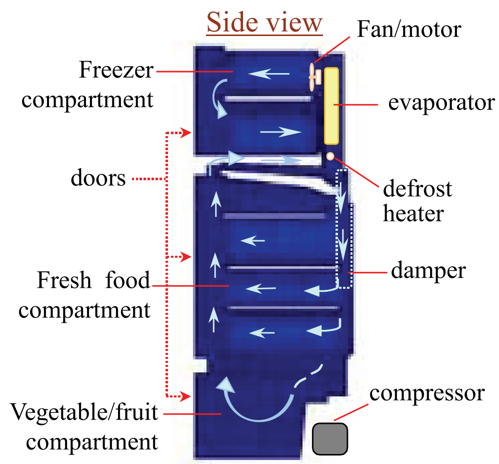
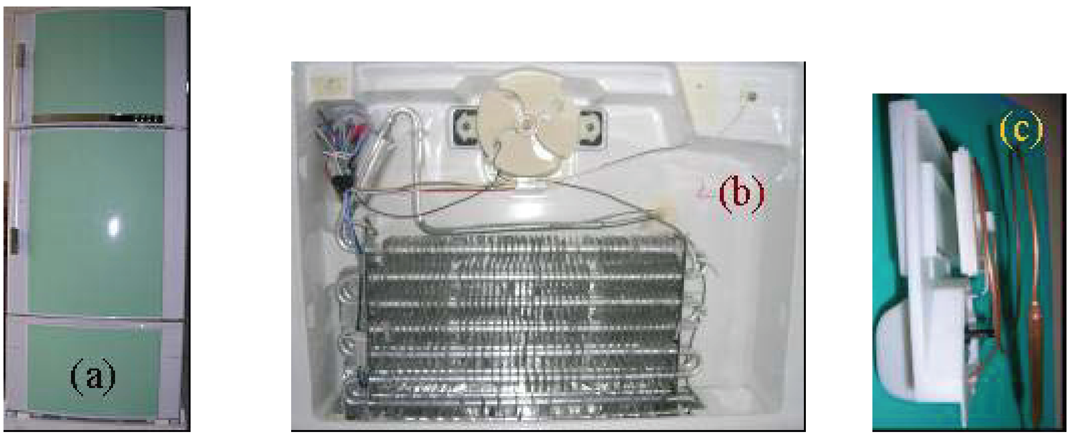


Figure 1: Schematic description for the studied top-mounted freezer HRF



(a)the VF HRF model (b)aluminum finned-tube evaporator and DC fan/motor (c)refrigeration damper

Figure 2: Photos for the VF HRF System and components in this study

Table 1 Specification and some results of the studied VF HRFs

Item	VF HRF A	VF HRF B	FF HRF C	FF HRF D
Refrigerant	R-600a	HFC-134a	R-600a	HFC-134a
Compressor	VF DC	VF DC	FF AC	FF AC
Power Input	110V/60Hz	110V/60Hz	110V/60Hz	110V/60Hz
Max. refrigeration capacity of the DC VF compressor	300W	300W	300W	300W
PU blowing agent	CP	CP	CP	HCFC-141b
Freezer Temperature(°C)	-18.0±2.7	-18.1±2.8	-17.9±3.0	-18.1±4.1
Fresh Food Temperature (°C)	3.4±0.4	3.5±1.7	3.2±0.7	3.2±2.6
Energy Consumption(kWh/day)	1.426	1.620	2.016	2.255
Percentage Operating Time of the Compressor motor(%)	90.8	69.4	56.42	54.37

Following the test standard CNS-2062(2001) applied in Taiwan to measure the electrical energy consumption and the corresponding thermal performance, the temperatures in the freezer compartment, fresh food compartment, ambient temperature and ambient relative humidity shall be set at –18°C, 3°C, 30°C, and 75% respectively with doors closed for 24 hours. The studied HRFs are tested in an environmental control room with PC based data acquisition and power measurement systems. To recognize thermal behavior of the HRF under the specified condition, T-type thermocouple(T/C) wires are used to detect the local temperatures of the cabinets and the ambient.

As following standards CNS-2062(2001) and ANSI/AHAM HRF-1(2007), some T/Cs are plugged into copper mass blocks, which heat capacity is not exceed that of 20g of water; and some T/Cs are exposed in the air located by the mass to detect the actual air temperatures in the cabinets. The ambient temperature is calculated from the average of three T/Cs in the masses in vertically different locations. Some electrical parameters are measured to evaluate the efficiency of HRF, including 24-hour energy consumption, running percentage of the compressor vs. its power factor. The uncertainties of T/C, relative humidity, and electric power in this study are under 0.3°C, 3% and 1% for this application range.

3. PERFORMANCE TESTS AND ANALYSIS

To confirm the performance of HRFs for commercialization, pull-down test and long-term steady test for energy consumption of 24h shall proceed in succession. No-load pull-down test is carried out to determine the rate at which the reduction of temperature in the storage compartment reaches some specified low value from ambient, as described in ANSI/AHAM HRF-1(2007). In this study, these two HRF samples A and B were kept at an ambient temperature of 30±0.5°C and relative humidity of 75±3% with doors open for over 12h to ensure a stable initial state. And then, all the doors were closed over one hour before power-on and the pull-down test proceeded as power turning on. The transient temperatures of the compartments and the electric parameters were measured simultaneously with a sampling period of 5s. The R-600a VF HRF A reached a maximum power of 205W after staring in 5 seconds, and run at power of 160W down to 140W during the pull-down period, which evaluation is about 3h. The freezer temperature reached -5°C in 1h, and the fresh food compartment temperature reached 10°C in 1.66h, what accords with the allowable largest period of 3h by CNS-2062(2001). Afterward the freezer compartment temperature reached -18°C in 3h, and the fresh food compartment reached 3°C in 2.85hr at the specified ambient temperature of 30°C. Meanwhile the discharge line temperature of the R-600a VF compressor reached a maximum of 84°C at the time of 1.29hr with instant electric power of 127W and current of 1.48A. After a pull-down operation, as all the compartment temperatures of reach to their specified thermostat values, a HRF will run in a state of normal operation with periodic cycles for the storage temperature variation.

At the starting period in one hour, the HFC-134a VF HRF B behaved similarly like sample A, and run at power of 210W down to 130W during the pull-down period. The freezer temperature reached to -5°C in 0.7h, and the fresh food compartment temperature reached to 10°C in 1.5h. These pull-down test results of the HFC-134a VF HRF B are also satisfactory the request of CNS-2062(2001). Afterward the freezer compartment temperature reached -18°C in 1.18h, and the fresh food compartment reached 3°C in 3.5h. Concerning the discharge line temperature of the HFC-134a VF compressor, the maximum value of 96.6°C occurred at the time of 0.87hr after turning on with instant power of 184W and current of 2.16A, which is higher than that of the R-600a VF HRF by 12.6°C.

After the no-load pull-down test, the compartment temperatures of the HRF samples were regulated to the specified standard thermostats under ambient temperature of 30°C. As all the storage temperatures reached the acceptable tolerances, said –18±0.5°C and 3±0.5°C for freezer and fresh food compartments respectively, closed-door energy consumption test proceeded for over 24h. Figures 3 shows the temperature profiles with time for the three compartments of the studied R-600a VF HRF sample under steady ambient condition. The solid line represents for the detective temperature by T/C exposed in the air for each compartment, and the dashed line for T/C plugged into a copper mass. From the results, the temperature measurement is smoothened by a metal mass, which averaged value in a long term differs a little from the datum detected by the air, but is below the uncertainty of temperature measurement. As shown in Figure 3, there are 21 operation cycles of the temperature controller for the compartment excluded the defrosting period, the average values of the compartment temperatures for the freezer, fresh food compartment, and vegetable compartment are 18.2°C, 3.2°C, and 6.8°C respectively during a 24h tested period, which includes the data in the defrost period. The energy consumption is 1.56kWh/day with double defrosting actions. If the defrost period is modified longer, the energy consumption is 1.43kWh/day, what is rechecked by another test run. The contribution of one-time defrost heating energy to the whole daily consumption is about 8~9%(~130Wh) for the R-600a VF HRF.

Figure 4 describes the instant power and its corresponding freezer temperature variations with time for R-600a VF HRF A during the defrost cycle. It is clear to indicate the step-change of power by the VF controller to reduce the fluctuation of storage temperature. One special function named deep-cooling mode(from point d to e in Figure 4) to pull down the average storage temperature, and then suppresses the raise of compartment temperature after defrosting. The power capacity of the defrost heater is about 200W and operates for 23.6 minutes(from e to f in Figure 4) during defrosting. If we calculate the time from the deep-cooling state(point d) to the recovery state of the freezer temperature(point h), the energy consumption is about 260Wh during 2.5 hours. On the other hand, it takes 136Wh during the same time under the other normal operation of the compressor(non-defrosting operation). This evaluation also confirms the previous result for additional energy consumption in one time defrosting by 130Wh to the refrigeration system. From the step-change of instant power in Figure 4, there are four control modes of running speed of the compressor for the normal operation, presented in power as 90W, 75W, 65W, and 0W(the compressor stops). For the deep-cooling or quick-freezing control function, the compressor can run highly to 153W with over 7 speeds to compensate the necessary thermostat. For the refrigeration piping system, the lubricant of the compressor is usually circulated with the refrigerant. To prevent possible damage due to lake of lubricant inside the compressor, the rotational speed shall not below 900rpm in this study. So the compressor stops corresponding its lowest speed as the thermostats reaches the limited value preset by the VF controller. The period for compressor stopping is named as idle state and consumes about 4W for the VF A HRF.

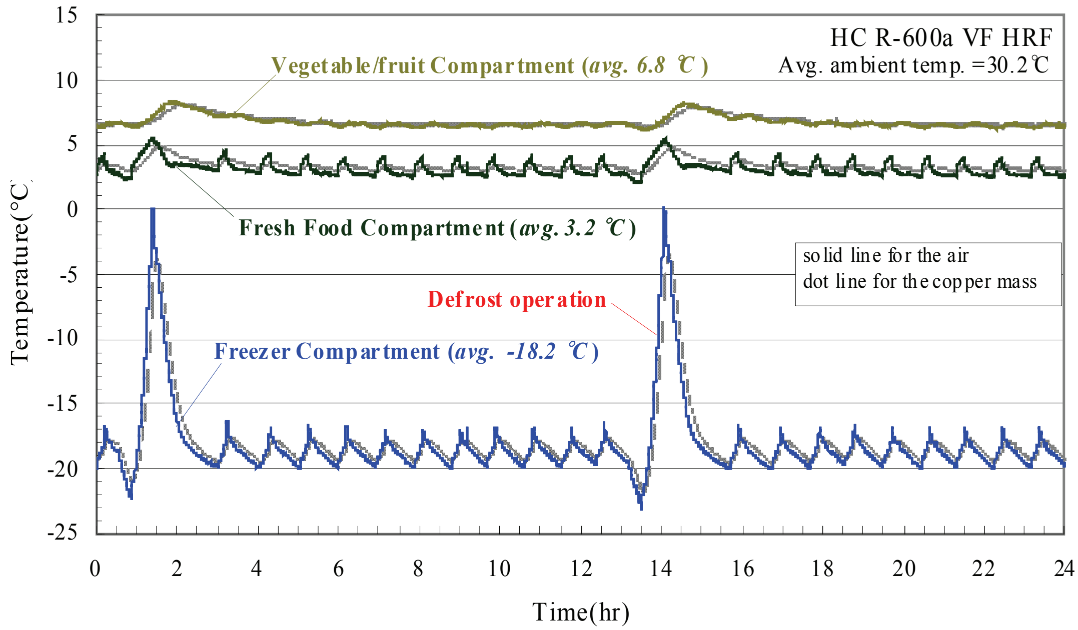


Figure 3: Compartment temperature variations of R-600a VF HRF during a 24-hour period.

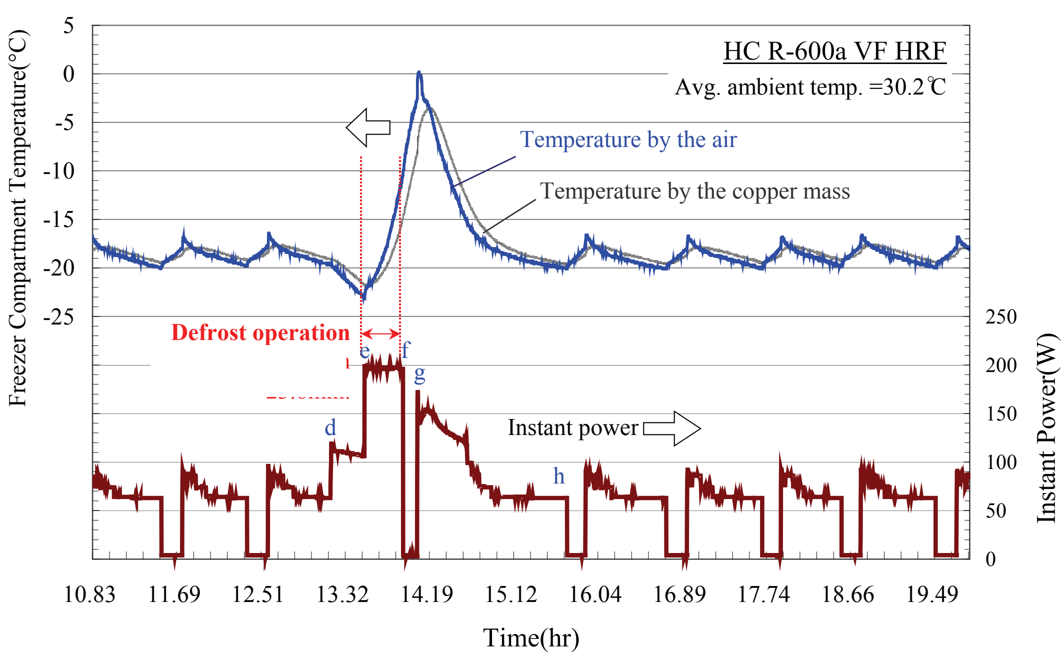


Figure 4: Temperature and power variations of R-600a VF HRF during a defrost period.

For HFC-134a VF HRF B, the time-variant temperature profiles of the compartments in 24h are shown in Figure 5. The average temperatures for the freezer compartment, fresh food compartment, and vegetable compartment are 18.4°C, 3.5°C, and 7.2°C, respectively, under steady ambient temperature of 30.1°C. There are 32.6 operation cycles of the temperature controller for the compartment excluded the defrosting period, and the average run percentage of the compressor is 69%. The 24h energy consumption is 1.62kWh. The defrosting heater capacity is about 205W and operates for 17.8 minutes as shown in Figure 6. Like the defrost control for VF R-600a HRF, there is a deep-cooling function from point p to q in Figure 6 before the action of defrost heater noted as point q. After turning off of the defrost heater, the system waits for 9 minutes to ensure the water on the evaporator surface dropping off. The total energy from the deep-cooling action to the recovery of the system takes 1.67hr with the evaluated energy consumption of 228.4Wh. The energy consumption under a stable cycle of the normal operation is about 110.9Wh in the same time period. The energy consumption during the defrost heating and recovery period is twice as high as the normal operation in the same time. It comes the same conclusion exposed in the previous paragraph and can be another issue to improve the defrosting efficiency to reduce the necessary power input by the defrost heater.

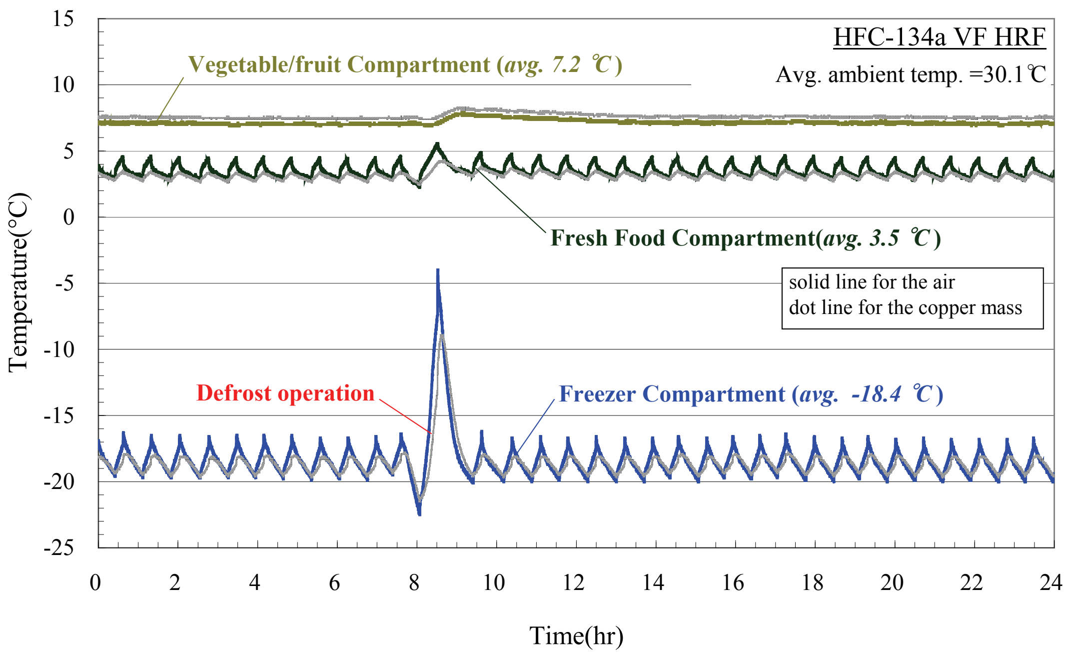


Figure 5: Compartment temperature variations of HFC-134a VF HRF during a 24-hour period.

As shown in Figure 6, there are three control modes for the run speed of the compressor under normal operation, presented in power as 95W, 82W, and 0W(the compressor stops). For the deep-cooling or quick-freezing control function, the compressor can run highly to 210W with over 8 speeds to compensate the necessary thermostat.

The specification and some results of the studied HRFs are indicated in Table 1 to distinguish the effect of refrigerants and control technologies of the compressor. Although the PU foaming agent for the HFC-134a FF HRF is HCFC-14b, the thermal conductivity of CP PU is about 10% higher than that of HCFC-141b in this study. For the same refrigerant HC R-600a, VF type consumes electric energy of 1.426kWh/day as low than that of FF type by 0.59kWh/day at ambient temperature of 30°C. For refrigerant HFC-134a, the electric energy consumption of VF type is 1.620 kWh/day with an efficient potential of 28.16% based on FF type. As comparing between R-600a and HFC-134a, the daily electric consumption of R-600a VF HRF is lower than that of HFC-134a VF type by 13.6%. For FF type, R-600a HRF is efficient than HFC-134a HRF by 10.6%. Another information of Table 1 is the temperature variation for each compartment of specified HRF. As the refrigeration system driven by a VF DC compressor, the temperature variation is below 1°C for the freezer compartment, and below 2.8°C for the fresh foot compartment. The percentage operating time of the compressor is evaluated from the running period dividing by the period of one operation cycle, excluded the defrosting period. As indicated in the previous paragraph, the running power of the R-600a VF HRF is normally lower than that of the others. To maintain the prescribed thermostat, the running percentage of the VF compressor is as high as to over 90%, due to the methodology of the VF controller to prevent high temperature of compressor discharge line especially for combustible refrigerant HC R-600a. Anyway, among the comparison between the refrigerants R-600a vs. HFC-134a and VF vs. FF, all the results for efficiency improvement of HRFs conducts the similar conclusion in the surveyed literature.

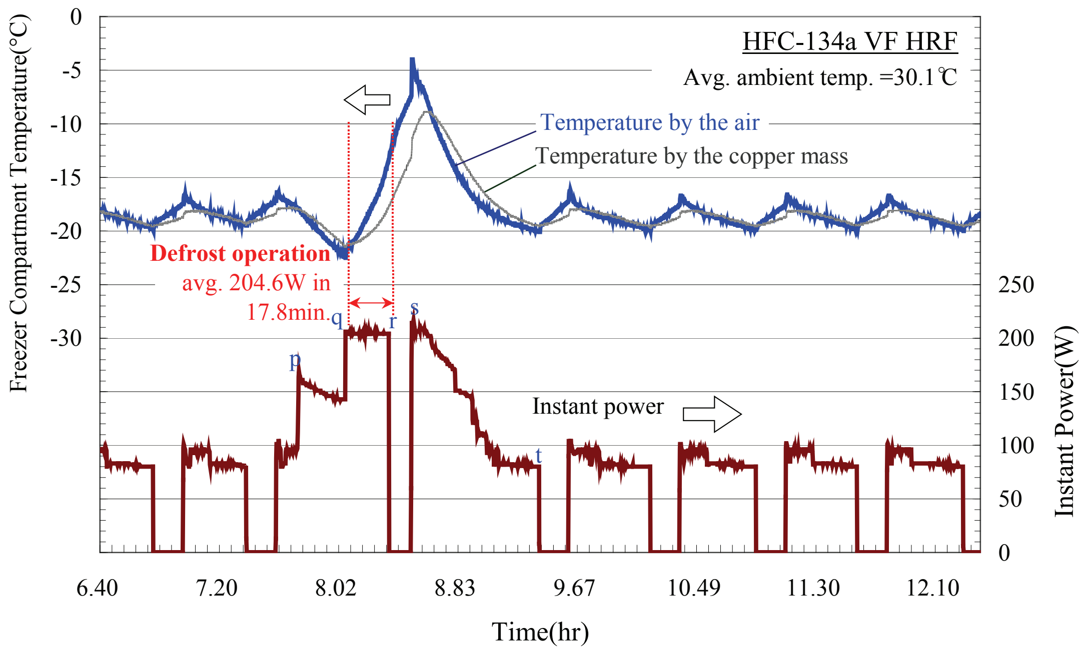


Figure 6: Temperature and power variations of HFC-134a VF HRF during a defrost period.

4. CONCLUSIONS

In recent years, the cost for digital signal processing micro-controller has been gradually dropping and gaining market competitive advantage. Therefore, home appliances can realize the idea of digital control. With the same mechanical and electrical configuration, many complicated control methods only need to expand software program and memory to process peripheral signals or drive key components in appliances, such as BLDC motor in compressor, fan motor and electric heater, so the need of optimization can be satisfied. Even by software upgrade, the newest control program can be copied to appliance through communication port. Consumers can enjoy updated and more convenient services. Development for inverter-controlled refrigerator can be considered as a revolutionary advancement for white appliances. It not only operates with lower noise, stable storage temperatures, fast freezing, freshness preservation and energy saving. Variable frequency control technology even makes truth for the smart refrigerators/freezers. It adjusts compressor speed and puts control over other components according to various conditions. A variable frequency refrigerator/freezer needs some proper control methods to obtain good performance. It also needs integration among all components to achieve optimization in speed and temperature control under different input conditions.

This paper introduced some benefits of inverter-controlled refrigerators/freezers and also described some implementation experience from the performance tests and their illustration of VF HRFs using refrigerants HC R-600a and HFC-134a. Some quantity results of the studied HRFs were described for the no-load pull-down test and the energy consumption test with closed door of 24h. The thermal characteristics of the HRF compartments were explored by the time-variant temperature profiles to describe the control capability of the VF refrigeration system. The advantage of DC compressors can be explored from the comparison of the refrigeration capacity with excellent efficiency over large application range by contrast with the AC compressor. As implementation for an inverter-controlled HRF, the energy efficiency of the VF HRF is higher than that of the FF type by up to 35%. The thermal stability is another advantage for the development of VF HRFs confirmed from the performance testing results in this study. The temperature variation of the refrigeration and freezing compartments are all reduced obviously for the change from the FF HRF to the VF type. The running percentage of the compressors was also evaluated and the larger of this running percentage will increase the energy efficiency for the brush-less DC compressor. As comparing with the refrigerants in HRF, HC R-600a improves the efficiency by 10 to 15% than that of HFC-134a system. Finally, for the pull-down test of the HRFs, the discharge temperature of the R-600a compressor is much lower than that of HFC-134a under the same ambient condition, and the suction temperature behaved with near the same magnitude.

REFERENCES

Akash BA, Said SA, Assessment of LPG as a possible alternative to R-12 in domestic refrigerators, Energy Conversion and Management, 44(3): 381-388, 2003.

Alsaad MA, Hammad MA, The application of propane/butane mixture for domestic refrigerators, Applied Thermal Engineering, 18(9-10):911-918, 1998.

ANSI/AHAM HRF-1-2007, American National Standard Household Refrigerators/Household Freezers, April 7, 2007.

Chang W.R., Liu D.Y., Chen S.G., and Wu N.Y., The Components And Control Methods for Implementation of Inverter-Controlled Refrigerators/ Freezers, International Refrigeration and Air Conditioning Conference at Purdue, R002, Page 1, July 12-15, 2004.

Chang W.R., Liu D.Y., Lin J.Y., and Chang Y.C., Implementation for Inverter Controlled Domestic Refrigerator/Freezer with Brushless DC Reciprocating Compressor, London Compressor Conference, London, Sep. 4-7, 2005, UK.

Chang W.R., Study on the Latest Regulation of Energy Efficiency for Household Refrigerators/Freezers, HVAC & Heat Exchange(published by EEL/ITRI, Taiwan), Jan., p.12-21, 2008(in Chinese).

CNS 2062, National Bureau of Standards: Chinese National Standard. Electric refrigerators and freezers, General No. CNS 2062, Classified No. C4084, 2001.

Granryd E., Hydrocarbons as refrigerants— an overview, Int. J. Refrigeration, 24(1):15-24, 2001.

Hammad MA, Alsaad MA, The use of hydrocarbon mixtures as refrigerants in domestic refrigerators, Applied Thermal Engineering, 19(11):1181-1189, 1999.

Huang C.H., Study on Revision Trend of Local Standard on Refrigerator Energy Factor, Seminar on Variable Frequency Refrigerator Technology, ITRI, Taiwan, 2005(in Chinese).

James RW, Missenden JF, The use of propane in domestic refrigerators, Int. J. Refrigeration, 15(2): 95-100, 1992.

Liu D.Y., Chang W.R., and Lin J.Y., Performance comparison with effect of door opening on variable and fixed frequency refrigerators/freezers, Applied Thermal Engineering, Vol: 24, Issue: 14-15, pp. 2281-2292, October, 2004.

Richardson R.N, Butterworth JS, The performance of propane/isobutane mixtures in a vapour-compression refrigeration system, Int. J. Refrigeration, 18(11):58-62, 1995.

Sekhar SJ, Lal DM, Renganarayanan S, Improved energy efficiency for CFC domestic refrigerators retrofitted with ozone-friendly HFC134a/HC refrigerant mixture, Int J. Thermal Sciences, 43(3):307-314, 2004.

Tashtoush B., Tahat M, Shudeifat MA, Experimental study of new refrigerant mixtures to replace R12 in domestic refrigerators, Appl. Thermal Eng., 22(5): 495-506, 2002.

Wongwises S, Chimres N, Experimental study of hydrocarbon mixtures to replace HFC-134a in a domestic refrigerator, Energy Conversion and Management, 46(1):85-100, 2005.

ACKNOWLEDGEMENT

The authors would like to thank the Bureau of Energy, Ministry of Economic Affairs, Taiwan, Republic of China, for the support of this study under the Energy R&D funding.