Journal of Engineering and Applied Sciences 8 (6): 192-197, 2013
ISSN: 1816-949X

Investigation of Effect of Phase Change Material on Compressor On/Off Cycling of a Household Refrigerator

Md. Imran Hossen Khan and Hasan M.M. Afroz
Department of Mechanical Engineering,
Dhaka University of Engineering and Technology (DUET),
Gazipur, 1700 Gazipur, Bangladesh

Abstract: Effects of Phase Change Material (PCM) on compressor on/off cycle of a household refrigerator have been investigated experimentally. PCMs are used behind the five sides of the evaporator cabinet and the evaporator coil is immersed in the PCM. Three types of PCMs at different thermal loads have been used for the investigation. Experimental results for the system with PCM show that the number of compressor on/off cycle within the tested time is reduced significantly. Depending on the types of PCM, the number of compressor on/off cycle for the system with PCM is around 3-5 times lower than that of the system without PCM. This reduction of compressor on/off cycle ultimately reduces the efficiency losses of the system as compared to a conventional refrigeration system. The experimental results with PCM also confirm that average compressor running time per cycle is reduced significantly and it is found about 2-36% as compared to without PCM.

Key words: Phase change material, household refrigerator, compressor, on/off cycle, energy loss

INTRODUCTION

The on/off mode is the method of control usually applied in domestic refrigeration equipment. This method of operation introduces cycling losses, the magnitude of which depends on a large number of parameters, such as the on/off cycle length. However, this on/off cycling causes refrigerant displacements within the cooling system that affects the overall performance. There are two types of losses caused by the on/off cycling. Firstly, during the on-period (time period in the on/off cycle when the compressor is on) the thermal load of the heat exchangers is higher than it would be for a continuously controlled system (variable speed compressor). This lowers the thermodynamic efficiency through increased temperature lift. Secondly, there are losses due to refrigerant displacements following a compressor start and stop. Moreover, the losses may be quantified in terms of capacity or efficiency. In total, efficiency losses of 5-37% are reported Coulter and Bullard (1997), Jakobsen (1995) and Janssen *et al.* (1992). During the on/off cycle Bjork and Palm (2006), experimentally found four types of losses occurring in a refrigeration system. The first loss is the refrigerant pulled out from evaporator as liquid during start-up, created during the first 20-30 sec after a compressor start-up. Due to this reason, the calculated cooling loss (cooling that occurs outside the refrigerated space) is 1.7 kJ $cycle^{-1}$ which translates in to a capacity loss of 2.3%. Since, the compressor run-time will increase at approximately the same degree, the efficiency loss is also approximately 2.3%. The second loss, due to refrigerant vapor pumped through the capillary tube before a liquid seal is formed at start-up. Saturated refrigerant enters the evaporator about 20 sec after a compressor start-up. It is assumed that before this moment only superheated gas passes through the capillary tube and the mass was assumed to 1.0 g (compressible flow through the capillary tube with choked outlet). The loss becomes 0.3 kJ $cycle^{-1}$ which translates in to a capacity and efficiency loss of approximately 0.4%. The third loss is caused by improperly charged heat exchangers during the on period that cause an unnecessarily high temperature lift. During on-period time averaged temperature difference was found to be 1°C at the evaporator side and 0.2°C at the condenser side. Thus, the redistribution process added a temperature lift of 1.2°C for the on-period. Finally, from inspection of compressor data the capacity loss was estimated to 6% and the efficiency loss to 3.6%. The fourth loss is caused by vapor entering the evaporator through the capillary tube during the off-period. This migration process can be subdivided in two parts, the first as long as a liquid seal is sustained at the capillary tube inlet (7.5 g, 0-80 sec), the second as the liquid seal is broken (2 g, 80-180 sec). The

Corresponding Author: Md. Imran Hossen Khan, Department of Mechanical Engineering, Dhaka University of Engineering and Technology (DUET), Gazipur, 1700 Gazipur, Bangladesh

loss becomes 1.8 kJ $cycle^{-1}$ which translates into a capacity and efficiency loss of approximately 2.4%. In total, the estimated loss of efficiency of the system is 9% and the capacity loss is 11. Moreover, higher number of on/off cycling also damage the compressor life. So, on/off cycle per specified time reduction is one of the most important works for today's refrigeration and air conditioning system. Wang and Wu (1990) determined experimentally that the addition of a shut-off valve to prevent off-cycle migration reduced the overall energy use of a small air conditioner by 4%. The only research found that experimentally investigated, the quantity of charge in different parts of a domestic freezer was carried out by Kuijpers *et al*. (1988). By weighing the heat exchangers they measured the quantity of charge in the evaporator and condenser. However, they only considered steady state conditions. For a domestic refrigerator, Bjork *et al*. (2002) measured the quantity of charge in different parts of the system of a domestic refrigerator at cyclic conditions by using quick-closing valves. Using Phase Change Material (PCM) as a latent heat thermal energy storage system could be a new option of reducing the number of on/off cycle of a household refrigerator by enhancing heat transfer of the evaporator. Azzouz *et al*. (2005) developed a dynamic model of the vapor compression cycle, including the presence of the phase change material and showed its experimental validation. The simulation results of the system with PCM show that the addition of thermal inertia globally enhances heat transfer from the evaporator and allows a higher evaporating temperature which increases the energy efficiency of the system. The energy stored in the PCM is yielded to the refrigerator cell during the off cycle and allows for several hours of continuous operation without power supply. Azzouz *et al*. (2008) enhance the performance of a household refrigerator by addition of latent heat storage and make a dynamic model for reducing the number of on/off cycles.

Most of the investigations cited above were focused on the mass charge of the refrigerant, heat transfer in the latent heat storage system. There are only few studies that have been reported in the literature on the behavior of a refrigerator coupled with a phase change material applied on the entire area of the evaporator. The purpose of this study is to propose a new option for reducing on/off cycling of a household refrigerator using a PCM storage system and to reduce energy losses.

MATERIALS AND METHODS

A conventional household refrigerator is used in the modified form with PCM box located behind the evaporator cabinet to carry out the necessary experiments. The experimental set up comprised with a refrigerator, pressure transducer, pressure gauge, thermocouple, phase change material box and data acquisition system. Figure 1 and 2 show the details of the location of the PCM box with the evaporator cabinet. The PCM box is made up by Galvanized Iron (GI) sheet have 1 mm thickness which is 0.56 m width, 0.44 m height and 0.47 m depth. The evaporator cabinet box of outer volume 0.04 m^3 with cooling coil (Fig. 1a) is inserted into the empty PCM box of internal volume 0.11 m^3 (Fig. 1b). The

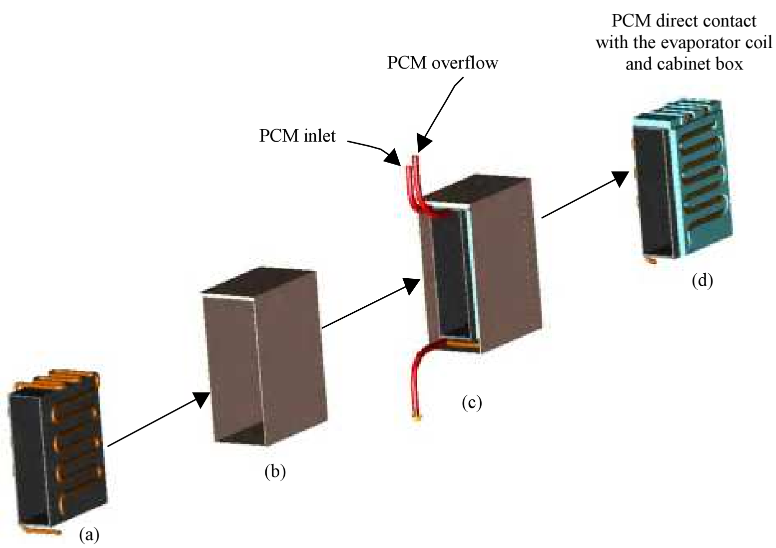

Fig. 1: The arrangement of the PCM based evaporator: a) Evaporator cabinet with coil; b) Empty PCM box; c) Evaporator box inserted into the PCM box; d) Shape of solid PCM after phase change (liquid tosolid)

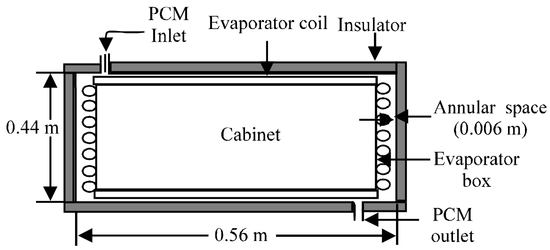

Fig. 2: Front view of the evaporator cabinet with PCM box

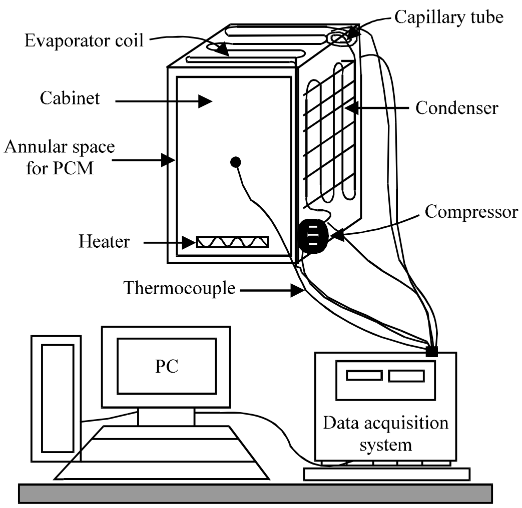

Fig. 3: Schematic diagram of the experimental set-up

thickness of the annular space between PCM box and evaporator cabinet box is 0.006 m. The open face of the annular space is sealed by a third sheet metal. The two copper tubes are attached with the top of the annular space for PCM supply in the box and to maintain the overflow. Another tube is attached in the bottom of the annular space to discharge the PCM if necessary. Figure 3 shows the schematic diagram of the experimental set-up and Fig. 4 shows details circuitry of the setup. The modified PCM based refrigerator has a single evaporator cabinet with a single door. The followings are the major technical specifications of the refrigerator:

- Cabinet: Internal volume, 0.03 m^3
- Evaporator: Mode of heat transfer-free convection, linear length of the coil/tube: 12.2 m, internal and external diameter of the tube : 0.0762 and 0.0772 m, respectively; material of the coil/tube, copper tube
- Condenser: Mode of heat transfer-free convection, linear length of the coil/tube: 5.8 m, internal and external diameter of the tube: 0.003 and 0.004 m, respectively; material of the coil/tube: Steel and wire tube
- Compressor: Hermetic reciprocating compressor, HITACHI FL 1052-SK, 13 FL 220-240 V, 50 Hz

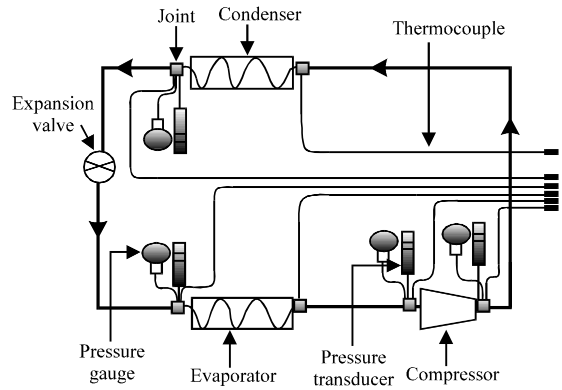

Fig. 4: Location of pressure transducer, pressure gauge and thermocouple

Table 1: List of Phase Change Material (PCM) used in this experiment

PCMs	Melting temperature (M_T) (°C)	Latent heat of fusion (kJ kg^{-1})
Distilled water (H_2O)	0	333
Eutectic solutions-1 (90% H_2O+10% NaCl) (wt.%)	-5	289
Eutectic solutions-2 (80% H_2O+20% KCl) (wt.%)	-10	284

- Expansion device: Capillary tube (internal diameter 1 mm)
- Expansion device: Capillary tube (internal diameter 1 mm)
- On/off control and self defrost
- Refrigerant: 1, 1, 1, 2-tetrafluoroethane (R-134a)

Temperatures at various locations (compressor, condenser, evaporator and cabinet) are measured with K-type (copper-constantan) thermocouples having 0.0005 m diameter as shown in Fig. 4. The 3 thermocouples are also positioned at the bottom, middle and the top of the PCM in the left face of the cabinet to measure the temperatures of PCM. The uncertainty of the temperature measurements by the thermocouples is estimated to be ±2.78% with respect to a high precision (0.002°C) thermometer (Begman thermometer) which can be found in Table 1. Two pressure transducers are used to measure the evaporation and condensation pressures at the inlet and outlet of the compressor. Another pressure transducer is placed at the inlet of the evaporator to measure the pressure drop in the evaporator section. Four pressure gauges are used to cross check the pressure measurements of the pressure transducer and the deviations have been found within ±0.03 kg cm^{-2}. The location of all of the pressure transducers and pressure gauges are shown in Fig. 4. A heater is used in the cabinet to do experiments at different thermal loads. The heater is located at the bottom of the cabinet box which is linked with a variable voltage transformer (variac) to control the supply voltage for required thermal load variation into the

Table 2: Estimated uncertainties of measurement

Measured parameter	Measuring device	Uncertainty
Temperature	Thermocouples	±2.78%
Pressure	Pressure transducer	±0.01bar
Pressure	Pressure gauge	±0.03 kg cm^{-2}

Table 3: Experimental conditions

Types of PCM	Quantity of PCM (m^3)	Test time (min)	Thermal load (Watt)	Ambient temp. (°C)	Cabinet setting temp. (°C)
Without PCM[2]	-	121	0, 5, 10, 20	22.8-23.8	-5
Water	0.003, 0.00425	121	0, 5, 10, 20	22.8-23.8	-5
Eutectic-1	0.003, 0.00425	121	0, 5, 10, 20	22.8-23.8	-5
Eutectic-2	0.003, 0.00425	121	0, 5, 10, 20	22.8-23.8	-5

cabinet. A K-type thermocouple is used for the measurement of the air temperature within the cabinet which is located at the center of the cabinet space. A thermostat is used to drive the compressor cycling; the thermocouple of the thermostat is located at the centre of the cabinet. The experimental set-up is equipped with a data acquisition system linked to a personal computer which allows a high sampling rate and the monitoring of all the measurements made by means of the thermocouples. The experiments have been carried out in a room where the temperature and humidity are maintained constant with the aid of air conditioner. All the data have been collected from the data acquisition system after ensuring the steady state condition of the refrigerator. To obtain the steady state condition the system is allowed to run for several minutes (about 70 min).

Three types of PCMs are used in this experiment. Table 2 shows their melting temperature and latent heat of fusion.

Experimental conditions: Experiments were carried out under four different thermal loads with three different PCMs of different quantities. Table 3 shows the details of the experimental conditions.

RESULTS AND DISCUSSION

The effects of different PCMs of different quantities at different thermal loads on the performance parameter of house hold refrigerator are given as:

Effect of different types and quantity PCMs on compressor on/off cycle: Figure 5 shows time versus compressor outlet temperature for different PCMs at different thermal load from which the number of compressor on/off cycle within a certain period of time for different PCMs and without PCM can be pointed up. In Fig. 5, the point where the compressor outlet temperature just start to decrease from its peak is identified as the moment of compressor just off and the point where the compressor outlet temperature just start to increase from its lower value is recognized as the moment of compressor just on. The following results can be drawn from these figures:

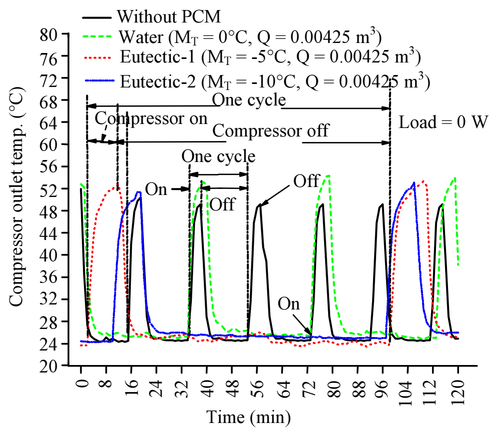

Fig. 5: The effect of PCM on compressor on/off cycling (L = 0 W, Q = 0.00425 m^3)

- Using PCM the number of compressor on/off cycle within certain period of time is reduced significantly compare to without PCM
- Depending on the types of PCM and thermal load the number of compressor on/off cycle is around 3-5 times lower than that of without PCM
- Among the different PCMs the reduction of the number of on/off cycles in comparison with no PCM maintain the sequence as Eutectctic-1 is higher than Eutectic-2 than water

The compressor on/off mode is triggered by the thermostat which is located in the evaporator compartment. The thermostat setting point has been adjusted so that it starts the compressor at -3.9°C and stops at -5°C. This adjustment is to keep the evaporator cabinet temperature around -5°C. In case of without PCM, during compressor off mode the cabinet temperature rises quickly due to the heat released by the internal thermal load and intake heat from the surroundings. As a result, the thermostat triggers the compressor in on mode quickly. On the other hand when PCM is used this excessive heat is absorbed by PCM due to its phase change nature (solid to liquid) which does not allow the compartment temperature rise quickly. A low enough temperature near to the desired point inside the cabinet is maintained during the whole melting period of PCM and the compressor is not triggered in on mode quickly by the thermostat. As a result, a prolonged off mode of compressor is obtained. This longer off mode of compressor ultimately reduces the number of on/off cycle significantly for a certain period of time.

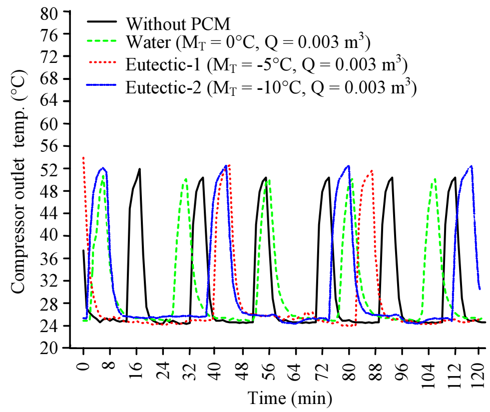

Fig. 6: The effect of PCM on compressor on/off cycling (L = 0 W, Q = 0.003 m^3)

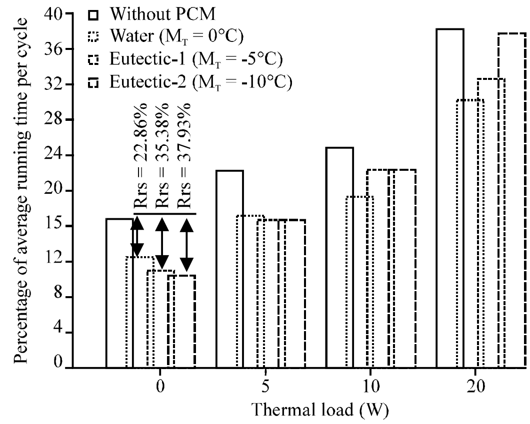

Fig. 7: The Effect of PCM on compressor running time at different loads (Q = 0.00425 m^3)

A PCM gives better performance for a house hold refrigerator if the melting point of the PCM is equal or greater than the setting temperature of the evaporator chamber and if it has high latent heat of vaporization. Among the three PCMs used in this research, Eutectic-1 aqueous solution shows lesser on/off cycle within a certain period of time because of its better phase change tendency. The melting point of Eutectic-1 is -5°C and setting temperature of the evaporator chamber is also -5°C. As a result, Eutectic-1 has a better phase change tendency. In case of Eutectic-2, the number of on/off cycle is slightly higher than Eutectic-1. In fact, the melting point of Eutectic-2 is -10°C, so its phase change tendency is better than Eutectic-1 but the latent heat of vaporization is slightly lower than Eutectic-1 which ultimately cause a little higher number of on/off cycle for the Eutectic-2. Though, the water has higher latent heat of vaporization, it shows more number of on/off cycle than other two PCMs within a certain period of time because of its poor phase change tendency for the -5°C setting temperature of the cabinet. Actually due to its 0°C melting temperature, it does not participate in the phase change process.

Figure 5 shows the effects of 0.00425 m^{3}of PCM on compressor on/off cycle and Fig. 6 shows the same with 0.003 m^3 of PCM. From Fig. 5 and 6, it can be observed that the off period of compressor with 0.00425 m^3 of PCM is higher than that with 0.003 m^3 of PCM which is simply for the higher total latent heat transfer of higher quantity of PCM. As for example, 0.00425 m^3 of water has a latent heat capacity of 1415.2 kJ while for 0.003 m^3 of water it is 999 kJ.

Effect of PCM on compressor running time at different thermal load: Figure 7 shows percentage of average compressor running time per cycle at different thermal loads. The followings are the significant findings:

- Average compressor running time per cycle is significantly reduced for the system with PCM in respect to without PCM which ultimately reduce the energy consumption for the system with PCM
- Depending on the thermal load and the types of PCM the reduction of average compressor running time per cycle is found about 2-38% as compared to without PCM
- Among the three PCM, the percentage of compressor running time with PCM in comparison with no PCM maintain the sequence as Eutectic-2>Eutectic-1>water at low load condition. In case of higher load, this sequence is changed and maintain the reverse sequence, i.e., Eutectic-2<Eutectic-1<water

At lower thermal load (0-5 W) the relative compressor running time savings (Rrs) for Eutectic-2 is better as compared to another two PCMs, this is because of their higher melting point (-10°C) which enhanced higher heat transfer rate and ultimately prolonged the off cycle of the compressor as compared to on cycle. As a result, percentage of running time reduced. In case of water at zero load, it is does not participate any phase change process because of its lower melting temperature (0°C) which ultimately reduces off cycle as compared to on cycle, as a result increase the percentage of running time.

At higher thermal load this phenomena is completely changed where water shows better performance than other two PCMs. At high thermal load of the cabinet some heat is extracted by solid water PCM during the compressor on mode and participate in phase change partially before reaching the thermostat setting temperature (-5°C). As a result, due to higher latent heat of vaporization of water, it shows better performance as compared to another two PCMs.

CONCLUSION

Experimental tests have been carried out to investigate the performance improvement of a household refrigerator using three different phase change materials of different quantities at different thermal loads. With PCM, the number of compressor on/off cycle within certain period is reduced significantly compare to without PCM. Depending on the types of PCM the number of compressor on/off cycle is around 3-5 times lower than that of without PCM. Among the different PCMs, the reduction of the number of on/off cycles in comparison with no PCM maintain the sequence as Eutectic-1>Eutectic-2>water. At low thermal load the reduction of the number of compressor on/off cycle for different PCMs with respect to without PCM is higher than that of the high thermal load. Reduction of compressor on/off cycle ultimately reduces the system losses due to on/off cycling which is about 9-11% (as reported in many literatures) and increases compressor life as compared to a conventional refrigeration system. Depending on the thermal load and the types of PCM average compressor running time per cycle is reduced significantly and it is found about 2-38% as compared to without PCM.

NOMENCLATURE

Enthalpy (h)	=	$kJ\ kg^{-1}$
Load (L)	=	Watt
Melting temperature (M_T)	=	°C
Pressure (P)	=	bar
Phase Change Material (PCM)		
Quantity of PCM (Q)	=	Liter
Cooling effect (q)	=	$kJ\ kg^{-1}$
Refrigerant (R)		
Temperature (T)	=	°C
Relative running time saving	=	Rrs

REFERENCES

Azzouz, K., D. Leducq, J. Guilpart and D. Gobin, 2005. Improving the energy efficiency of a vapor compression system using a phase change material. Proceedings of the 2nd Conference on Phase Change Material and Slurry, June 15-17, 2005, Yverdon-les-Bains, Switzerland -.

Azzouz, K., D. Leducq and D. Gobin, 2008. Performance enhancement of a household refrigerator by addition of latent heat storage. Int. J. Refrig., 31: 892-901.

Bjork, E., A. Rucker, A. Phudungsilp, E. Isgren and S. Nozadze, 2002. Charge distribution in a domestic refrigerator. Proceedings of the Joint Meeting of the IIR, Section B and E On Zero Leakage–Minimum Charge, Efficient Systems for Refrigeration, Air Conditioning and Heat Pumps, August 26-28, 2002, Stockholm, Sweden -.

Bjork, E. and B. Palm, 2006. Refrigerant mass charge distribution in a domestic refrigerator, part I: Transient conditions. Applied Thermal Eng., 26: 829-837.

Coulter, W.H. and C.W. Bullard, 1997. An experimental analysis of cycling losses in domestic refrigerator-freezers. ASHRAE Trans., 103: 587-596.

Jakobsen, A., 1995. Energy optimization of refrigeration systems: The domestic refrigerator: A case study. Ph.D. Thesis, Refrigeration Laboratory, The Technical University of Denmark.

Janssen, M.J.P., J.A. de Witt and L.J.M. Kuijpers, 1992. Cycling losses in domestic appliances: An experimental and theoretical analysis. Int. J. Refrig., 15: 152-158.

Kuijpers, L.J.M., M.J.P. Janssen and P.J.M. Verboven, 1988. The influence of the refrigerant charge on the functioning of small refrigerating appliances. ASHRAE Trans., 94: 813-828.

Wang, J. and Y. Wu, 1990. Start-up and shut-down operation in a reciprocating compressor refrigeration system with capillary tubes. Int. J. Refrig., 13: 187-190.