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ENERGY EFFICIENT DOMESTICREFRIGERATOR-FREEZERS – A REVIEW

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ABSTRACT—*Domestic refrigerators are now ubiquitous. They have become an integral part of our living. Almost every household in developed countries uses a domestic refrigerator today. On the other handuse of refrigerators in households in developing countries is expected to grow at the rate of 10% to 15% per year for the next few years, increase in efficiency of refrigerator means a considerable amount of energy saving and consequent reduction in greenhouse gasses. The objective of this paper is to review work done on energy-efficient technologies for domestic refrigerator/freezer system. This review is limited to a handful of research papers and only prominent technological innovations have been discussed. Apart from these innovations, some more alternatives are available that can help in improving the efficiency of a domestic refrigerator/freezer unit. A more comprehensive review in this area is needed.*

While each technological innovation increases the cost of the refrigerator/freezer unit, there are some that have the promise of improving the efficiency of the refrigerator/freezer unit with little increase in cost. Apart from an increase in unit hardware cost, technological changes also increase the system's complexity and reduce its reliability, which in turn further increase the cost of the system. Therefore, future work shall analyze the cost-effectiveness and reliability of the design options suggested so that the energy-efficient technologies can be successfully incorporated in future refrigerator/freezer units.

KEYWORDS-*Dual-Cycle, Alternating Evaporator Duty (AED) Cycle, Tandem System, Lorentz-Meutzner Cycle, Suction-Line Heat Exchanger, Energy-Saving Valve, Subcooling, High-Efficiency Compressor.*

1. INTRODUCTION

Domestic refrigerator-freezers used primarily for food preservation are an important end-user of electricity. Approximately 58 million new units are manufactured worldwide each year and hundreds of millions are currently in use [1]. It is anticipated that the production of refrigerator-freezers will substantially increase in the near future as a result of increased demand, especially in developing countries, where growth is expected to be of the order of 10% to 15% per year for the next few years.

Domestic refrigerators contribute to greenhouse gases in two ways. First, indirectly by the use of electrical energy, they lead to the generation of carbon dioxide as most of the electrical energy even today is being produced in power plants based on fossil fuels such as coal and gas and secondly by the release of refrigerants in the environment during the production, operation and maintenance of refrigerators. For domestic refrigerator-freezers operating on alternative refrigerants such as R-134a, the indirect contribution to global warming potential resulting from the energy consumption of the unit is approximately 100 times greater than the direct contribution of the refrigerant alone.

Therefore, in response to global concerns over greenhouse gases, efforts are being made to produce refrigerator-freezers with low energy consumption [2]

2. DUAL-CYCLE

In most domestic refrigerators, refrigeration for fresh food and freezer compartments is cooled by a single vapour-compression cycle that operates at freezer evaporating saturation temperature. The coefficient of performance (COP) of the vapour-compression cycle decreases with evaporator temperature. Therefore, the overall performance of a single vapour-compression cycle based refrigerator is reduced because the coefficient of performance (COP) at the freezer temperature is lower than that for refrigeration at the fresh food evaporator conditions. For this reason, some energy savings can be expected if two separate vapour-compression cycles are employed to meet the cooling loads of freezer and fresh food compartment separately.

Gan A.I. et al. [3] have investigated the benefits of using two separate refrigeration cycles to meet demands for both freezer and fresh food compartments in domestic refrigerators. Their analysis is based on mathematical formulation of a parameter called power difference ration (DR), which is a function of the cabinet load ratio (LR - defined as the ratio of the fresh food load to the freezer cabinet load) and the COP ratio (CR – defined as ratio of the freezer and refrigerator cycle COPs). A graph of DR for a wide range of values of LR and CR was plotted and it was concluded from the graph that depending on the values of LR and CR, the energy requirement for a dual-cycle system can be up to 30% (maximum) lower than that for a comparable single-cycle system meeting the same cabinet loads.

Won, S. et al. [4] modified an existing household refrigerator-freezer system into a dual-loop system. Additional insulation between refrigerator and freezer compartments reduced the amount of heat transfer between the two compartments. A number ofother modifications in compressor, condenser and evaporator f the existing system were also made as per the requirements of the dual-loop system. R-12 was used as the refrigerant in the modified system. A 4.3% reduction in the overall energy consumption was obtained in the modified system without taking into account reduction in the defrost load due to the dual-loop system. They found that, if the smaller compressors used in the dual-loop system were equally efficient a total energy saving of 20% could be achieved.

The dual-cycle system also offers the advantages of reduced defrost, ability to maintain higher humidity conditions in the fresh food compartment and separate temperature control for each compartment.

Disadvantages of dual-cycle are additional hardware requirements and they score low on capital cost and space when compared with the single-cycle refrigeration system.

3. ALTERNATING EVAPORATOR DUTY (AED) CYCLE

The alternating evaporator duty cycle refrigerator, like the dual-cycle system, has two vapour compression refrigeration loops. However, unlike the dual-cycle system, the two loops in AED share a common compressor, condenser, and suction line heat exchanger. Each of the refrigeration loops has an expansion device and evaporator. One evaporator is located in the fresh food compartment and the other is located in the freezer compartment. A bistable solenoid valve directs the flow of the refrigerant through one loop at a time. Only one of the two compartments is cooled at any given time. With this configuration, the food compartment is cooled at a higher evaporator temperature than the freezer. Consequently, due to improvement in COP, the energy efficiency of the refrigerator improves over conventional domestic refrigerator/freezer.

Lavanis M. et al. [5] simulated the AED cycle and two-evaporator-in-series cycle on computer. Both the models were simulated for steady-state - they did not account for the transient effects during pull-down or cycling. Isobutane was the only refrigerant used in this investigation. It was found that the total energy consumption of the AED cycle was 12.3% less than that of the series cycle for identical conditions of condenser pressure, subcooling, evaporator superheat, compressor isentropic efficiency, load etc. This cycle also allows for completely independent temperature control of the freezer and fresh food compartments.

For an AED cycle, it is not possible to optimize both the freezer and the food compartment loops at the same time. Hence, this cycle is not as efficient as a conventional dual-cycle using a compressor of the same size. However, due to the reduced load on each compressor, the conventional dual-cycle would use smaller compressors, which have lower efficiency.

4. LORENTZ-MEUTZNER CYCLE

As per the thermodynamic analysis, the Lorenz-Meutzner cycle having a zeotropic refrigerant mixture shows better performance than the systems working with pure refrigerants based on reverse Rankine cycle working with [6, 7, 8, 9].

Zhou Q. et al. [10] conducted a study on a modified Lorenz-Meutzner cycle. The mixture tests were conducted with an undisclosed mixture. A 16.5% reduction in daily energy consumption was achieved compared to the thick-insulation system with the high-efficiency compressor.

Jung and Radermacher [9] studied the performance of two-evaporator refrigerators through computer simulation for pure and mixed refrigerants working on a Lorentz-Meutzner cycle. They observed that for pure fluids, performance of two evaporator systems improve by about 6% and for mixtures such as R22-R123 and R32-R142bperformance of two evaporator systems may improve by about to 18%.

5. INCREASING INSULATION

Improved insulation leads to proportionate saving in electrical energy. Pedersen et al. [11] concluded that the amount of heat flux is decreased by 40% when the insulation thickness is increased by 1 to 1.5 inches.

Zhou Q. et al. [10] compared two refrigerator/freezers with different insulation thickness and the same usable volume under AHAM [12] conditions. Their tests showed a 26% saving in energy consumption.

Vineyard E.A. et al. [13] performed energy consumption tests to determine the cabinet heat load. It was observed that the power was reduced by 8% by the addition of insulation to the cabinet exterior. The result was obtained by modelling simulation and corroborated by conducting tests on laboratory prototype incorporating the above improvement.

However, the drawback of this approach is a decrease in the ratio of useful volume (inside volume of the freezer and fresh food compartment) to used volume (outside volume of the refrigerator/freezer).

The alternative to using thicker insulation is to use better insulation material. The results are indicative of what is technically achievable given new technologies, such as vacuum insulation, which are on the horizon.

It is noted, however, that new insulations are unproven in terms of long-term reliability and heat transfer degradation over time. Therefore, these two factors must be addressed while evaluating new technologies.

Insulation improvements also require refrigeration systems with smaller capacity compressors to achieve a balance between thermal load and refrigerating capacity. Since the efficiency of refrigerator-freezer compressors tends to fall off sharply at lower capacities, eventually there will be an optimum beyond which insulation improvements will result in higher energy consumption. Therefore,a further increase in insulation will depend on the efficiency of small capacity compressors.

Energy savings up to 20.4% are achievable by using vacuum insulation panels [18] and up to 25% by way of improved insulation[19, 20]. Advanced vacuum insulation panels having thermal conductivity as low as 9.6 x 10-3 W/m K have been designed. HFC foams with high global warming potential may be replaced by newer insulations such as R744 and HFO-1234ze [21], HBA-2 [22], AFA-L1 [23] and FEA-1100 [24].

6. SUCTION-LINE HEAT EXCHANGER

The primary function of the suction-line heat exchanger is to ensure that refrigerant entering the compressor is fully vaporized. However, suction-line heat exchanger also affects system performance.

The effect of a suction-line heat exchanger on steady-state performance of a refrigeration cycle (neglecting the effects of pressure losses) can be quantified in terms of relative capacity index, Klein et al. [14]. They used a mathematical formulation to evaluate the performance of a dual-cycle refrigeration system using refrigerant R-134a in both cycles with suction-line heat exchangers of effectiveness = 1 and zero pressure loss. For typical domestic refrigerator applications, the suction-line heat exchanger on the freezer cycle was found to reduce the required compressor work by as much as 8%, whereas the suction-line heat exchanger for the fresh food cycle was found to reduce the required compressor work by 4%.

Vineyard E.A. et al. [13] have reported that by improving suction-line heat transfer by 10%, energy savings of the order of 0.6% energy can be obtained. The result was obtained by modelling simulation and corroborated by conducting tests on laboratory prototype incorporating the above improvement.

The suction-line heat exchangers are inexpensive and easy to implement. They also provide some protection against liquid refrigerant entering the compressor. Implementation of suction-lien heat exchangers is recommended, especially for the freezer cycle.

7. ENERGY-SAVING VALVE

The usefulness of an energy-saving valve can be explained as follows. In systems without such a valve, a large amount of warm refrigerant enters the evaporator during the off-cycle. Therefore, heat is rejected into the freezer through the evaporator. This heat load, which decreases the off-time significantly, is about 2.4 times greater for rotary-compressor systems than for reciprocating compressor systems [15]. The large difference in the potential unwanted heat gain during the off-time explains why standard refrigeration systems with rotary compressors but without such energy-saving valves are not as efficient as systems with reciprocating compressors. The energy-saving valve makes it possible to prevent the flow of refrigerant from the condenser to the evaporator; thereby it reduces the heat rejected to the freezer during the off-cycle. It is more effective for rotary compressor systems. Energy consumption can be reduced by up to 22% (as claimed by the manufacturer) compared to a conventional rotary-compressor system without energy-saving valves [15].

Vineyard E.A. et al. [13] have reported that by using liquid-line shut-off valve, energy savings of the order of 6.7% energy can be obtained. The result was obtained by modelling simulation and corroborated by conducting tests on laboratory prototype incorporating the above improvement.

8. MECHANICAL SUBCOOLING

Direct mechanical subcooling uses a small and separate refrigeration cycle to subcool the refrigerant exiting the compressor. The additional subcooling cycle requires additional power;however this cycle operates at lower temperature lift and therefore has the potential to improve the overall efficiency of the cycle.

It is also possible to use the fresh food compartment to provide indirect subcooling for the freezer cycle. This shifts part of the load from the freezer cycle to the fresh food cycle, which operates at higher COP. Hence this also has a potential of improving the overall efficiency of the dual cycle.

Gan A.I. et al. [3] developed a simulation model to study the performance of refrigerators employing suction-line and indirect mechanical subcooling heat exchangers. Indirect mechanical subcooling was found to enhance the performance of the dual-cycle system by as much as 9%. However, this figure corresponds to a situation with no fresh food cabinet load and no suction-line heat exchanger in the freezer cycle.

The performance improvement corresponding to more typical conditions is about 3%.

Advantages of indirect mechanical subcooling are not substantial.

9. IMPROVED DOOR SEAL

Flynn, Rouch, and Fine [16] studied the leakage through the doors of a refrigerator/freezerusing Finite element analyses. They observed that heat flux entering through the gaskets can be reduced to about 50% by using twin gaskets.

Zhou Q. et al. [10] have observed that 3% to 7% reduction in energy consumption can be obtained by improved door seals.

Vineyard E.A. et al. [13] have reported that by reducing door gasket leaks by 25%, energy savings of the order of 2.8% energy can be obtained. The result was obtained by modelling simulation and corroborated by conducting tests on laboratory prototype incorporating the above improvement.

10. HIGH-EFFICIENCY COMPRESSOR

Using high EER compressors can also save on energy substantially. Energy-saving up to 7% were achieved with the new compressor, whose EER is 12% higher than that of the original [10].

Vineyard E.A. et al. [13] have reported that by using 6.1 EER-rated-speed 134a Compressor, energy savings of the order of 11.2% energy can be obtained. The result was obtained by modelling simulation and corroborated by conducting tests on laboratory prototype incorporating the above improvement.

The cycling losses of the rotary compressor system were also found to be lower than those of the system with the reciprocating compressor when both systems are using an energy-saving valve [10].

Most of the early refrigerator-freezers work on reciprocating compressors which match the thermal load through on-off cycles. However, they incur high cycling losses. Moreover, they have to be designed for peak load. Variable-speed linear compressors (VSLC), variable capacity compressors (VCC) and Variable-speed compressors (VSC) adjust their speed and refrigerant volume flow rate according to the thermal load and run continuously. As a result, the overall efficiency of the system improves due to no cycling losses. Better matching between refrigerant flow rate with thermal load helps restrict unnecessary drop in the evaporator temperature leading to further improvement in the efficiency.

Linear compressors don't have traditional piston and crank mechanism; instead piston is propelled by a linear permanent magnet and a resonant mechanical spring [25]. Frictional losses are significantly lower, and efficiency of the smaller compressors is not affected adversely as the fraction of frictional losses remains low [26-28]. Linear compressor with a capacity modulation from 1000 and 6000 W, can save up to 25% of energy as compared to traditional reciprocating compressors [29].

The oil-free linear compressor can improve energy efficiency of refrigerator-freezers by 30% [30]. Linear compressors use variable voltage power device, which is much cheaper than variable frequency devices [31]. Linear compressors are likely to be in wide use in the near future.

Variable-capacity compressors rely on three control systems, i.e. variable capacity valve, inlet valve and a pressure switch. Each system needs to be synchronised to obtain maximum efficiency. With time subsystems lose synchronisation leading drop in efficiency [32]. It is seen that VCC can improve refrigerator-freezer efficiency by 45% [33].

Variable-speed compressors (VSC) based on inverter technology are already in use in high-end systems.

11. CONCLUSIONS

There are many technologies available to improve the efficiency of a refrigerator/freezer. Apart from the technologies discussed above, it is possible to improve the efficiency of the system also by increasing the condenser and evaporator areas, using high-efficiency condenser and evaporator fans and using low-glide refrigerant mixtures.

While each change increases the cost of the system, there are some that show the promise of improving the efficiency of the system with minimal increase in its cost; such technologies shall be pursued rigorously.

Apart from an increase in unit hardware cost, technological changes also increase system's complexity and reduce its reliability, which in turn further increase the cost of the unit by way of additional service and warranty expenses. Therefore, future work shall analyze the cost-effectiveness and reliability of the design changes suggested so that the energy-efficient technologies can be successfully incorporated in future refrigerator/freezer units.

REFERENCES

[1] United. Nations Environment Programme, Athens, 11 October 1991.

[2] Fischer, S. K., Hughes, P. J., Fairchild, P. D., Kusik, C. L, Dieckmann, J. T., McMahon, E., and Hobday, N., 1991, Energy and global warming impacts of cfc alternative technologies. AFEAS/DOE.

[3] Gan A.I., Klein S.A., and D.T. Reindl. Analysis of refrigeration/freezer appliances having dual refrigeration cycles. *ASHRAE Transactions,* Vol. 106, Part-2, Yr. 2000.

[4] Won S., Jung D., and Radermacher R. 1994. An experiment study of the performance of a dual-loop refrigerator/freezer system. *International Journal of Refrigeration 1994*, Volume 17 Number 6.

[5] Lavanis M., Haider I., and Radermacher R. 1998. Experimental investigation of an alternating evaporator duty refrigerator/freezer. *ASHRAE Transactions*, TO-98-18-1.

[6] Lorentz A., and K. Meutzner. 1975. On application of non-azeotropic two component refrigerators in the domestic refrigerators and home freezers. *XIV International Congress of Refrigeration*, Moscow. Paris: IIR.

[7] Rose R. J., Jung D. S., and Radermacher R. 1992. Testing of domestic two-evaporator refrigerator with zeotropic refrigerant mixtures. *ASHRAE Transactions* 98(2).

[8] Sand J. R., Ries C. K., and Vineyard E.A. 1992. Alternative refrigerants and refrigeration cycles for domestic refrigerators. *ORNL-M2270. Oak Ridge*, TN: Oak Ridge National Laboratory.

[9] Jung D.S. and Radermacher R. 1991. Performance simulation of a two-evaporator refrigerator/freezer charged with pure and mixed refrigerants. *International Journal of Refrigeration 1991,* Volume 14 September.

[10] Zhou Q., Pannock J., and Radermacher R. 1994. Development and testing of a high- efficiency refrigerator. *ASHRAE Transactions* 94-20-3.

[11] Pedersen, P. H., J. Schjaer-Jacobsen, and J. Norgard. 1986. Reducing electricity consumption in American type combined refrigerator/freezer. *37th Annual International Appliance Technical Conference*, Purdue University, May.

[12] AHAM, 1985. *American national standard for household refrigerators/household freezers*. Chicago: Association of Home Appliance Manufacturers.

[13] Vineyard E.A., Sand J. R., and Bohman R. H. 1995. Evaluation of design options for improving the energy efficiency of an environmentally safe domestic refrigerator-freezer. *ASHRAE Transactions*, CH-95-24-2.

[14] Klein S.A., D.T. Reindl, and K.A. Brownell. 2000. Refrigeration system performance using liquid-suction heat exchangers. *International Journal of Refrigeration*, Vol. 23, Issue 8, December 2000.

[15] Okazaki M. 1992. Energy-saving valve for refrigerator. *Matsushita Refrigeration Company*, August.

[16] Flynn, S., K. Rouch, and H. A. Fine. 1992. Finite element analysis of heat transfer through the gasket region of refrigerator/freezer. *EPA/430/R-92/009*, October.

[17] Kim k, Kopko B., and Radermacher R. 1995. Application of tandem system to high efficiency refrigerator/freezer. *ASHRAE Transactions* 95-16-5.

[18] E.A. Vineyard, J.R. Sand, Experimental and cost analyses of a one kilowatthour/day domestic refrigerator-freezer, ASHRAE Transactions 103 (2) (1997) 9 Paper No BN-97-7-2.

[19] H. F. Eberhardt, 2007, Vacuum Insulation Panels (VIP) in energy efficient cooling appliances for improving the environment of our children's world, 8th International Vacuum Insulation Symposium 2007, pp 1e9.

[20] M. Kudoh, A. Ohira, H. Nakamura, K. Araki, Simple method to support optimization of layouts for vacuum insulation panels (VIPs) for refrigerators, Heat TransfereAsian Research 35 (7) (2006) 2006.

[21] EPA., Substitutes in rigid polyurethane, Appliance (2009).

http://www.epa. gov/ozone/snap/foams/lists/applianc.html (Washington DC).

[22] R. Fleischer, 2009, Advances in environmentally sustainable refrigerants and blowing agents, 5th International conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'09), http://www.eedal.eu/index.php? id¼11575, Berlin, June 16e18.

[23] B. Chen, J. Costa, P. Bonnet, M. Elsheikh, L. Abbas, Investigation of low GWP blowing agents, Appliance Magazine (January 2009).

http://www.ApplianceMagazine.com 10 pages.

[24] Formacel. http://www2.dupont.com/Formacel/en_US/index.html (2011).

[25] Shin-Hyun Park and Jong-Woo Choi, "Control of Linear Compressor System Using Virtual AC Capacitor", Journal of Electrical Engg Technology, 2017; 12(6): 2167-2173, ,

[26] Nan-Chyuan Tsai and Chao-Wen Chiang, "HighFrequency Linear Compressor and Lateral Position Regulation", IEEE Transactions on Control Systems Technology, vol. 20, no. 1, January 2012, pp. 127-138.

[27] Zhengyu Lin, Jiabin Wang, and David Howe, "A Learning Feed-Forward Current Controller for Linear Reciprocating Vapor Compressors", IEEE Transactions on Industrial Electronics, vol. 58, no. 8, August 2011, pp. 3383-3390.

[28] Jiabin Wang, David Howe, and Zhengyu Lin, "Design Optimization of Short-Stroke Single-Phase Tubular Permanent-Magnet Motor for Refrigeration Applications", IEEE Transactions on Industrial Electronics, vol. 57, no. 1, January 2010, pp. 327-334.

[29] H. Lee, S. Ki, W. Rhee, "The innovative green technology for refrigeratorsdevelopmentof innovative linear compressor", International CompressorEngineering Conference at Purdue, July 2008, 14e17, 6 pages.

[30] F&P, Will oil-free compressor Revolutionize Fridge energy consumption?Appliance Magazine (2010). http://www.appliancemagazine.com/news.php?article¼1430214 &zone¼0&first¼1 September 16.

[31] Embraco, Oil-less linear compressor (2011). www.embraco.com.

[32] https://www.thecompressedairblog.com

[33] VCC - Variable Capacity Compressor. http://www.embraco.com/ingles/produtos.htm (2010).