Review of Alternative Refrigeration Technologies to the Vapour Compression Refrigeration Technology

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Abstract— This paper present a review of only five alternative refrigeration technology to replace the conventional vapour compression refrigeration technology for domestic application. Such technologies are demanded to provide energy saving and other environmental benefits. These alternative technologies are: Magnetic refrigeration, thermo acoustic refrigeration, thermoelectric refrigeration, and thermo tunneling / thermionic refrigeration and pulse tube refrigeration. The paper provides a snapshot of the future R&D needs for each technologies along with the associated hurdles. Only thermo acoustic and magnetic refrigeration technologies draw attention because recent developed in materials and prototype. And the potential efficiencies are medium to high.
Key words: Refrigeration, Vapour Compression

I. Introduction

Vapour compression refrigeration systems are the most commonly used among all refrigeration systems. As the name implies, these systems belongs to the general class of vapour cycles, where in the working fluid (refrigerant) undergoes phase change at least during one process. In vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperatures. The input to the system is in the form of mechanical energy required to run the compressor. Hence these systems are also called mechanical refrigeration systems. Vapour compression systems are available to suit almost all application with the refrigeration capacities ranging from few watts to few megawatts. A wide variety of refrigerants can be used in these systems to suit different application.

The ideal refrigerant for the vapour compression systems should be non-toxic, non-corrosive, efficient cost effective and more importantly environmentally begin. There is high demand of heating, cooling, and refrigeration worldwide and this will eventually lead to the high negative environmental impacts due to refrigerant charge leaks from the system and their corresponding high global warming potential. Thus, many efforts are in progress to obtain suitable low GWP alternative energy efficient technologies and more environmentally friendly systems for the future.

The paper reviews emerging alternative technologies to the vapour compression system that offer the potential for significant energy savings and environmental benefits. In addition, the status of emerging technologies that are useful in a household, including space conditioning, water heating and refrigeration. This paper reviews the status of five alternative technologies namely magnetic refrigeration, thermo acoustic refrigeration, thermoelectric refrigeration, thermo tunneling refrigeration and pulse tube refrigeration and their respective impact on energy consumption in household. And summary of the R&D opportunities that could develop such technologies further. Potential hurdles to implement these technologies in the market place present along with options for each technology to achieve significant improvements in energy efficiency or other environmental benefits for their application. [1]

II. Magnetic Refrigeration

The magnetic cooling utilizes the application of an alternating magnetic field to cool ferromagnetic materials via the magneto caloric effect. The application of magnetic field heats the material under adiabatic conditions. Rejection of heat to the environment, followed by removal the magnetic field, cools the material below its initial temperature. The cooled material may then be warmed by the cooling load, completing the cycle.

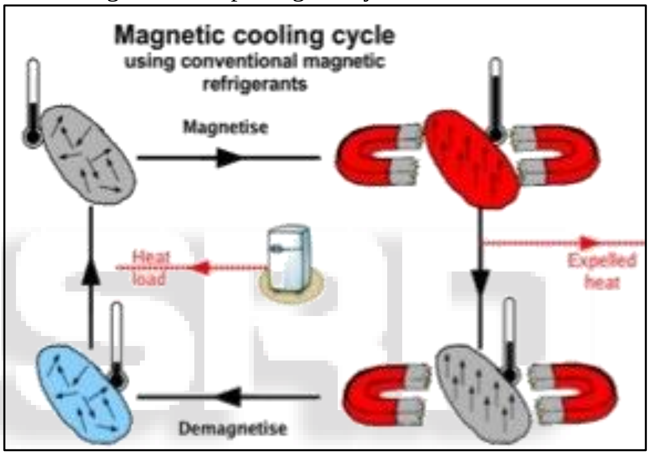

Fig. 1: Magnetic cooling cycle.

When magnetic field is applied to magnetic material near its curie temperature, the magnetic moments of the atoms are aligned, which reduces the magnetic entropy of the material. In turn this requires an increase an increase in the temperature of the material under adiabatic condition. If heat is removed from the material when magnetized, the material will cool below its initial temperature when the magnetic field is removed, thus providing a mechanism for a cooling cycle. [2]

A. *Previous Research*

- Concept of magnetic cooling derived by Warburg in 1881.
- Magnetic cooling has been used since 1930 to produce temperature less than 1k.
- The first apparatus for cooling near room temperature was developed by brown in the 1970.
  - In 1990 Green and co-workers. Thereafter from late 1990s many prototypes were developed worldwide.
  - Kitanovski et al. in 2008 they examined the prospects for magnetic cooling in nine applications namely household refrigerators, central cooling systems, room air conditioners, and supermarket refrigeration.

B. Performance

- For central cooling application the COP of air cooled chiller is 2.7 if compared with Vapour compression it is 3.9. And for the water cooled chiller the COP is 5.4, if compared with vapour compression it is 7.5.
- For the rom air conditioner application, the air cooled package unit having COP 3.2 if compared with window unit which was 3.5.

C. R&D Status

Magnetic cooling effect can be improved by following keys

- By reducing or managing thermal and magnetic hysteresis losses in high magnetic refrigerant (MCE) materials.
- By increasing the field strength and/ or reducing the cost of permanent magnets.
- Mass production of (MCE) materials.[1,3]

D. Comment

Magnetic cooling have higher Carnot efficiency than air cooled vapour compression system. In addition, recent advances in high MCE materials contributes more in developing this technology.

III. THERMO ACOUSTIC REFRIGERATION

Thermo acoustic refrigeration system mainly consists of a loudspeaker attached to an acoustic resonator (tube) filled with a gas. In the resonator, a stack consisting of a number of parallel plates and heat exchangers are installed. The loudspeaker, which acts as the driver, sustains acoustic standard waves in the gas at the fundamental resonance frequency of the resonator. The acoustic standing waves displaces the gas in the channel of stack while compressing and expanding relatively leading to heating and cooling of the gas. The gas which is cooled due to expansion absorbs heat from the cold side of the stack and as it is subsequently heats up due to compression while moving to the hot side, rejects the heat to stack. Thus the thermal interaction between the oscillating gas and the surface of the stack generates an acoustic pumping action from the cold side to the hot side. The heat exchangers exchange heat with the surroundings, at the cold and hot side of the stack

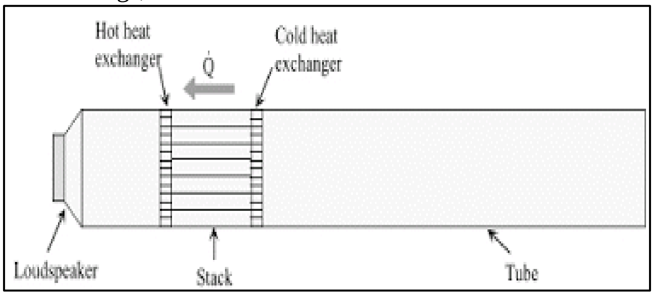

Fig. 2: Simple thermo acoustic refrigerator

Figure 2 shows schematic representation of the construction of the thermo acoustic refrigerator where the loudspeaker is used as the driver the resonance tube sustain standing wave.

The heat exchangers are used so that heat interaction with the surronding takes place. heat is pumped from the cold end heat exchanger to the hot end heat exchanger figure 3. Shows the pressure variation and displacement of sound waves in thermoacoustic refrigeration system. It is knon that sound waves are longitudinal waves. They produce compression and rarefaction in the medium they travel. Maximum pressure occcurs at the point of zero velosity and minimum velosity.[4]

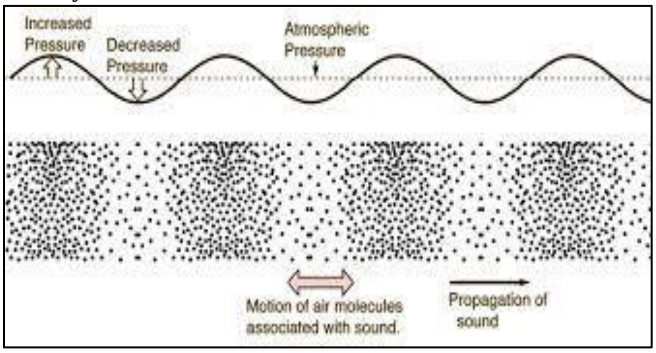

Fig. 3: Pressure variation and displacement of sound waves.

A. Previous Research

- In 1777, Byron Higgns conducted experiments in which oscillations in a tube were excited by the application of hydrogen flame
- In 1816, Laplace corrected Newton's calculation of the speed of sound in air.
- In 1962 Carter et al. realized that placing closely spaced parallel plates inside of tubes greatly increased the thermo acoustic effect.
- Hofler et al. invented a standing waves thermo acoustic refrigerator by Appling the mathematics introduced by Rott to a temperature gradient too small to sustain oscillations.
- In 1998 Garret et al. finished work on a 10-kw thermo acoustic cooler/ air conditioned named TRITON. The name comes from the fact that the cooler was designed to deliver 3 tons cooling
- In 2000, Backhaus and Swift published a paper describing a thermoacoustic-stirling engine that achieves a heat-to-acoustic energy efficiency comparable to energy conversion technology.

B. Performance

In thermo acoustic cooling devices only one moving part which is vibrating loud speaker, so the technology is reliable and low in cost. Thermo acoustic devices having ability to adjust cooling output to the heat load. Thermo acoustic coolers can also be powered by directly from a heat source. This is done by coupling thermo acoustic engine and cooler in to one device.

C. R&D Status

Thermo acoustic refrigeration can be improved with following keys.

- Major difficulties in achieving higher efficiencies with acoustic refrigerators have been the relatively low power density.
  - Low cooling capacities, large physical size, heat conduction between the heat heat exchanger and hence poor performance of the heat exchanger.
  - Design and control of compact heat exchangers in oscillating floe presents a unique challenge for thermo acoustic refrigeration units with large capacities.[1,5]

D. Comment

Due to these deficiencies, thermo acoustic refrigeration will continue to be noncompetitive technology for domestic application in the foreseeable future.

IV. THERMOELECTRIC REFRIGERATION

Peltier effect was discovered more than 150 years ago, thermoelectric devices have only been applied commercially during recent decades. Lately, a dramatic increase in the application of TE solutions in optoelectronic devices has been observed, such as diode lasers, photo detectors, solid-state pumped lasers, charge coupled devices and others. The thermoelectric module consists of thermocouple formed by pairs of P type and N-type semi-conductor thermo element which are electrically connected in series configuration and thermally connected in parallel configuration. Due to their solid state construction the modules are considered to be highly reliable. For most application they will provide long, trouble free service. For cooling application, an electrical current supply is given to the module, heat is transferred from one side to the other, and the result is that the module will become cooler at one side and hotter at the other side.

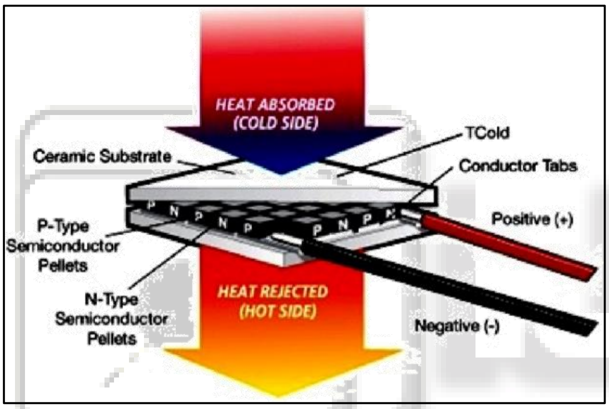

Fig. 4: Thermoelectric module assembly

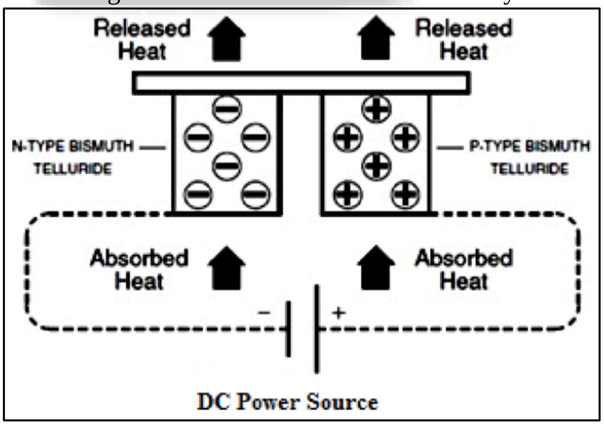

Fig. 5: Module working.

The figure 4 shows a particular thermoelectric module assembly. The main advantages of using TE modules in cooling applications are, they are solid state, have no moving parts and are miniature in size, its reliability and flexibility in design to meet particular requirements.

The figure 5 shows the working of thermoelectric module. When a DC voltage is applied to the TE module, the positive and negative charge carriers in the pellet assemblage absorb heat energy from one of the surface and reject it to the other at the opposite side. The surface area where heat energy is absorbed gets cooler; the opposite surface where heat energy is released gets hotter. Reversing the polarity will result in reversed hot and cold sides. [6]

A. Previous Research

- In 1821 Thomas seebeck discovered thermoelectricity when he noticed that a compass needle would deflect when placed near a circuit constructed out of two different metals with the junction at different temperatures.
- In 1834, Jean Peltier observed the heating and cooling that occurred when current passed through junctions between two dissimilar metals.
- In 1851, William Thomson explained the seebeck and peltier effects and discovered a thermodynamics relationship between the two. Also explained third thermoelectric effect known as Thomson effect.
- In 1954, H. J. Goldsmid and R. W. Douglas demonstrated thermoelectric cooling to below $0\,^{0}c$ in a room temperature environment.

In the1990, one was the introduction of phonon rattlers to reduce thermal conductivity while having little impact on electrical conductivity. Another was the use of low dimensional structures (quantum wells, nanowires, and quantum dots) to fine-tune the properties of the materials for better thermoelectric performance. Rama Venkata subramanian and others were able to create thermoelectric materials with figure or merit above 2.0.

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B. Performance

The efficiency of thermoelectric cooling devices is only between 10-15% of Carnot COP approximately 1-1.5, but this is based on semiconductor materials with ZT values around 1.0. The highest ZT values are in $Bi_2\ Te_3$ – based super lattices and PbTe- based quantum dot super lattice, with values of 2.5and 2 respectively.

C. R&D Status

The application of thermoelectric technology are restricted to those where the following condition exists

- Where the cooling load varies considerably
- For spot cooling.
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- Where reliability and silent operation are important.
- For small cooling loads less than 25W.
- For small temperature differences less than 10^{0}c.
- When the ability to heat and cool with the same unit is important, and where space is limited.[1,3]

D. Comment

Thermoelectric technology is currently too costly and its efficiency is too low to compete with vapour compression in most space cooling and food refrigeration applications. But, it is the most successful and the closest to competing with vapour compression of any of the cooling concept.

V. THERMO TUNNELING REFRIGERATION

Thermo tunneling is a thermoelectric process where electron transfer from one surface to another is enabled by the two surfaces being within a few nanometers of each other. Under an applied electrical potential, hot electrons emitted by the cathode are at a higher energy level than those that are left behind, which reduces the average energy (temperature) level of the cathode. Since the electrons being absorbed on the other side of the gap are at a higher energy level than those in the electrode, the average energy level is increased, and the electrode (anode) is heated. The new types of materials called elect rides that requires only small amount of energy to emit electrons at lower temperatures, make this technology attractive. [7]

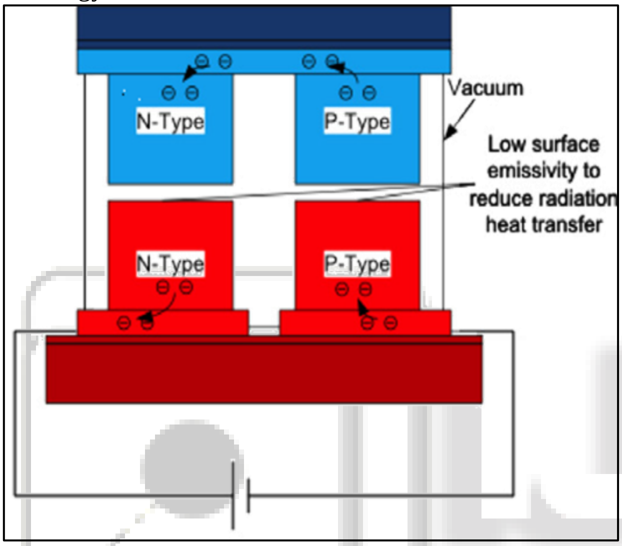

Fig. 6: Thermo tunneling refrigeration

A. Previous Research

- In early 1940 Fleming and Henderson, and Nottingham studied differences in energy between electrons emitted from a surface during field emission and replacement electrons.
- In 1960 Huffman investigated thermo tunnelling across thin layers of oxides between metal layers in the context of generating power from a thermal gradient.
- In 2003 Hishinuma et al. were able to measure the cooling effect created by the room temperature emission of electrons across a 1-2 nm gap.
- In 2007 Weaver et al. were unable to develop a prototype with a measurable cooling effect.
- Borealis Exploration limited has developed nearly 40 patents but has not yet developed a commercial product.
- In 2010 Dillner calculated an upper limit for the dimensionless thermoelectric figure of merit attainable by thermo tunneling as $\frac{\pi^2}{12}$

B. Performance

Borealis, Tempronics estimated only theoretical performance of thermo tunneling devices operating near room temperature in the range of 50% to 80% of Carnot. But no any experimental data is available.

C. R&D Status

R& D required development of low cost effective low work function surfaces, with typically less than 0.3 eV. In addition the requirement for extremely small inter -electrode spacing (nanometer sized gap) presents a unique challenge for large manufacturer. [1, 3, 5]

D. Comment

The theoretical performance of thermo tunneling for room temperature cooling is similar to vapour compression technology, but the design hurdles will be difficult to overcome**.**

VI. PULSE TUBE REFRIGERATION

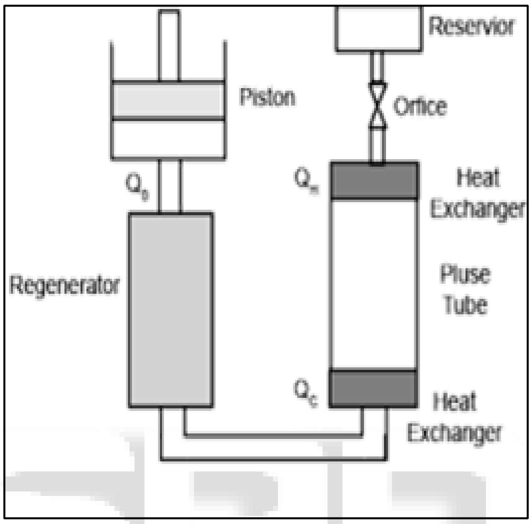

Fig. 7: Basic pulse tube refrigerator

Figure 7 shows schematic diagram of basic pulse tube refrigerator. Basic pulse tube refrigerator consists of a compressor, regenerator, cold heat exchanger, hot exchanger and pulse tube. The periodic pressurization and expansion produced by the compressor causes the gas to flow back and forth through the generator and during the compression processes, pressurized gas moves towards the hot heat exchanger exchanges located at the closed end of the pulse tube. The gas element in the pulse tube experiences near adiabatic compression and an associated temperature rise. The gas at the boundary layer exchanges heat with the tube wall. Heat transfer, through the hot heat exchanger wall, cools the gas in the hot heat exchanger during the subsequent expansion process, the depressurization gas moves towards cold heat exchanger. The gas element experiences near adiabatic expansion and an associated temperature drop. The wall releases heat to the gas. The net heat transfer between the gas and the pulse tube wall thus, shuttles heat from the cold end to the warm end. However the net amount of heat transfer is relatively small and disappears when the temperature gradient in the wall becomes sufficiently large to match the temperature excursion developed in the gas during the compression and expansion process. [8]

A. Previous Research

- The pulse tube concept was developed by Gifford and Longworth in the 1963 from his observation of heating in blanked off plumbing lines attached to gas compressor.

- Later Mikulin and Radebaugh improved the COP of the pulse tube by adding an orifice and an expansion chamber to the high temperature end of the tube.
- J. Yaun and J.M Pfotenhauer in 1998-1999 demonstrate the thermodynamic analysis and experimental confirmation of higher thermodynamic efficiency for 5-valve pulse tube refrigerator as compared to other 2-valve configuration.
- H Pan et al. investigated a single stage, 4-valve and 4-active buffler pulse tube refrigerator has been performed in Germany using a 7KW scroll compressor with four solenoid valve. The no-load temperature of 24-6 KW was achieved in this configuration.
- HU et al. in 2010 investigated that Pulse tube refrigerator are commercially available for temperature applications between -196^0C down to -269^0C

B. Performance

Pulse tube refrigerator systems are well suited for cryogenic application because there are no moving parts at the low temperature.

C. R&D Status

A single pulse tube cannot be enlarged beyond an optimum surface to volume ratio which depend on the cycle efficiency and the desired temperature range. The capacity is increased by the operation of several tubes in parallel from the same source of compressed gas.[1,3,5]

D. Comment

The modeled COPs for this system are extremely low and there is no independent corroboration of these this values so calculated energy use data are highly questionable. Installed costs would need to be thousands of dollars per ton less than conventional heat pumps to have comparable life cycle cost. There are two configuration for pulse tube cooling. One using a compressor and the other pump and valve. The compressor configuration is unlikely to have any significant equipment cost. Saving relative to conventional electric heat pump.

VII. Conclusion

A Review of alternative technologies has been presented in this paper. Thermo tunneling has a high efficiency potential but difficulty of creating and maintaining the nanometer scale gaps required by the technology significantly lowered its rating. Pulse tube refrigeration can be improved by developing heat transfer co relation between the gas and pulse tube wall. Thermoelectric and magnetic technologies are more energy saving technologies because of recent development in the better materials.

References

[1] DR Brown, N Fernandez, JA Dirks, TB Stout "The Prospects of Alternatives to Vapor compression Technology for Space Cooling and Food Refrigeration Application." March 2010. U. S. Department of Energy under Contract DE-AC05-76RL01830.
[2] Robin Langebach, Marcel Klaus, Chiristoph Ha-berstroh "Magneto caloric Cooling near Room Temperature – A Status Qua with respect to household Refrigeration." 2014 International Refrigeration and Air conditioning Conference.
[3] Pradeep Bansal, Edward Vineyard, Omar Abdelaziz, "Status of not-in-kind refrigeration technologies for household space conditioning, water heating, and food refrigeration." (2012) 1, 85-101 International Journal of Sustainable Built Environment.
[4] Bammann T. C., Howard C. Q., Cazzdabo B. S, 9-11 November 2005 "Review of flow through design in thermo acoustic refrigeration" Acoustic 2005, Busselton, and Western Australia.
[5] Steve fischer, Soloman Labinov, February 2000 "Not-in-kind technologies for Residential and Commercial Unitary equipment." Oak Ridge National Laboratory Oak Ridge, Tennessee.
[6] Sujith G, Antony Varghese, Ashish Achankunju, Vol-2 Issue 4 April 2016 International Journal of Science Engineering and applied science. "Design and fabrication of thermoelectric refrigerator with with thermo siphon system".
[7] Avto Tavkhelidze, Vasiko Svanidze, and Leri Tsakadze "Thrmotunnel Refrigerator with vacuum/ insulator tunnel barrier a theoretical analysis." Tbilisi state university, chavchavadze ave-13 0179 Tbilisi, Georgia.
[8] Jong Hoon, "Design methods in Active valve pulse Tube refrigerator." Baik University of Wisconsin-Madison 2003.