ANALYSIS OF NON-CFC AUTOMOTIVE AIR CONDITIONING

by

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ABSTRACT

Concern about the destruction of the global environment by chlorofluorocarbon (CFC) fluids has become an impetus in searching for alternative non-CFC refrigerants and cooling methods for mobile air conditioning (MAC). While some alternative refrigerants have been identified, they are not considered a lasting solution because of their high global warming potential (GWP), which could result in their eventual phase-out. In view of this dilemma, environmentally acceptable alternative cooling methods have become important. This study discusses the advantages and the limits of some of the alternative automotive cooling methodologies.

INTRODUCTION

While MAC is still an optional item, its market share has reached 90% in passenger cars and 70% in light trucks in North America. It is estimated that MAC accounts for over 33% of all R-12 consumption in the United State (Statt 1988) and for over 30% in Japan (Ushimaru 1989). MAC also accounts for about 7% of total fuel consumption for a passenger car. Furthermore, a significant potential for growth exists in the MAC field as the use of private cars and trucks becomes more common in other places of the world.

R-134a has been identified as the best R-12 replacement. Much research work has been accomplished on the application of R-134a to MAC. It is likely, however, that R-134a will be used for new cars only. For aftermarket service for cars equipped with R-12 systems, use of recycled R-12 is the first choice. If the supply of R-12 becomes scarce in later years, the options are a retrofit to either R-134a or one of the new refrigerant blends (Bateman et al, 1990).

While alternative refrigerants with zero ozone-depleting potential, such as R-134a, have been identified, there are still regulatory uncertainties remaining for R-134a, ternary blends, and other alternative fluorocarbon refrigerants because of their association with the greenhouse effect. The GWPs of the fluorocarbon R-12 substitutes could make them only an interim solution. Alternative non-CFC MAC technologies will be needed in the future.

In this study, some alternative non-CFC MAC methods were investigated. They can be divided into two categories: work-actuated systems and heat-actuated systems. Some potential work-actuated systems including hermetic vapor-compression systems, reversed Brayton air-cycle systems, and thermoelectric cooling were presented. For heat-actuated systems, four concepts were identified for possible MAC applications: ejector cooling, absorption cooling, adsorption cooling, and metal hydride cooling. While traditional MAC's are work-actuated, heat-actuated systems may provide better energy saving potential. Each cooling method was discussed for its advantages and limits.

WORK-ACTUATED MAC

Refrigerant Vapor-Compression Cycle: Electrically Driven Hermetic Systems

Electrically driven hermetic MAC minimizes refrigerant leakage, which is important because of the CFC issues. Bessler and Forbes (1987) discussed the application of dc motors to hermetically sealed MAC systems. Their system uses a variable-speed brushless dc motor to drive a fixed displacement compressor, thus achieving continuous control of cooling output. Compared with variable-displacement systems, the electrically driven MAC provides the following additional benefits:

- A hermetic motor/compressor assembly means no shaft seal refrigerant leakage.
- The compressor is smaller and less complex.
- The packaging is more flexible (no drive belt).
- Full cooling capacity can be achieved at any engine speed.
- The conditioned air temperature can be controlled without reheat.
- Hermetic MAC can be easily installed on electric cars.

Bessler and Forbes found that in order to reduce the system power consumption to a reasonable level, fresh air intake had to be limited to around 30%. Their study indicated that the hermetic MAC system would require a control strategy, compressor, and electrical system that are different from those used in today's automobiles. Ikeda et al. (1990) studied a MAC system using a hermetically sealed electrical air conditioning (AC) system with a variable-speed scroll compressor coupled with a brushless dc motor for electric vehicles. The electric MAC had a COP of 1.53, which was lower than the baseline case of 1.81.

Nartron Corp. (1991) is developing a novel hermetically sealed MAC system with an electrically driven turbine compressor coupled with a DuPont low-pressure non-CFC refrigerant. The system is compact and variable-speed. It is claimed that the system has a COP about 30% higher than that of conventional R-12 and R-134a MAC systems.

Reversed Brayton Air Cycle

Reversed Brayton air cycle is to expand air from passenger compartment to achieve low temperature cooling purpose and then the low pressure air is compressed above ambient pressure and vented. Figure 1 shows the schematic of a reversed Brayton air-cycle air-conditioning system. They are commonly used on aircraft because of their light weight, compact size, and readily available bleed air. The ASHRAE Applications Handbook (1991) discusses the basic air cycle, the bootstrap cycle, and the basic three-wheel bootstrap air cycle. Garrett, Inc., (1977) also made a Brayton-cycle MAC study and concluded that the system COP was around 1.04.

Edwards Air Cycle

The Edwards air cycle has been called the "ROVAC" (for rotary-vane compressor) system in many publications (e.g., Edwards 1975). It uses a rotary-vane compressor to compress and expand air simultaneously. The tested system COP was somewhat lower than that of a conventional MAC system.

Thermoelectric Cooling System

The theory of thermoelectric (TE) cooling is based on the Peltier Effect of certain materials. This idea for MAC has several important advantages, such as no need for refrigerant, adjustable cooling capacity, fast response, high initial cooling capacity, no moving parts except a fluid circulating pump, and the ability to operate as a heat pump when the dc current direction is reversed. This concept has been experimented with by the French for cooling of railway passenger cars, and for space conditioning of underwater vehicles. TE cooling systems are also very rugged, which means little maintenance is needed. A mathematical model was developed for MAC application by Mathiprakasam et al. (1991). With realistic design factors and with off-the-shelf TE module properties, their model indicated that a system COP of 0.42 could be achieved. Figure 2 shows the schematic of a TE MAC system.

Stirling Cycle Cooling System

The Stirling cycle is composed of two constant temperature and two constant volume processes. Theoretically, Stirling cycle could have Carnot efficiency. It does not use CFC fluids, and it can have modulated cooling capacity. Stirling cycle is usually used in "high lift" applications such as cryogenics. Equipment has not yet been developed to the point where it is competitive with the conventional vapor compression systems for MAC in terms of cost, performance, or reliability. One of the fundamental problems of Stirling cycle is associated with heat transfer. It is difficult to achieve a constant temperature compression or expansion in a machine operating at a reasonable speed.

Domingo et al. (1984) conducted a third order computer code simulation of a Stirling machine for space heating applications. They concluded that the system heating COP was insensitive to ambient temperatures. Chen et al. (1988) tested a Stirling cooler and showed the existence of a performance maximum. This performance maximum can be shifted and optimized through design modifications (Berchowitz 1991). More recently, Stirling Thermal Motor, Inc. has demonstrated a variable-displacement Stirling machine which could lead to the applications of the Stirling cycle to MAC with a projected COP for cooling of 1.6 to 2.0, depending on the temperature difference between the air temperature and the Stirling heat exchangers (Godett 1990).

HEAT-ACTUATED MAC

Ejector Cooling Systems

The theory of ejector AC systems is similar to that of steam-jet refrigeration. A schematic of an ejector cooling system is shown in Figure 3. Ejector cooling is an alternative with many attractive advantages, such as a minimum of moving parts, high reliability, low maintenance cost, etc. Balasubramaniam et al. (1976) studied the energy impact of such MAC systems on cars. They concluded from their analysis that over 70% of fuel consumption used to run MACs could be saved by using ejector MAC systems and reducing the system weight. However, theoretical analyses indicate that this system has a low COP—around 0.3 (Chen 1978). Because of the low system COP, passenger cars might not have enough waste heat to power an ejector MAC system.

Absorption Cooling System

The key moving parts in an absorption system is only a fluid circulating pump. An absorption system rejects 2.5 to 3.5 times as much heat as a vapor compression system. The heat rejection is at a lower temperature, which results in the system's requiring very large heat exchangers compared with those of vapor compression MAC systems. Absorption systems use a pair of fluids. The most commonly used fluid pairs are ammonia/water and water/lithium-bromide. R-22/dimethyl ether of tetraethylene glycol (DME-TEG) has also been considered. Figure 4 shows the schematic of a single-stage absorption cooling system. The cooling COP is around 0.6 for a single-effect system and 0.95 for a double-effect system. Mei et al. (1979) analyzed absorption refrigeration systems for long-haul trucks.

Adsorption Cycle (Desiccant) Cooling Systems

It is possible to use molecular sieves or other solid desiccants to achieve MAC. A closed-cycle desiccant cooling MAC systems is depicted in Figure 5. There are several advantages of desiccant cooling systems: solid desiccants are usually low-cost materials; the choice of refrigerants is more flexible since solid desiccants can adsorb a number of refrigerant vapors; the cooling COPs (thermal) are higher than those of the absorption systems, on the order of 0.75, as calculated by Shelton et al. (1990); there are broad choices of solid fluid pairs; the system design is simple; and the desiccant can be regenerated by waste heat from car exhaust gas. Schaetzle (1982) experimentally studied desiccant MAC systems. A prototype unit was built with molecular sieve as the desiccant. Though the system worked, Schaetzle found that heat generated by the adsorption and regeneration processes was difficult to dissipate and thus slowed down the cooling process. Open cycle desiccant systems can be developed for MAC as well. They operate at ambient pressure resulting in large and bulky systems; contrary to the compactness requirement necessary for MAC application.

Metal Hydride Cooling Systems

Hydriding alloys are intermetallic absorbent compounds that can absorb very large quantities of hydrogen gas, and the process is reversible. The sorption and desorption processes are exothermic and endothermic reactions, respectively. It is during the desorption process that the cooling effect is achieved. Figure 6 illustrates the cycle of a metal hydride cooling system. Metal hydride MAC systems can potentially be operated with waste heat from engine exhaust gas and can potentially have high COPs. They do not use CFC fluids, and they have a fast response rate. Some major design considerations should be considered, such as the expansion of hydriding materials. Most hydride materials are also very brittle, which must be considered in the system design. It is estimated that for a one- to one-and-a-half ton cooling system, around 50 to 100 lb of hydriding material is needed, but metal hydride materials are not costly.

CONCLUSIONS

Because of the global environmental concerns, CFC fluids will be phased out in the near future. While some alternative refrigerants have been identified, these might be only the interim solutions. The search for other alternatives is becoming important in view of the CFC concerns. Much work in alternative non-CFC cooling technology needs to be accomplished before some of it can be viable in the MAC market. To develop a long-term environmentally acceptable MAC technology while saving energy represents a great challenge to us. In this study, several work-actuated and heat-actuated MAC systems were discussed. While each one of these has its unique advantages and limits, some of them have the potential to meet the challenge. Further research and development work is needed before a lasting solution for MAC can be accomplished.

In the long term, the systems with the greatest potential for eventual application to automobiles are the work actuated systems. Of these, the electrically driven, hermetically sealed vapor compression systems will probably first appear in electric vehicles in the late nineties. These systems have the greatest technical advantages and the least risks. The Stirling cycle cooling system also shows promise. Its high efficiency is its biggest advantage. A Stirling machine with the reliability and durability required of automotive systems is its biggest hurdle. Of the waste heat actuated systems, adsorption cooling systems have the best chance of being applied to a vehicle of some kind. Transit buses are the best application of this technology however, as they have an abundant supply of waste heat and enough space for the bulky desiccant and heat exchangers.

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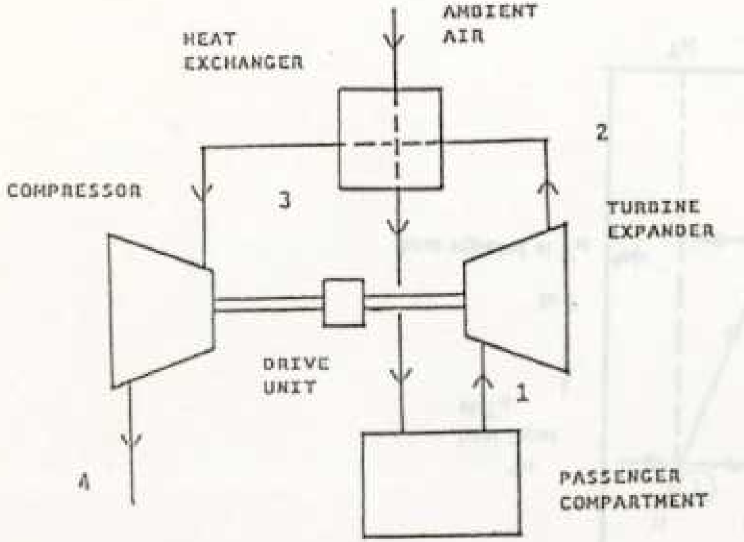

Fig. 1 Schematic of reversed Brayton air cycle cooling system

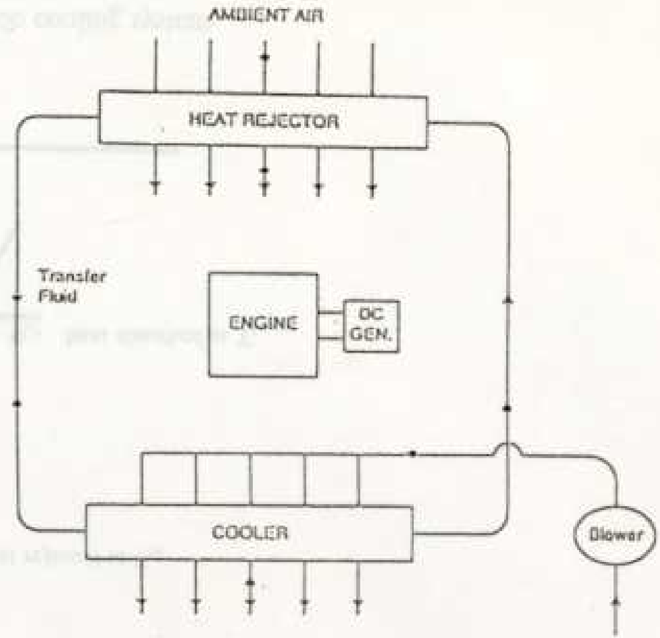

Fig. 2 Schematic of thermoelectric cooling system

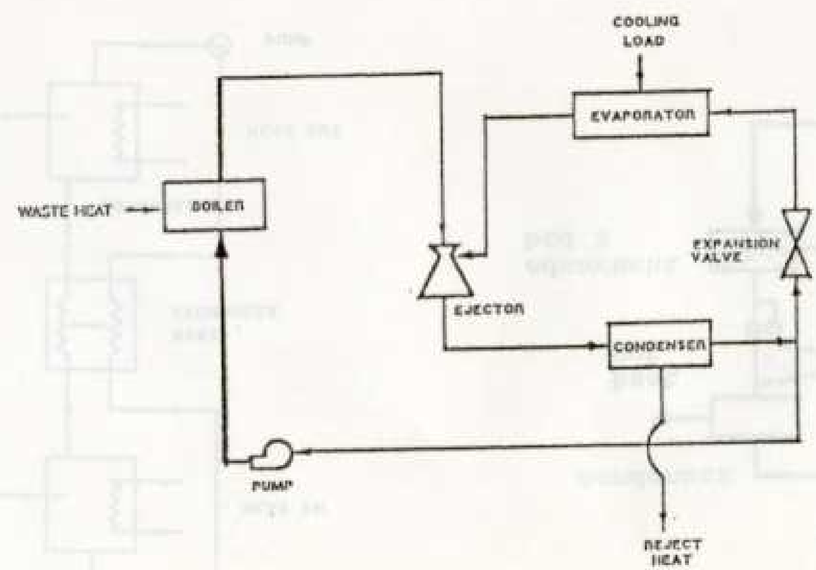

Fig. 3 Schematic of ejector cooling system

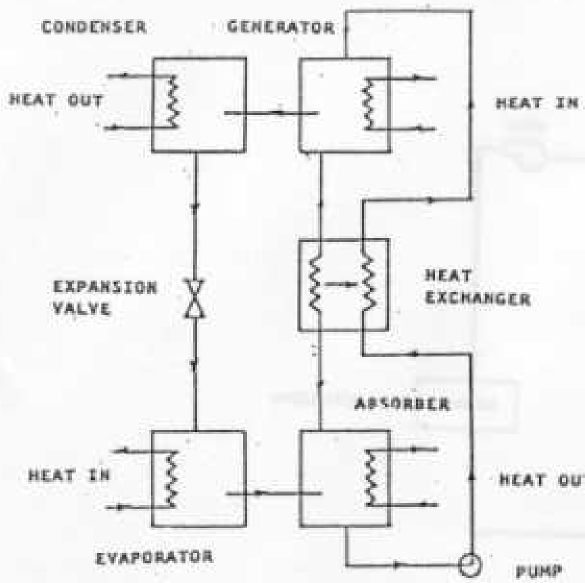

Fig. 4 Schematic of absorption cycle cooling system

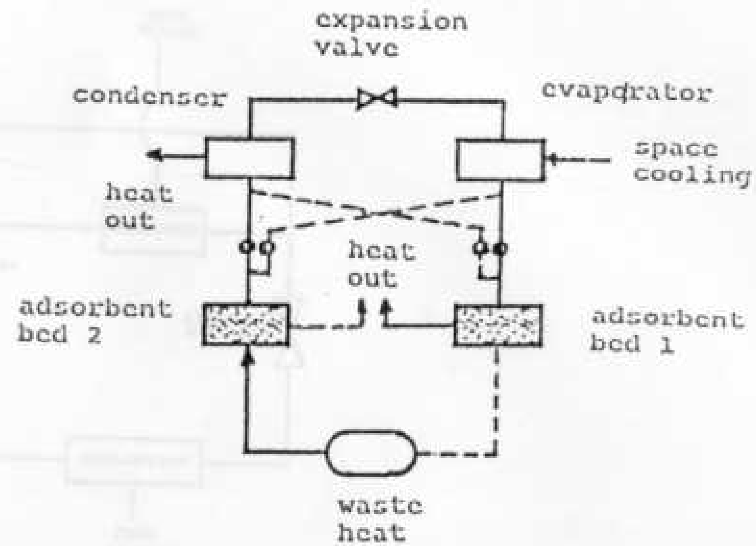

Fig. 5 Schematic of adsorption cycle cooling system

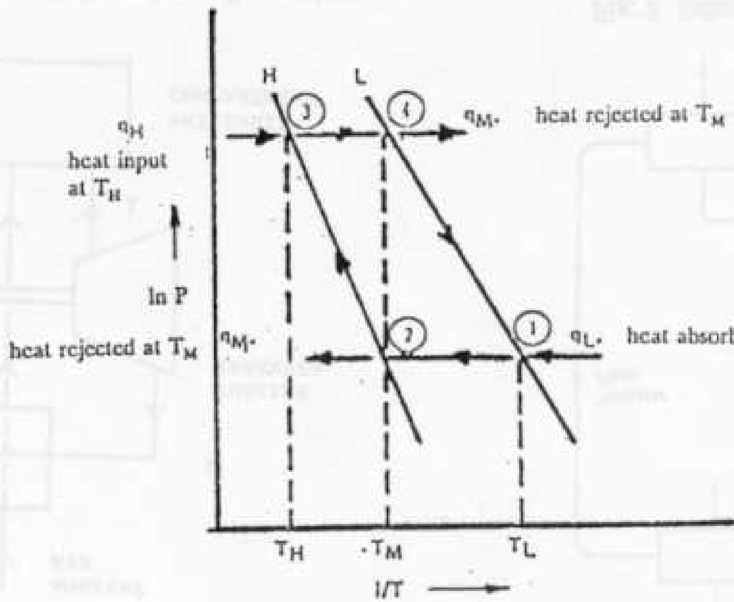

Fig. 6 Cycle diagram of metal hydride cooling system