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Heat-Generated Cooling Opportunities in Vehicles

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ABSTRACT

Utilizing heat-generated cooling in vehicles offers the opportunity to reduce the amount of fuel used today for air conditioning. The U.S. uses approximately 7.1 billion gallons of gasoline each year for air conditioning in vehicles. By using waste heat as the primary energy source for heat-generated cooling, we have the potential to reduce the national fuel use by 7.1 billion gallons. An engine operating at a 30% thermal efficiency releases the remaining 70% of the fuel energy as waste heat through the coolant, exhaust gases, and engine compartment. Waste heat available for a representative 115-kW engine varies from 20 to 400 kW across the engine map, with an average value over the FTP cycle of 23 kW. Temperatures of the waste heat range from 200°C surface temperatures to 600°C gas temperatures. Therefore, the magnitude of energy currently wasted is significant, and a large opportunity exists to utilize this waste heat for productive purposes. This paper outlines the heat-generated cooling potential of metal hydride cooling systems, absorption heat pumps, zeolite heat pumps, and thermoacoustic cooling. System performance, material issues, advantages, disadvantages, and the current state of research is outlined for these technologies. All of these heat generated cooling systems offer great opportunities for utilizing waste heat and reducing fuel use in vehicles.

INTRODUCTION

Utilizing heat-generated cooling in vehicles offers the opportunity to reduce the amount of fuel used today for air conditioning. The U.S. uses approximately 7.1 billion gallons of gasoline each year for air conditioning in vehicles [1]. By using waste heat as the primary energy source for heat-generated cooling, we have the potential to reduce the national fuel use by 7.1 billion gallons.

Before researching heat-generated cooling opportunities, one must first determine the magnitude of the waste heat energy available from the engine in a vehicle to see if it is significant. The average fuel economy of a car in the U.S. is near 21 mpg [2], and a representative vehicle could be the Ford Taurus with a 3.0-L engine and a maximum output power of 115 kW. Figure 1 shows that the waste heat available for a representative 115-kW engine varies from 20 to 400 kW across the engine map, with an average value over the FTP cycle of 23 kW. The temperatures of the waste heat range from 200°C surface temperatures to 600°C gas temperatures. These values are based on ADVISOR simulations [2].

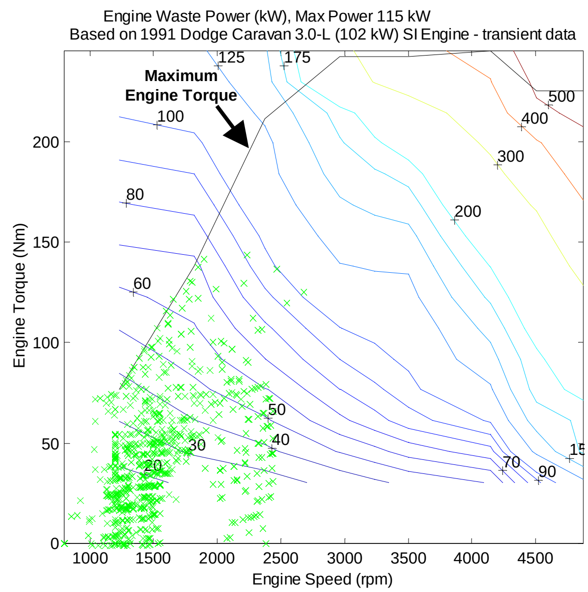

Figure 1: Engine waste heat for a 3.0-L 115 kW engine (x's are engine operating points for a 21-mpg vehicle over an FTP drive cycle)

Thinking of vehicle waste heat in another way, the waste heat available is generally twice as much as the mechanical output of the engine. An engine operating at a 30% thermal efficiency is releasing the remaining 70% of the fuel energy as waste heat through the coolant, exhaust gases, and engine compartment warm-up. During a typical drive cycle, the engine efficiency is lower than its maximum efficiency, and as this operating efficiency decreases (e.g. 30% to 15%), the magnitude of the waste heat increases, thus representing a larger energy potential to use for cooling via heat-generated cooling.

Clearly, the magnitude of energy currently wasted is significant, and a large opportunity exists to utilize this waste heat for productive purposes.

This paper outlines the heat-generated cooling potential of metal hydride cooling systems, absorption heat pumps, zeolite heat pumps, and thermoacoustic cooling. System performance, material issues, advantages, disadvantages, and the current state of research is outlined for each technology.

HEAT-GENERATED COOLING SYSTEMS

METAL HYDRIDE SYSTEMS – Metal hydride heat pumps utilize the fact that when hydrogen is adsorbed by the metal, heat is released because it is an exothermic reaction. The process is reversible so that desorbing or releasing the hydrogen is endothermic, consuming heat. This desorption cooling step acts the same as the evaporator in a vapor-compression system. In the equation below, *M* represents the rare earth metal alloy, and MH_x the metal hydride:

$$M + \frac{x}{2} H_2 \leftrightarrow MH_x + Heat$$

Figure 2 shows the basic operation of a hydride heat pump, for one particular configuration. This system uses two metal hydride beds (a low temperature and high temperature metal), three heat exchanger sections (high, ambient, and low temperatures), and cycles the beds through these heat exchangers through time to achieve cooling. Continuous cooling can be obtained by having four hydride beds.

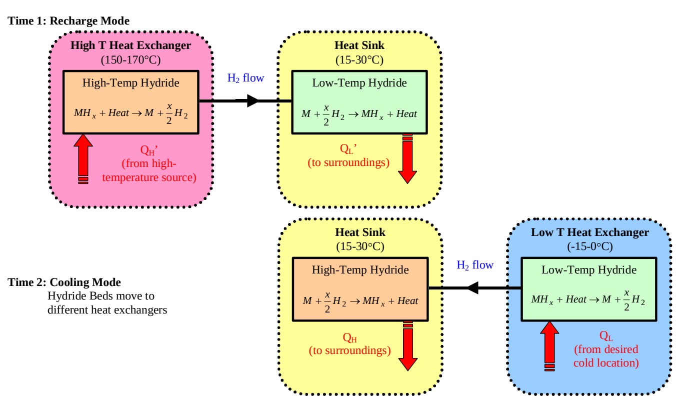

Figure 2: Basic Operation of Metal Hydride Heat Pump

Materials - Example high-low temperature hydride materials are $LaNi_{4.75}Al_{0.25}$ (160°C) and $MmNi_{4.15}Fe_{0.85}$ (-10°C), or $ZrCrFe_{1.1}$ (120°C) and $LaNi_5$ (20°C). Note that Mm refers to misch metal, or a rare earth metal alloy. The cost of the hydride is ~$300/kg and the amount of hydride in a bed ranges from 0.122-0.6 kg ($37-180). Hydride metals have been cycled 100,000 times reliably (Ergenics, [4]). Development on hydrides by companies has been mainly related to nickel-metal-hydride battery research and solid-state storage applications (e.g. fuel cell energy sources).

Advantages and Disadvantages - Metal hydride systems have fewer total parts and fewer moving parts than a conventional vapor compression air-conditioning system, as the system doesn't use a compressor or evaporator. Therefore, a hydride system would also have lower maintenance costs. Hydride systems also occupy a smaller volume compared to conventional AC systems. Another advantage of a metal hydride system is that it does not require chloroflourocarbons (CFC) for cooling. CFC's, such as freon, have been linked to the destruction of stratospheric ozone that limits the amount of UV radiation the earth sees.

A significant obstacle to overcome before hydride cooling systems will be viable in a vehicle is a low Coefficient of Performance (COP), which ties directly to the weight and cost of the system. Currently their typical COP is 0.4, with maximum values up to 2.5. These numbers are lower than commercial vapor compression refrigerators, whose average COP's are near 1.5. Even at these low COP's, however, a large amount of cooling is available for the vehicle cabin. For example, the sedan driving over the FTP generated 23 kW of waste heat, which would yield over 9 kW of cooling. A typical vehicle cabin uses 6 kW of cooling. In order to increase the performance of the system, it is necessary to research improved heat exchanger efficiency, smaller component sizes, and system integration with the vehicle waste heat. These are all significant and challenging areas.

Past Research Performed - Ergenics, based in New Jersey, created a metal hydride 5-kW AC system powered by waste heat from simulated exhaust gases in 1992-1993. Ergenics has been awarded several patents surrounding their metal hydride cooling system. The system mass was 22 kg and the COP was 0.33. They didn't see strong external interest, so as a company they've focused on development of metal hydrides for solid state hydrogen storage.

Thermacore, based in Pennsylvania, constructed two prototype metal hydride heat pumps in 1997-1998 based on two Russian inventions that could significantly improve the efficiency of a hydride system. They were awarded U.S. Patent #6,000,463 in 1999 for a "Metal Hydride Heat Pump." Thermacore is not currently funding hydride development.

Advanced Materials Corporation, a small company based in Pennsylvania, developed a prototype hydride system a few years ago for a contract for the state of Pennsylvania. Their hydride heat pump used a pump to transfer the hydrogen and provide heating and cooling using a different configuration than that described above. They put the system in the trunk of a vehicle and cooled the cabin. The system had a mass of 40 kg and achieved 350 W of cooling at 16°C.

Other work and modeling of hydride systems has been performed at the University of New Mexico, Albuquerque, the University of Illinois at Chicago, the University of Melbourne, Australia, and the National Academy of Sciences of Ukraine (1998-present).

ABSORPTION SYSTEMS - Absorption refrigeration cycles differ from vapor-compression cycles in the manner in which compression is achieved. In the absorption cycle, the low-pressure refrigerant (e.g. ammonia or lithium bromide) vapor is absorbed in water and the liquid solution is pumped to a high pressure by a liquid pump. Figure 3 shows a schematic of the essential elements in an absorption system. A lithium bromide absorption heat pump uses LiBr as the working solution. The lithium bromide-based absorption chiller has been around commercially since the late 1950's and uses bromide brine with concentrations of ~60%. The ammonia-water absorption system has been around since the early 1900's.

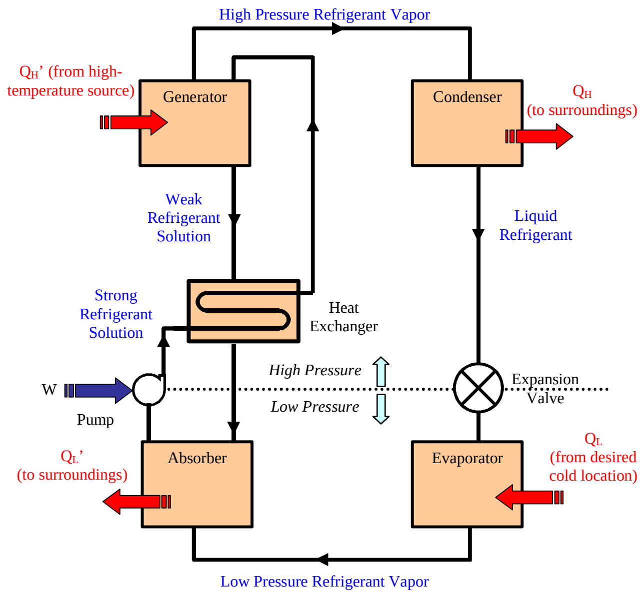

Figure 3: Schematic of Absorption Heat Pump Cycle

Advantages and Disadvantages - The distinctive feature of the absorption system is that very little work input is required because the pumping process involves a liquid. Another advantage is that they have been around for a long time, such that there is a manufacturing basis for larger systems (e.g. applications for manufacturing plants, buildings).

However, there is more equipment in an absorption system than in a vapor-compression system, and it can usually be economically justified only when a suitable source of heat is available that would otherwise be wasted. A source of heat from 100° to 200°C must be available for the absorption system; this is the case if vehicle waste heat is used. COP's for absorption systems are near 1. There may be some safety related issues in transporting ammonia or lithium bromide in vehicles, which could cause significant resistance to absorption systems in the automobile industry. Another disadvantage is that corrosion in the evaporator can occur. Lithium bromide, a highly corrosive brine, attacks ferrous metals such as steel. The corrosion process generates hydrogen gas that reduces the internal vacuum inside the evaporator, and the system operates poorly. In addition, the debris resulting from the corrosion fouls narrow openings in the system.

Past Research Performed - Gas Research Institute, based in Chicago Illinois is researching absorption heat pumps. Shuangliang Teling Lithium Bromide Refrigeration Machine Co., Ltd, as implied by its name, produces lithium bromide refrigeration systems. However, not much work has been performed on integrating such a system into a vehicle.

ZEOLITE SYSTEMS - Zeolite systems are similar to metal hydride systems, but use zeolite and water in the place of a metal hydride and hydrogen. The natural mineral zeolite (e.g. porous aluminosilicate) has the property to attract (adsorb) water vapor and to incorporate it in its internal crystal lattice while releasing heat at the same time:

$$Zeolite + H_2O \leftrightarrow ZeoliteH_2O + Heat$$

A zeolite system requires cycling between adsorption and desorption. Figure 4 shows the basic operation (adsorption and desorption) of a zeolite system. The sequence of adsorption/desorption processes is reversible.

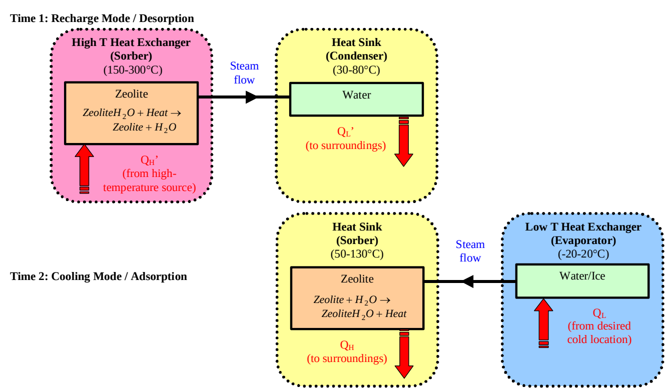

Figure 4: Adsorption phase of a Zeolite system

For a comparison to the absorption heat pump described in Figure 3, the top left container (sorber) in Figure 4 takes on the role of the Generator, and the top right container is the Condenser. When the zeolite is saturated with water, desorption is initiated by heating the zeolite at high temperatures. The adsorbed water molecules are forced to evaporate (desorption), and condensation takes place in the water tank (condenser).

Again, for a comparison to the absorption heat pump described in Figure 3, the bottom Sorber in Figure 4 takes on the role of the Absorber, and the bottom-right container is where cooling occurs, or is like the Evaporator. In an evacuated (airless) environment, during absorption the zeolite attracts water in a forceful manner and internal pressure drops dramatically. The remaining water evaporates, cools down and freezes immediately due to the heat of evaporation. The resulting ice can be used for cooling and air conditioning while the simultaneously produced heat of adsorption within the zeolite tank can be used for heating.

Materials - Currently the chemical industry produces more than 1.4 million tons of synthetic zeolite annually and worldwide demand and consequently the production will further increase in the future. Zeolites are currently used as catalysts for refining oil in the petroleum industry, as filler in paper production, and as ion exchange material in detergents. The price, e.g. for laundry detergent zeolite, is between $0.45-3.60/kg, depending on the type and consistency of material delivered.

Advantages and Disadvantages - The adsorption of zeolites is very strong, thereby providing the family of materials with unique adsorption properties and permitting high efficiencies for adsorption heat pump cycles with air-cooled condensers (COP's around 1.2). Another advantage of zeolite systems is that they allow heating and cooling at the same time. This might useful, for example, to heat the catalyst for quick lightoff, while cooling the cabin compartment for interior thermal comfort.

One disadvantage of zeolite systems is that to provide continuous cooling, systems need to cycle between multiple sorption modules. As with metal hydride systems, research needs to be performed to develop smaller components and system integration with the waste heat in a vehicle.

Past Research Performed - Zeo-Tech, a German company, has developed a zeolite heat pump in 2000. The device was fired by a gas-burner, and saw energy savings of 25% over state of the art technologies (e.g. condensing boiler) for heating. In the future, Zeo-Tech plans to build and optimize a zeolite heat pump with integrated ice-storage for a typical one-family house with a rated heating power of approximately 10 kW.

The Gas Research Institute, Chicago, IL, and Zeopower, Co., MA, created a closed-cycle regenerative zeolite heat pump fired by natural gas in 1989. Combining the zeolite technology with the principle of energy regeneration resulted in a single-effect system with seasonal cooling coefficients of performance (COPs) of 1.2 and heating COPs above 1.8 and initial equipment cost comparable to electric heat pumps.

A demonstration unit with ZAE-Bayern, Germany, was performed in 2000.

Other research has been performed at Korea Institute of Energy Research (KIER). The capacity of a prototype zeolite adsorption heat pump was 1.4 W , the system COP was 0.3, and the system cycle time was two hours.

THERMOACOUSTICS - Thermoacoustic refrigerators use sound waves to pump heat. They are based on the fact that accompanying pressure and velocity changes with a sound wave are small temperature oscillations. With intense sound waves in suitable geometries, these thermoacoustic effects can be harnessed to produce powerful thermoacoustic engines and refrigerators. Sound levels inside reach 180 dB, but outside the system is as quiet as a conventional AC system. An example working fluid is helium.

The American Scientist [5] describes the heat exchanger operation in a thermoacoustic system as follows. “As a parcel of gas moves to one side, say to the left, it heats as the pressure rises and then comes momentarily to rest before reversing direction. Near the end of its motion, the hot gas transfers heat into the stack, which is somewhat cooler. During the next half-cycle, the parcel of gas moves to the right and expands. When it reaches its rightmost extreme, it will be colder than the adjacent portion of the stack and will extract heat from it. The result is that the system pumps heat from right to left and can do so even when the left side of the stack is hotter than the right.”

Figure 5 shows the basic operation of a thermoacoustic heat pump. A stack is utilized to keep the sound wave in location long enough for heat transfer to occur.

Standing Wave vs. Traveling Wave - Initial work on thermoacoustics centered on developing a standing acoustic wave in a resonant cavity. In an example standing wave system, cooling of 400 W was seen with an input of 200 W acoustic power (COP = 2, which was 17% of ideal Carnot efficiency). Recently, the DOE group at Los Alamos National Laboratory (LANL) has made a breakthrough developing a thermoacoustic heat engine that uses a variation of the Stirling cycle (with a porous regenerator), and uses a traveling acoustic wave. Their first heat engine of this design produced power from a heat input at an efficiency of over 40% of Carnot, 150% greater than the best standard thermoacoustic heat engines (e.g. 42% vs. 17% efficient).

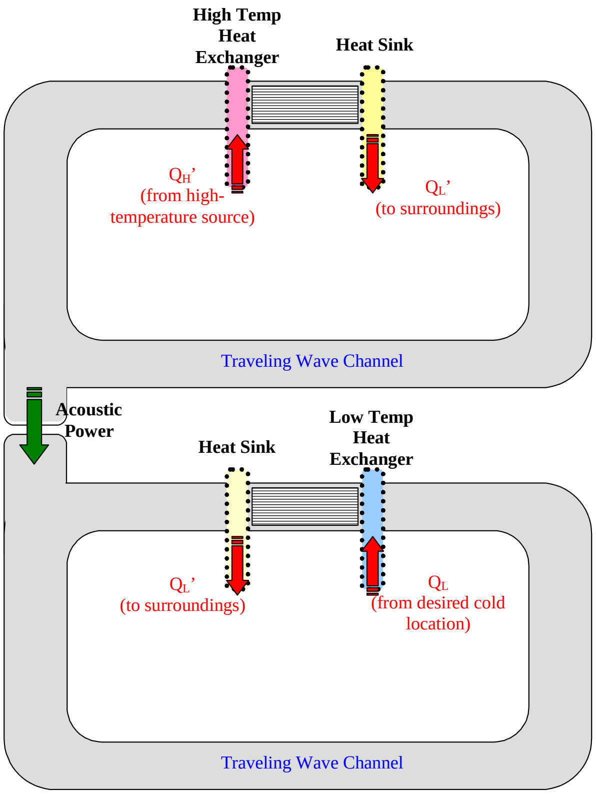

Figure 5: Basic Operation of a Traveling Wave Thermoacoustic Heat Pump

Advantages and Disadvantages - Thermoacoustic systems appear attractive because of their elegance, reliability, and low cost, in spite of only modest efficiency. They are environmentally safe and have no sliding parts. This difference makes thermoacoustic devices much simpler and potentially much more reliable than conventional engines and refrigerators, because they can avoid wear associated with valves, piston rings, crankshafts, connecting rods and so forth. Thus thermoacoustic devices require no lubrication.

Disadvantages of thermoacoustic systems are low efficiency and low power density. Research is predicted to give efficiencies comparable to vapor-compression refrigerators. Another significant disadvantage of thermoacoustic systems is their typically large size. Also, thermoacoustic devices are very sensitive devices—if the standing or traveling wave gets out of phase for any reason (e.g. dirty heat exchangers, shock or vibration), the cooling can be disrupted. Today, thermoacoustic refrigerators are used in special applications and temperature changes of 20°C have been achieved. More research is needed in order to get commercially marketable devices, in particular research to focus on heat exchanger design, transducer design, sizing, robustness, and increasing overall efficiency and decreasing price.

Past Research Performed - A qualitatively accurate theory was developed in the 1970s and the first thermoacoustic refrigerator was built in 1985. Hence, this technique is relatively new. So far, most machines of this variety reside in laboratories, but prototype thermoacoustic refrigerators have operated on the Space Shuttle and aboard a Navy warship (cooling radar electronics).

Most of the work related to thermoacoustics has been performed at LANL (funded by the DOE's Office of Basic Energy Sciences), Penn State University, and the Naval postgraduate school (CA), with additional work at the University of Utah, and Chalmers University of Technology. The First International Workshop on Thermoacoustics was held in 2001 in the Netherlands with 80 attendees. The workshop showed that an understanding of combustion oscillations by thermoacoustics is on its way, and numerical simulations are in reasonable agreement with experiments. LANL's numerical simulation tool is named DeltaE (Design Environment for Low-amplitude Thermoacoustic Engines).

Additionally, large-scale thermoacoustic traveling wave machines are under development. These machines are used to drive large-scale pulse-tube coolers in the kW or MW range. As an example, the thermoacoustic Stirling engine designed at LANL weighs 200 kilograms and measures 3.5 meters long. This device is under development for the commercial application of liquefying natural gas.

At Penn State, a program called Sundrive, sponsored by the Office of Naval Research, consists of a thermoacoustic engine/refrigerator combination that uses the focused energy of the sun as an energy source. The device is designed to move 30 Watts from the cold side and freeze water.

CONCLUSION

All of the heat-generated cooling systems described above offer great opportunities for reducing fuel use in vehicles, with various advantages and research challenges.

METAL HYDRIDE SYSTEMS - Metal hydride systems have the potential for good performance in utilizing waste heat for cooling, are environmentally friendly, and use less components than a conventional vapor compression AC system. There are significant research obstacles to overcome, however, before such a system can be put in a vehicle. These research areas include improving heat exchanger efficiency, reducing the size and weight of the components, and vehicle system integration issues.

ABSORPTION SYSTEMS - Absorption systems (Lithium bromide and Ammonia) have a higher complexity than conventional AC systems, but do offer a potential increase in efficiency if high temperature waste heat is available. This is an older technology, but one could use the background and history as advantages in problem solving and obtaining more readily available components. However, previous work was not on a small scale, and vehicle systems integration issues, including safety, would need to be addressed.

ZEOLITE SYSTEMS - Zeolite systems have a good potential for use in vehicle cooling, and good efficiencies have been proven. The materials (zeolite) are more readily available than metal hydrides. A disadvantage is that the working fluid becomes ice during the cooling and may present vehicle integration issues, as well as a lower limit on the cold side temperature. Research is needed to develop small components. Currently, companies (outside of the U.S.) are developing larger scale home zeolite systems (10 kW).

THERMOACOUSTICS - Thermoacoustics represent a longer-term but large opportunity for an elegant vehicle cooling solution. Current development is happening with LANL and Penn State University. The Navy is sponsoring Penn State to build a thermoacoustic refrigerator capable of moving 10 kW of heat–the largest capacity thermoacoustic refrigerator built to date. Thermoacoustics needs development to achieve its theoretical efficiencies, which are close to vapor-compression efficiencies, to reduce the size of the systems, and to increase system robustness.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS\

AC: Air Conditioning

DOE: Department of Energy

FTP: Federal Test Procedure, a standard city drive cycle

NREL: National Renewable Energy Laboratory

U.S.: United States