Feasibility Study of an Automotive Thermoacoustic Refrigerator

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ABSTRACT

Concerns regarding the environmental impact associated with the use of current vapour-compression refrigeration systems in automobiles have led to the investigation of alternative 'green' technologies. Thermoacoustic refrigeration, an emerging 'green' technology based upon the purposeful use of high-pressure sound waves to provide cooling, is the most promising replacement investigated so far. Thermoacoustic refrigerators use environmentally benign gases, are relatively simple and inexpensive to manufacture and can operate using a heat source, which leads to their appeal as a sustainable waste heat recovery device. In this paper, the feasibility of a thermoacoustic refrigerator driven by recovered heat from the waste exhaust gases of an automobile is investigated. Practical considerations and calculations incorporating typical performance characteristics indicate that an automotive waste-heat driven thermoacoustic air-conditioner is potentially feasible and warrants further investigation.

GLOSSARY OF TERMS

AHX	ambient heat exchanger
AMR	active magnetic regenerator
ATAR	automotive thermoacoustic refrigerator
CFC	chlorofluorocarbon
CHX	cold heat exchanger
COP	coefficient of performance
COP_r	Carnot relative coefficient of performance
GWP	global warming potential
HDTAR	heat driven thermoacoustic refrigerator
HHX	hot heat exchanger
TAR	thermoacoustic refrigerator
TE	thermoelectric
TEWI	total equivalent warming potential
VAR	vapour absorption refrigeration
VC	vapour compression
VMAC	vehicle magnetic air conditioner

INTRODUCTION

'Thermoacoustic' refrigeration is an emerging technology based upon the purposeful use of intense acoustic waves to pump thermal energy into or out of a volume of fluid. This technology offers comparable efficiency to conventional systems, without environmentally harmful working fluids, significant maintenance requirements or high construction costs. Thermoacoustic refrigeration can be driven using heat as a direct input energy source, and as such is appealing for waste energy recovery from heat sources such as hot exhaust gas streams from existing thermodynamic processes.

Current refrigeration and cooling systems for automobiles are vapour-compression systems, which have been continuously developed and refined since their inception in the 1930s. They work by a heat transfer process that occurs when a working fluid is compressed and expanded. Vapour compression systems are well understood, reliable, and compact. Although vapour-compression systems are widely used in the automotive industry, the compressor draws significant power from the engine, which decreases the overall efficiency of the vehicle. The refrigerant often leaks from the air-conditioner into the atmosphere, and is a contributor to global warming.

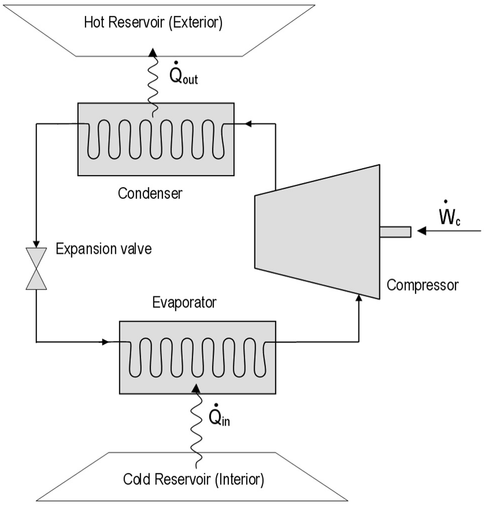
Advances in the development of thermoacoustic refrigeration could provide an alternative solution for cooling vehicles which could use hot exhaust gases as an energy source. A thermoacoustic refrigerator does not need a compressor, and hence lowers fuel consumption, increases the available engine power and overall system efficiency. Thermoacoustic refrigerators can use easily-obtainable noble (inert) gases as a working fluid, which pose a significantly reduced environmental impact compared to R-134a and R-22 refrigerants used in modern vapour-compression systems. In addition, the construction of thermoacoustic refrigerators is relatively simple, potentially resulting in a lower priced system compared to a vapour-compression system, and virtually eliminating ongoing maintenance costs.

This paper contains a discussion of the feasibility of a thermoacoustic refrigeration system in an automotive application powered by the waste heat present in a vehicle's exhaust. First, a comparison will be made between vapour compression systems and other systems considered to be alternative automotive refrigeration systems with less environmental impact. Following this, the basic operation of a thermoacoustic system is reviewed. Several key considerations regarding the waste heat available from vehicle exhausts and in the design of an automotive thermoacoustic refrigerator is then discussed.

VAPOUR COMPRESSION REFRIGERATION SYSTEMS

Modern automotive air conditioning and refrigeration systems are based upon the vapour-compression (VC) refrigeration cycle as shown in Figure 1, which is a non-ideal form of the Carnot refrigeration cycle. Automotive air conditioning systems based on the VC cycle have been in development since the 1930s (Bhatti 1999b).

In an automotive VC air-conditioning system, a refrigerant is expanded such that it removes heat from a heat exchanger in the return air duct to the vehicle interior, and compressed in a rotary compressor to deliver heat to a heat exchanger outside the vehicle interior. Compression is typically achieved by drawing power from the engine crankshaft. Expansion of the refrigerant is provided by the use of a simple one-way throttling valve. Heat exchangers are likely to be finned-tube radiators, with modern examples constructed from aluminium.



Source: adapted from Moran and Shapiro (2000:517)

Figure 1. Main components of a vapour-compression cycle.

Refrigerants

For over fifty years until the early 1990s, the most common refrigerant in VC cycles was the chlorofluorocarbon (CFC) Refrigerant 12, termed 'R-12' (Moran 2000). The presence of chlorine in R-12 (and also in the widely used Refrigerant 22) was found to be a major contributor to depletion of the ozone layer in the earth's atmosphere when released. Refrigerant 22, another common refrigerant termed 'R-22', is widely used in VC systems and offers reduced environmental impact by replacing some of the chlorine atoms with hydrocarbons (Moran 2000). In a progressive move away from refrigerants with a high potential for ozone layer depletion, Refrigerant 134a (R-134a) was accepted as a replacement for R-12 in the early 1990's (Brown 2002).

There are a diverse range of alternative air-conditioning refrigerants under consideration for use in VC systems. Ammonia, propane and methane are all under investigation as replacements; however the toxicity of ammonia and the flammability of propane and methane demand careful consideration in design.

Brown *et al.* (2002) comment on strong research efforts into CO_2 in the late 1990's. The use of CO_2 as a refrigerant was common in the 19th century, and it is now a potential replacement for R-134a. CO_2 has a global warming potential around 1,300 times less than R-134a and 8,500 times less than R-12 (Bhatti 1999a), and in 1998, Gentner (1998) showed that in comparison to R-134a systems, CO_2 systems in passenger vehicles had acceptable efficiency and cooling power capacities. However, Bhatti (1999a) argued that although CO_2 (as a released gas) has a reduced global warming potential than R-134a, the increase in fuel burnt to compensate for the decreased efficiency and increased weight of an equivalent CO_2 system would actually lead to greater global warming impact. Similar arguments have been made for VC systems using air as the refrigerant.

Other Drawbacks

Importantly, the adverse effects and pollution generated by petrol and diesel engines are amplified by the additional load imposed by the compressor, since the compressor draws precious mechanical power from the output of the vehicle engine.

Vapour compression refrigeration systems are complex and also require many parts distributed throughout the vehicle, connected to each other via a pressurised refrigerant circuit. In addition to the four main components as shown in Figure 1, modern automotive systems also use what is referred to as an 'accumulator' between the evaporator and compressor. The accumulator is used to contain the mixed liquid / gas phases of the refrigerant such that the compressor draws only the vapour phase. Compressors are bulky, require the use of lubricants and seals, and a faulty pressure sensor or leakage in the accumulator or any section of the system can lead to rapid wear and failure of the compressor.

ALTERNATIVE AUTOMOTIVE REFRIGERATION SYSTEMS

Efforts to address drawbacks in the use of vapour compression refrigeration systems include the development of alternative refrigeration systems besides thermoacoustics. Several of the most promising alternative technologies to vapour compression and thermoacoustic refrigeration systems are vapour absorption, solid adsorption, active magnetic regenerator, and thermoelectric refrigeration systems and they are discussed in the following sections.

Vapour Absorption Refrigeration Systems

Figure 2 shows a Vapour Absorption Refrigeration (VAR) system. This system differs from vapour compression refrigeration systems in that heat itself is used to compress the working fluid, as opposed to compression by mechanical work. Energy delivered to the generator is used to heat the working fluid to a vapour and 'pump' it at high-pressure and temperature to the condenser, where it rejects heat to its cooler surroundings. Liquid refrigerant exiting the condenser is throttled to a low pressure and at its coldest state in the cycle, accepts heat from the vehicle interior via the evaporator. The liquid refrigerant is then returned to the absorber (and to the generator via the small mechanical pump) to complete the cycle.

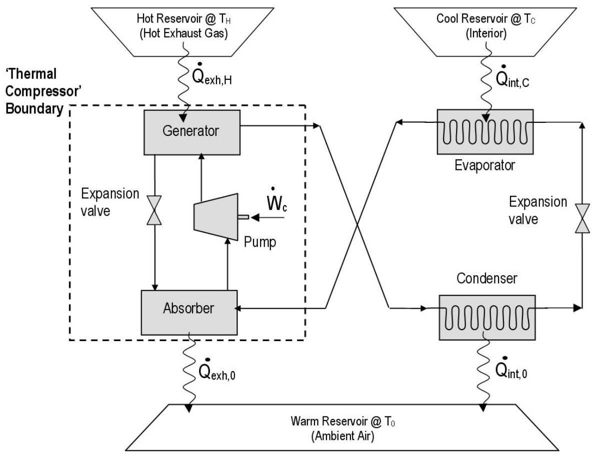


Figure 2. Diagram of a single-stage vapour-absorption refrigeration (VAR) cycle using an exhaust gas stream as an energy source.

Little mechanical work is required to operate the VAR cycle. The working fluid is usually an ammonia-water or lithium-bromide solution in water, which as a liquid is circulated with greater comparable efficiency than compressed gas. Ammonia-water systems were first developed around the start of the 20th century with the lithium-bromide systems around since the 1950's (Johnson 2002), which suggests there is already some manufacturing basis for development of an automotive application.

Regardless, VAR systems are bulkier, more expensive, heavier and less efficient than VC systems (Butler 2001). There is more equipment in a VAR system compared to a vapour compression system, a higher cost that is economically justified only when a suitable amount of otherwise wasted heat is available (Johnson 2002). In addition, the greater weight of the VAR system requires additional power from the engine to move the vehicle. The use of ammonia and corrosive lithium bromide require additional design considerations: ammonia is toxic and poses a risk to safety if leaked; lithium bromide is corrosive and creates hydrogen gas when it contacts ferrous containment systems (Johnson 2002) which affects the system efficiency.

Solid Adsorption Cooling Systems

Two types of solid adsorption cooling cycles, Metal Hydride and Zeolite, have both been successfully driven by hot exhaust gas streams (Johnson 2002).

Metal Hydride systems operate using two beds or pads of two different metal hydrides, and three heat exchangers, at hot, cold and ambient temperatures. Metal hydrides are metallic compounds which release heat upon absorbing hydrogen, and consume heat upon releasing hydrogen. Since the performances of metal hydrides are temperature-dependant, typical metal hydride systems use a high temperature (e.g. $ZrCrFe_{1.1}$, $LaNi_{4.75}Al_{0.25}$) and a low temperature hydride (e.g. $LaNi_5$, $MmNi_{4.15}Fe_{0.85}$) (Johnson 2002) paired together.

Using two beds of such metallic compounds, with one at a higher temperature than the other, heat is absorbed from the hot heat exchanger (exhaust gas stream) into the high-temperature hydride, which upon receiving heat, releases hydrogen into the low-temperature hydride, which in turn releases heat to the ambient heat exchanger. The pads are then moved, such that the high-temperature pad is at the ambient heat exchanger and the low-temperature pad is at the cold heat exchanger. This arrangement allows heat to enter the low-temperature hydride, which returns the hydrogen to the high-temperature hydride, which upon receiving the hydrogen releases heat to the ambient heat exchanger. The process is then repeated; however a pair of pads could be used to continuously draw heat from both the hot and cold heat exchangers.

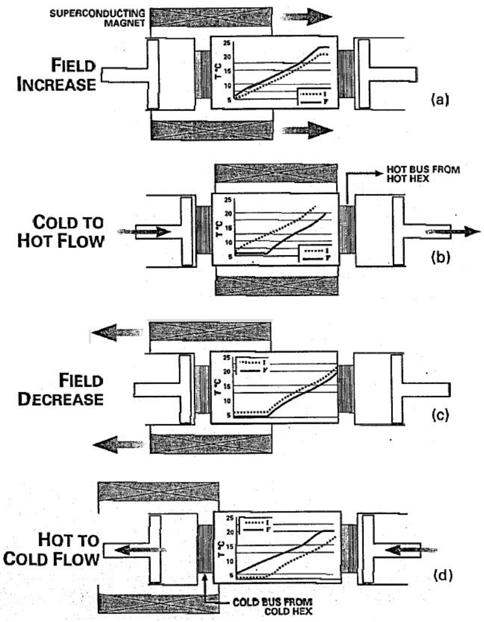
Zeolite systems have higher efficiencies than metal-hydride systems, and zeolite materials are inexpensive to obtain: the cost of enough metal hydride for a 2-pad refrigeration unit ranging from US$74 to US$360 (Johnson 2002). Zeolite systems are also non-toxic, non-flammable and insignificantly corrosive, however difficulty exists in their design due to the poor thermal conductivity of zeolite materials themselves (Lang 1999). The mass of zeolite systems seem to be similar to vapour-compression systems with specific cooling power densities approximately 0.1-0.3kW/kg (Wang 2002).

Active Magnetic Regenerator Systems

Active Magnetic Regenerator (AMR) systems operate in principle as shown in Figure 3 by using a magnetic element to magnetize and demagnetize a magnetic 'refrigerant,' and a porous bed through which a heat transfer fluid flows. The system makes use of a magneto-calorific effect in the solid refrigerant, whereby the addition and removal of the magnetic field increases and decreases the temperature of the refrigerant respectively. Magnetization is achieved by moving the superconducting magnetic sleeve over the solid refrigerant. A liquid coolant such as water is pumped into the porous refrigerant with suitable timing with the magnetic sleeve such that liquid flows from cold to hot whilst the refrigerant is magnetized and vice versa. Using this principle, the solid refrigerant doubles as a regenerator with high surface contact areas. Gschneidner *et al.* (2002) describe an automotive application of the technology referred to as the Vehicle Magnetic Air Conditioner (VMAC).

The major benefits of AMR technology is that as with thermoacoustic systems, there are no environmentally harmful refrigerants and efficiencies are higher than comparable VC refrigeration systems (Butler 2001). The porous magnetic bed is a solid which cannot easily escape the system, and the heat transfer medium is a liquid, which can be pumped with greater efficiency than gases. Gschneidner *et al.* (2002) argue that the process could result in Carnot efficiencies approaching 100%. In practice the efficiency is less than 100% and the preliminary design of Gschneidner *et al.* was expected to generate 1kW of cooling power at 30% Carnot efficiency.

The two most limiting issues with AMR technology are mass and cost. The 2002 study by Gschneidner *et al.* found that their VMAC was 2 to 3 times heavier than equivalent-capacity VC refrigeration systems. Furthermore, Butler (2001) states that whilst active magnetic refrigeration is more efficient than VC systems, the technology is still cost-prohibitive for building applications, where in comparison to automotive applications, the weight of the system is supposedly unimportant.



Source: Gschneidner *et al.* (2002)

Figure 3. Sketch of the active magnetic regenerator system cycle

Thermoelectric Devices

Thermoelectric (TE) device development arguably began in the early 19th century, when Seebeck (1822) demonstrated changes in the electrical potential across a junction of two dissimilar metals when a thermal gradient was applied to the junction. Now termed the Seebeck Effect, this phenomenon is used worldwide as an accurate form of temperature measurement, where such probes today are generally termed 'thermocouples'.

Peltier (1834) found indications that the reverse was true; application of an electric potential across a junction of two dissimilar metals resulted in a temperature difference across the junction not in agreement with Joule heating. Lenz (Ioffe 1957) demonstrated the results of Peltier's experiments were indeed due to the reverse of the Seebeck effect, and this form of TE cooling has since been referred to as the Peltier Effect.

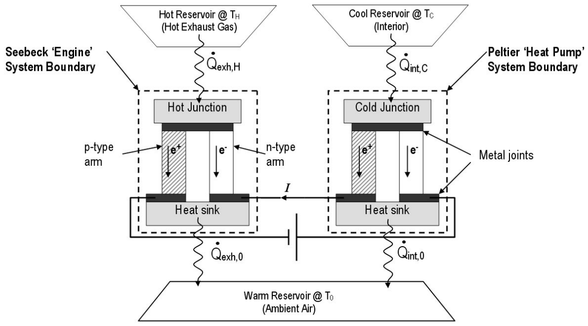


Figure 4. Sketch of Peltier cooler powered by a Seebeck generator

Figure 4 shows a conceptual combined Seebeck ('Engine') and Peltier ('Heat Pump') system, where electrical power extracted from the hot exhaust gas by the Seebeck device is used to drive a Peltier thermoelectric air-conditioner. The 'engine' and 'heat pump' shown in Figure 4 are shown to be identical in construction but opposite in usage.

Peltier-Seebeck thermoelectric devices have highly desirable qualities for automotive refrigeration in their scalability, adaptability, reliability and lack of refrigerants.

The greatest shortcoming with the use of Peltier thermoelectric devices is their poor thermal efficiency, which for the best TE material combinations (operating at room temperature) is less than 10% Carnot efficiency (DiSalvo 1999). Improvements in the efficiency of TE devices has been admittedly slow since the 1950's, in most part due to limitations in the thermoelectric properties of available materials.

An interesting comparative study between vapour compression, vapour absorption and thermoelectric refrigerators by Bansal and Martin (2000) highlighted the inefficiency of thermoelectric systems at a commercial product level. The refrigeration systems tested were all commercially available small hotel fridges of similar capacity, operated to maintain a fridge interior temperature of 5°C. The measured overall coefficient of performance of the TE refrigerator was 0.66, a COP almost 4 times less than the vapour compression system (2.59), however still a result better than that of the vapour absorption system (0.47).

Comparative Summary of Alternative Refrigeration Systems

Table 1 provides a simple comparison of the benefits offered by each alternative refrigeration system to vapour-compression (VC) refrigeration systems, in terms of relative cost to manufacture, total equivalent warming impact (TEWI) (Bhatti 1999a) relative coefficient of performance (COP_r), unit weight, and power density.

Table 1. Comparison of Refrigeration Systems.

System	Cost	TEWI	COP_r	Weight	Power Dens.
VC	OK	Poor	Good	Good	V.Good
VAR	Poor	Good	Poor	Poor	OK
Metal Hyd.	V. Poor	Good	Poor	OK	Poor
Zeolite	OK	Good	OK	OK	OK
AMR	Poor	Good	V. Good	Poor	OK
TE	Good	V. Good	V. Poor	OK	Poor
TA	V. Good	V. Good	Poor	Good	OK

THERMOACOUSTIC REFRIGERATION

The term 'thermoacoustic' is often used in reference to the observation that such systems convert heat power into acoustic power and vice versa. However, thermoacoustic systems so far constructed to date are also a complex application of both thermodynamic and acoustic theory.

Thermoacoustic systems can be divided into two different classes - 'heat engines' (also known as 'prime movers') and 'heat pumps'. In principle, heat engines take heat energy from a hot reservoir, convert some of the heat energy into acoustic energy and dump the unused heat to a cool reservoir. Heat pumps use acoustic energy to pump heat from one temperature reservoir to another, resulting in a temperature gradient between the two reservoirs.

Thermoacoustic refrigerators are typically driven either by a gas displacement system (such as a loudspeaker) or a thermoacoustic heat engine that generates high amplitude sound. Loudspeakers or electrodynamic shakers convert electrical power into acoustic power, are relatively easy to implement and can be inexpensive. In comparison, thermoacoustic heat engines have typically higher acoustic efficiencies. These devices also do not have moving parts, which suggests a long service life with no maintenance. Experimental heat engines commonly use resistive heating elements to convert electrical power into thermal power, which the heat engine converts into acoustic power.

Figure 5 shows a system diagram for an automotive thermoacoustic refrigerator (ATAR), in which the waste heat $Q_{exh,H}$ is used by a heat engine to produce acoustic power W_{acous}, which is then delivered to a heat pump to extract heat $Q_{int,C}$ from the vehicle interior. As shown in Figure 5, the major sources of heat entering the vehicle interior are the convective and radiant heat loads from the exterior environment, and the heat produced by the vehicle occupants.

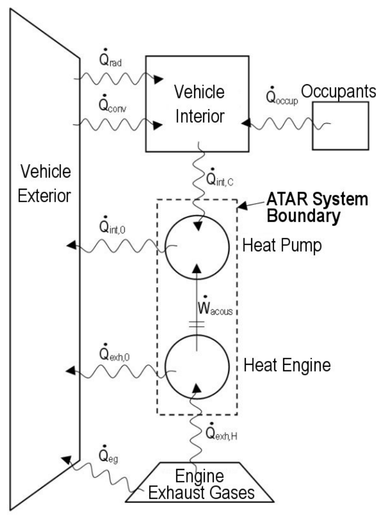
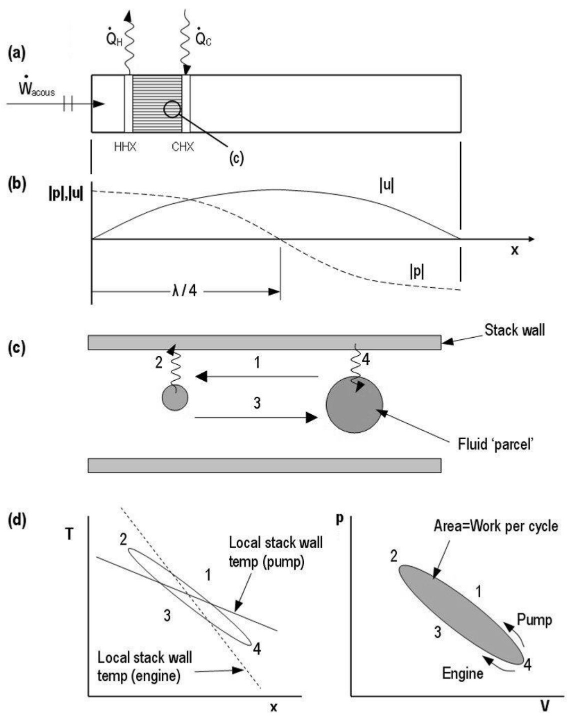


Figure 5. Diagram of automotive thermoacoustic refrigerator (ATAR) system

Principles of Thermoacoustics

Figure 6(a) shows a sketch of a simple half-wavelength thermoacoustic heat pump, in which the fluid inside the tube is excited by an acoustic source (not shown), such as a loudspeaker or heat engine. A 'stack' is located in the tube between a hot heat exchanger (HHX) and a cold heat exchanger (CHX), and its purpose here is to provide a continuous temperature distribution with intentionally imperfect thermal contact with the oscillating fluid. Stacks in thermoacoustic devices vary in geometry and construction but all provide a series of narrow gaps through which the fluid oscillates. Stacks are often constructed from assembling a stack of thin plates (Tijani 2002c), rolling up a sheet into a spiral (Tijani 2002c) or drilling holes through a solid billet (Hatazawa 2004).

Figure 6(b) shows the distribution of pressure and velocity throughout the device: the acoustic particle velocities are zero at the terminations of the tube, and a velocity antinode is present at the midsection. Quarter-wavelength designs, such as that shown in Figure 7, use an open termination, with a suitably tapered buffer volume to minimise fluid-wall separation losses (since the velocity antinode exists at the opening to the buffer volume). Besides being somewhat more compact in length, the quarter-wavelength configuration has less viscous flow losses than an equivalent half-wavelength design, since the acoustic velocity in the buffer volume is lower.



Source: (a) and (b) adapted from Wetzel and Herman (1997), (c) and (d) adapted from Backhaus and Swift (2002).

Figure 6. Sketch diagram of a half-wavelength thermoacoustic pump; the tube is closed at each end and an acoustic source (such as a loudspeaker) is used to pump heat; (b) Distribution of acoustic pressure and velocity amplitude along the axis of the device shown in (a); (c) Sketch of the thermodynamic cycle of a gas parcel inside the stack shown in (a); (d) Temperature versus position and pressure versus volume for the gas parcel shown in (c).

Figure 6(c) shows a close-up sketch of the stack in Figure 6(a), showing the stages in which the thermoacoustic heat pump cycle operates. The first and second graphs of Figure 6(d) indicate the temperature versus position and pressure versus volume of a parcel of fluid oscillating inside the stack respectively. With reference to Figures 6(c) and 6(d), consider a parcel of fluid oscillating along the axis of the device, in thermal contact with the stack plates. The four stages of the thermoacoustic heat pump cycle the fluid experiences are

1. **Compression**: The parcel of fluid is compressed as it moves from a lower pressure region to a higher pressure region, which causes an increase in its temperature;

2. **Heat Rejection**: The fluid parcel in its compressed state is hotter than the local stack temperature (Figure 6(d)), so heat is transferred to the stack, cooling the parcel of fluid;

3. **Expansion**: The parcel is returned to a lower pressure, and under expansion the fluid experiences a decrease in temperature; and

4. **Heat Withdrawal**: The parcel is now colder than the local stack temperature (Figure 6(d)), so heat is transferred from the stack to the fluid.

Two critical aspects to the sustainability of the cycle are (a) the thermal delays associated between the stack and the working fluid, and (b) the resonant acoustic environment in which the cycle takes place.

The material of the stack and its surrounding walls usually has good thermal capacity but poor conductivity, such that little heat is conducted from the HHX to CHX via axial conduction in the wall. It is desirable for the two heat exchangers to each have excellent thermal conductivity for contact with external heat sources and sinks. In this way, heat is 'pumped' between the ends of the stack, which are themselves exchanging heat with the exterior of the device.

Standing wave thermoacoustic heat engines operate in reverse to heat pumps, with the local stack temperature gradient higher than that of the cycle, as shown by the dashed line in Figure 6(d). A thermal gradient, dT_m/dx, is created by applying hot or cold temperature sources to the heat exchangers. Theoretically, when the thermal gradient in the stack exceeds what is commonly termed the critical temperature gradient (∇T_{crit}), an acoustic response in the stack is generated.

Working Gases

Thermoacoustic systems typically use commercial-grade helium, or mixtures of noble gases such as helium-argon or helium-xenon. The choice of working gas is often based upon the thermoacoustic power density, which Swift (2002) showed in a dimensionless analysis to be proportional to $p_m a$, the product of the mean pressure (p_m) and speed of sound of the gas (a). Since helium has the highest sound velocity and thermal conductivity of all inert gases (Tijani 2001), it makes for an excellent initial design choice. The high speed of sound allows the construction of relatively high-frequency devices without the necessary dimensions being too small. The high thermal conductivity increases the thermal penetration depth of the device, which increases the stack geometry to sizes that can be accommodated by relatively inexpensive manufacturing methods (Swift 2002).

Thermoacoustic devices are unique amongst potential automotive refrigeration systems in their use of helium gas. The environmental benefits that exist in using helium in thermoacoustic systems over rival technologies include

- zero global warming potential (GWP) from direct emissions;
- zero ozone depletion potential from direct emissions;
- the working gas does not necessarily need to be recaptured if replaced;
- the working gas is non toxic or flammable; and
- the system operates at comparably lower gas pressures to VC systems, reducing the weight of the system.

Other refrigerants used in rival technologies such as ammonia, butane, propane, HFCs, CFCs, HCFCs, and carbon dioxide have one or more of these problems.

WASTE HEAT ENERGY AVAILABILITY

Thermoacoustic refrigeration is a potential alternative in automotive or other transport applications since the cycle can be powered by heat, as opposed to electricity or mechanical power. In an automobile, the low thermal efficiencies of petrol or even diesel engines result in a significant amount of heat released to the environment, through various paths from the point of combustion, such as

- conduction through the combustion chamber walls into the engine cooling system, exiting via the radiator and exposed pipework;
- conductive transfer from the combustion chamber walls to the engine block exterior, and then convective and radiative transfer to the engine bay compartment;
- heat transfer from the exhaust gas stream to the exhaust manifold and exhaust system, then transfer to the environment; and
- retained heat in the exhaust gas stream exiting directly to the atmosphere at the exhaust outlet.

Hatazawa *et al.* (2004), who suggested that as much as 35% of the thermal energy generated from combustion in an automotive petrol engine was lost to the environment via hot exhaust gas and other radiation losses. Johnson (2002) indicated that for a typical 3.0L petrol engine with a maximum output power of 115kW, the total waste heat dissipated can vary from 20kW to as much as 400kW across the range of usual engine operation.

Horuz (1999) drove a domestic ammonia-water VAR system (of 10kW rated capacity) using the exhaust gas stream of a 6-litre turbocharged diesel engine, as used in large road transport vehicles. Horuz (1999) calculated the required heat input to reach full capacity to be 23.2kW, a heating load he demonstrated to exist in the exhaust gas stream for engine outputs above 35kW and 200Nm. Garrabrant (2003) estimated the average available heat energy in the exhaust stream of a typical truck diesel engine (such as that used by Horuz) at full engine load to be 66kW, whereas Horuz estimated it to be 120kW (with an engine output of ~103kW and ~470Nm) (Horuz 1999). However both Horuz and Garrabrant acknowledge that sufficient power to operate a VAR system is unavailable during idle conditions and low throttle inputs.

For a typical driving cycle, the time-averaged available heating power is around one to two orders of magnitude above the required cooling power. Johnson (2002) noted that for a typical and representative driving cycle of a three-litre petrol engine, the average heating power available was ~23kW, compared with the 0.8 to 3.9kW of cooling capacity provided by typical passenger car VC systems (Gschneidner 2002, Bhatti 1999a, 1999b). Furthermore, in the instance of a bus air-conditioner, refrigerant compressors are often driven by a separate smaller engine. If a thermoacoustic refrigerator with sufficient cooling capacity could be driven using the heat from the diesel engine's exhaust gas only, the compressor and its associated smaller engine could be eliminated altogether.

Hatazawa *et al.* (2004) used heat from the exhaust gas of a 4-stroke automotive petrol engine to drive a standing wave heat engine. The engine of Hatazawa *et al.* used very little heat input, was not tapered to address Rayleigh streaming, and was of small diameter (30mm) and capacity (W_{acous}=3W) (M Hatazawa 2004, pers. comm., 30 September), however their research confirmed that at typical operating speeds, sufficient temperatures and promising levels of heating power were present in the exhaust gas. For stable operation, thermal inputs to the thermoacoustic engine of Hatazawa *et al.* were reported to be in excess of 300W and at over 300°C, achieved with an engine speed of 2600rpm and a throttle opening of 35% (M Hatazawa 2004, pers. comm., 30 September).

Regardless, the amount of heat energy in an exhaust gas stream could be increased by reducing the heat transfer into the engine block, which in turn could lead to an increased acoustic power output. Research by Taymaz *et al.* (2003) showed that heat losses into the engine block of a diesel engine could be reduced as much as 25% by coating the internal faces of the cylinder and piston with a 0.5mm thick composite ceramic layer. Use of the insulative layer was shown to further increase the thermal energy and therefore the temperature of the exhaust gas. This would also increase the combustion efficiency of the engine.

Wendland (1993) calculated that at low Reynolds numbers (low engine speeds), nearly half of the total heat loss in a typical standard exhaust system occurred in the engine manifold section. It would be reasonable to expect that for continuous operation whilst the engine is at idle, a suitably designed thermoacoustic refrigerator would be located in the near vicinity to the exhaust manifold or immediately downstream of the catalytic converter, or an electric heating coil would be used to augment the available exhaust gas heating power.

PRELIMINARY DESIGN OF A HEAT-DRIVEN THERMOACOUSTIC REFRIGERATOR

A conceptual design of a heat-driven thermoacoustic refrigerator (HDTAR) is shown in Figure 7. This design is similar to the 'beer cooler' described by Wheatley *et al.* (1986) in that the thermoacoustic engine is placed close to the heat pump, with the ambient heat exchanger (AHX) of each closest together. In this way, the four heat exchangers are located in order of descending operating temperature from hot (HHX) to ambient (AHX1 and AHX2) to cold (CHX). Wheatley *et al.* (1986) acknowledge this arrangement of thermoacoustic engine and pump is suboptimal. The heat pump, which comprises a ceramic substrate stack sandwiched between the second ambient heat exchanger (AHX2) and cold heat exchanger (CHX), should ideally be located closer to the closed (left as shown) end, where the pressure amplitude is maximised and acoustic velocity (and associated viscous losses) is at a minimum. The HDTAR is approximately 950mm long, with ceramic stacks 50mm in nominal diameter.

To reduce construction costs, the HDTAR is designed using many of the components used for the loudspeaker-driven thermoacoustic refrigerator (TAR) that was completed in late 2004. The HDTAR is designed for use with helium pressurised to 700kPa, as per the existing 2003 TAR design. This was to minimise manufacturing costs and so that comparisons in the operating characteristics between using the thermoacoustic heat engine and the loudspeaker could be made.

The modelling program *DeltaE* (Ward and Swift 2003) is a useful design tool in the development of thermoacoustic systems. By entering the geometry and materials used in the construction of the HDTAR into DeltaE, the cooling performance of the device can be estimated for various operating conditions. For the preliminary design of the HDTAR, a heat input of $Q_{exh,H}$=300W and a desired cooling power of $Q_{int,C}$=30W with an ambient temperature of 27°C were arbitrary chosen. For these conditions, DeltaE estimated the fundamental resonance frequency to be 256Hz. For this frequency of operation, DeltaE was used to determine the steady-state temperature difference achieved at the CHX. In an automotive application, the CHX would theoretically be in contact with return air to the vehicle interior.

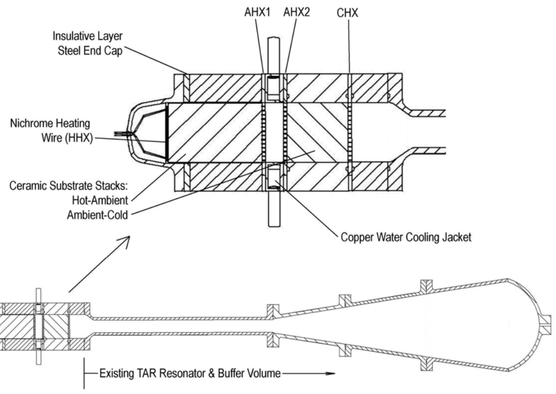


Figure 7. Cross sectional view of conceptual heat-driven 2003 TAR (HDTAR).

Figure 8 shows predictions made with DeltaE of several key parameters of the system under steady state operation. The internal axial coordinate x, where x=0 is on the left side of the HDTAR shown in Figure 7. As one would expect, particle velocities at each rigid end of the device are zero, and a pressure node (velocity antinode) exists at the end of the resonator. Also notable is the generation (increase) of acoustic power in the heat engine (HHX to AHX1) which is consumed in the heat pump (AHX2 to CHX).

As shown in Figure 8, DeltaE estimated the CHX and resonator temperature to be ~2°C, for 30W of cooling capacity and a 300W heat input. The maximum acoustic pressure amplitude was estimated to be ~186kPa (199dB re 20µPa) at x=0, and the maximum acoustic particle velocity to be 252ms^{-1} (Mach ~0.25) at the resonator termination (x=0.64m).

Practical Considerations for an Automotive Thermoacoustic Refrigerator (ATAR)

The authors are currently developing an automotive thermoacoustic refrigerator (ATAR), which is powered by the waste heat extracted from the exhaust gases of a typical passenger vehicle engine. The ATAR should provide sufficient cooling power yet be acceptably compact and of no more weight than a comparable VC system. Exhaust gas flow disturbances lead to backpressures, which adversely affect the engine efficiency, so the flow pressure drop across the heat extraction system for the ATAR must be minimised as far as practicable.

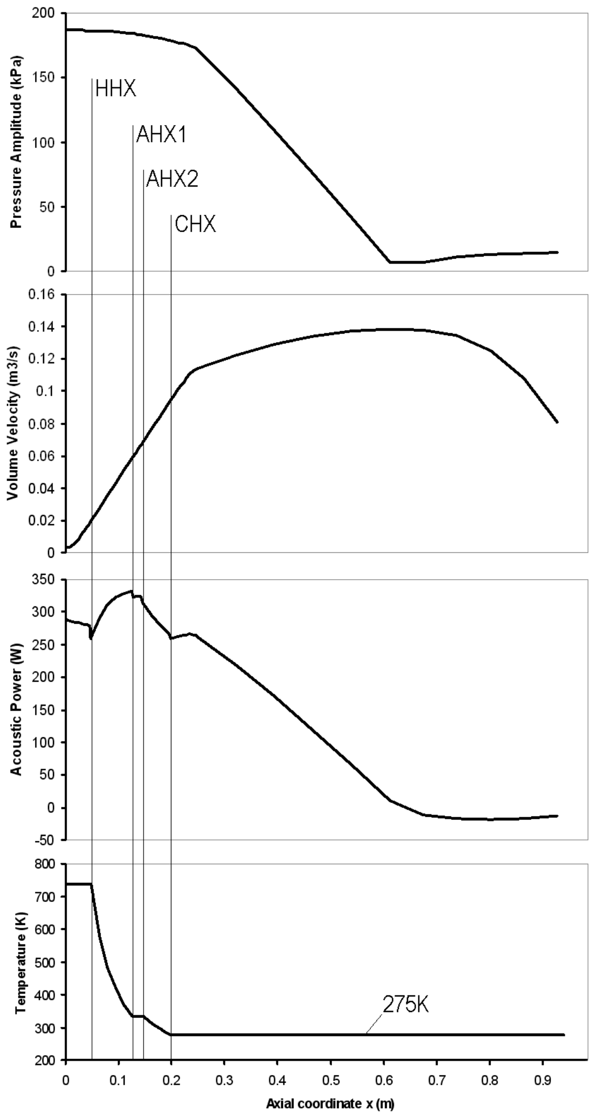


Figure 8. State variable plot of the HDTAR using 700kPa helium, 300W heat input, 30W cooling load, 256Hz operating frequency.

The cooling capacity of the ATAR could be increased by joining multiple ATAR units together. The power density could be increased by increasing the mean pressure of the working fluid from 700kPa to say 1.5MPa.

The size of the ATAR could be reduced by coiling the resonator into helix or spiral. In a production version, high strength injection-moulded plastics such as ABS could be used to achieve this shape, provide a smooth internal finish and minimise weight. If the uncoiled length of the device was 500mm, the operating frequency would be approximately 1,000Hz if helium gas was used as the working fluid.

An order of magnitude estimate for the total rate of heat exchanged at each heat exchanger (H_2) (i.e. total power) of the proposed ATAR was calculated using Swift (2002, Eq. 5.33):

$$\dot{H}_2 \approx \frac{1}{8}|p_1||U_1| \approx \frac{|p_1|}{p_m}\frac{|\langle u_1\rangle|}{a}\frac{p_m a A}{8} \tag{1}$$

where $|p_1|/p_m$ is the ratio of the acoustic pressure amplitude to mean static pressure; $|\langle u_1\rangle|/a$ is the ratio of mean acoustic velocity $\langle u_1\rangle$ (along the device axis) to gas sound speed a; and A is the cross sectional area of the device through which the working fluid oscillates. It is assumed that the temperature gradient in the engine stack is 50% above the critical (onset) temperature gradient, i.e. $|(dT_m/dx)/\nabla T_{crit}| \approx 1.5$.

Preliminary design characteristics of the ATAR suggest that with $|p_1|/p_m = 0.08$, $|<u_1>|/a = 0.05$, an operating pressure p_m of approximately 15bar helium and a stack diameter of 75mm, the order of magnitude estimate is 3.3kW. On the basis of this initial estimate, the total capacity of a single ATAR is likely to be of same order of magnitude as the maximum cooling requirement.

In this region of high pressure amplitude thermoacoustics, non-linear effects are likely to significantly affect the predicted performance of the system using computational or current analytical methods. However, the environmental and economic benefits of thermoacoustic systems are factors in driving the research of the technology to a technology demonstrator.

DISCUSSION

The costs in implementing a production-ready thermoacoustic system in an automotive application appear to strongly outweigh those of VC systems and alternative automotive refrigeration systems discussed here. The two largest concerns with such an application, being cooling capacity and available heating power, are not insurmountable barriers to the development of the technology as a replacement. Advances in the design and understanding of high-amplitude thermoacoustic systems will lead to more efficient, powerful systems, and the use of electrical heater elements to augment the exhaust gas heating power is a possible option.

CONCLUSION

Of all the alternative refrigeration technologies considered as replacements for automotive vapour-compression systems, thermoacoustic refrigeration is most appealing in terms of economic and environmental benefits.

Practical considerations and performance estimates indicate that an automotive waste-heat driven thermoacoustic air-conditioner is functionally feasible, however further investigation is needed with regards to sufficient cooling capacity.

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REFERENCES

Backhaus, S.N., and Swift, G.W. (2002) ‘New varieties of thermoacoustic engines’, *Proceedings of the Ninth International Congress on Sound and Vibration*, Orlando FL, July 8-11, vol. 502.

Bansal, P.K., and Martin, A. (2000) ‘Comparative study of vapour compression, thermoelectric and absorption refrigerators’, *Int. J. Energy. Res.*, vol. 24, pp. 93–107.

Bhatti, M.S. (1999a) ‘Enhancement of R-134a automotive air conditioning system’, *SAE Technical Paper*, no. 1999-01-0870.

Bhatti., M.S. (1999b) ‘Evolution of automotive air conditioning - riding in comfort: Part II’, *ASHRAE Journal*, September.

Brown, J.S., Yana-Motta, S.F. and Domanski. P.A. (2002) ‘Comparitive analysis of an automotive air conditioning systems operating with CO2 and R-134a’, *Int. Journal of Refrigeration*, vol. 25, pp. 19–32.

Butler, D. (2001) *Life after CFCs and HCFCs*. Technical report, Building Research Establishment (BRE), Watford UK.

DiSalvo, F.J. (1999) ‘Thermoelectric cooling and power generation’, *Science*, vol. 285, pp.705–706.

Garrabrant, M.A. (2003) ‘Proof-of-concept design and experimental validation of a waste heat driven absorption transport refrigerator’, *ASHRAE Transactions*, vol. 109 no. 1, pp. 401–411.

Gentner, H. (1998) ‘Passenger car air conditioning using carbon dioxide as refrigerant’, *Proceedings of the Natural Working Fluids ‘98*, IIR-Gustav Lorentzen Conference, Oslo, Norway, pp. 303–313.

Gschneidner, K.A., Pecharsky, V.K., Jiles, D. and Zimm, C.B. (2002) *Development of vehicle magnetic air conditioner technology*. Technical report, Institute for Physical Research and Technology, Iowa State University, Iowa.

Hatazawa, M., Sugita, H., Ogawa, T. and Seo, Y. (2004) Performance of a thermoacoustic sound wave generator driven with waste heat of automobile gasoline engine. *Transactions of the Japan Society of Mechanical Engineers (Part B)*, vol. 70, no. 689, pp. 292–299.

Horuz, I. (1999) ‘Vapor absorption refrigeration in road transport vehicles’, *Journal of Energy Engineering*, vol. 125, no. 2, pp. 48–58.

Ioffe, A.F. (1957) Semiconductor thermoelements and thermoelectric cooling. *Infosearch*, London.

Johnson, V.H. (2002) Heat-generated cooling opportunities in vehicles’, *SAE Technical Papers*, no. 2002-01-1969.

Lang, R., Roth, M., Stricker, M. and Westerfield, T. (1999) ‘Development of a modular zeolite water heat pump’, *Heat and Mass Transfer*, vol. 35, pp. 229–234.

Leivo, M.M., Pekola, J.P. and Averin, D.V. (1996) ‘Efficient Peltier refrigeration by a pair of normal metal / insulator / superconductor junctions’, *Appl. Phys. Lett.*, vol. 68, no. 14, pp. 1996–1998.

Lu, Y.Z., Wang, R.Z., Jianzhou, S., Zhang, M., Xu, Y.X. and Wu, J.Y. (2003) *Performance of a diesel locomotive waste-heat-powered adsorption air conditioning system*. Technical report, Inst. of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200030, China.

Mei, V. (1979) ‘A truck exhaust gas operated absorption refrigeration system’, *ASHRAE Transactions*, vol. 85, pp.66–76.

Moran, M.J. and Shapiro, H.N. (2000) *Fundamentals of Engineering Thermodynamics*. John Wiley and Sons Inc, New York.

Peltier, J.C. (1834) ‘Nouvelles experiences sur la caloricite des courans electriques’, *Annales de Chimie*, vol. 56, pp. 371–387.

Seebeck, T.J. (1822) ‘Magnetische polarisation der metalle und erze durch temperatur-differenz’, *Abhandlugen der Deutschen Akademie der Wissenschaften zu* (Berlin), pp. 265–373.

Sun, D., Qiu, L., Zhang, W., Yan, W. and Chen. G. (2004) ‘Investigation on travelling wave thermoacoustic heat engine with high pressure amplitude’, *Energy Conversion and Management*, vol. 46, pp. 281–291.

Swift, G.W. (2002) *Thermoacoustics: A unifying perspective for some engines and refrigerators*. Acoustical Society of America, Melville, NY.

Taymaz, I., Cakir, K., Gur, M. and Mimaroglu, A. (2003) ‘Experimental investigation of heat losses in a ceramic coated diesel engine’, *Surface and Coatings Technology*, vol. 169-170, pp. 168–170.

Wang, R.Z. (2002) *Adsorption refrigeration research and applications in SJTU*, Technical report, Institute of Refirgeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200030, China.

Ward, B., and Swift, G.W (2001) *Design Environment for Low-Amplitude ThermoAcoustic Engines (DeltaE) Tutorial and User's Guide.* Version 5.1, Los Alamos National Laboratory, New Mexico.

Ward, B. and Swift, G.W. (2001) *Design Environment for Low-Amplitude ThermoAcoustic Engines (DeltaE) Tutorial and User's Guide (Version 5.1)*, Los Alamos National Laboratory, New Mexico.

Wendland, D.W. (1993) 'Automobile exhaust-system steady-state heat transfer', *SAE Technical Paper*, no. 931085.

Wetzel, M. and Herman, C. (1997) 'Design optimisation of thermoacoustic refrigerators', *Int. J. Refrig*., vol. 20, no. 1, pp. 3–21.

Wheatley, J.C., Swift, G.W. and Migliori, A. (1986) 'The natural heat engine', *Los Alamos Science*, vol 14, Los Alamos National Laboratory, New Mexico.