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An Overview of Vehicle Test and Analysis from NREL's A/C Fuel Use Reduction Research

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An Overview of Vehicle Test and Analysis Results from NREL's A/C Fuel Use Reduction Research

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Abstract

The primary mission of the National Renewable Energy Laboratory's Vehicle Ancillary Load Reduction Task is to develop and evaluate technologies that reduce the fuel use for automobile air conditioning. Using thermal comfort-based logic, we project that the United States uses 7 billion gallons of fuel per year for air conditioning light-duty vehicles. This paper summarizes results of air-conditioning fuel use reduction technologies and techniques evaluated over the last 10 years.

1 INTRODUCTION

It takes energy and therefore fuel to provide climate control for vehicle occupants as well as energy for defrosting. In the past, air conditioning has been provided by a compressor driven directly by engine power while heating was provided by engine waste heat via engine coolant or in severe climates supplemented by a fuel-fired heater or an electric heater. Little thought has gone into significantly reducing fuel use for vehicle climate control. However, recent times with higher fuel prices, stricter emission requirements, down-sized engines with less waste heat, and advanced powertrain control strategies, such as idle-off controls (where there are times with little waste heat and no engine output power), have lead to a concerted effort to develop new, effective climate control systems. Likewise, plug-in hybrid electric vehicles may have long periods without engine operation.

Fuel used for vehicle climate control significantly affects the United States energy security by decreasing the fuel economy of the 229.8 million light-duty conventional vehicles(1). Using the vehicle simulation software ADVISOR(2), a National

Renewable Energy Laboratory (NREL) analysis shows air conditioning (A/C) increases fuel consumption between 1.8 and 2 l/100 km for a conventional gasoline and diesel powered medium-sized sedan over the Federal Test Procedure drive cycle (Figure 1).

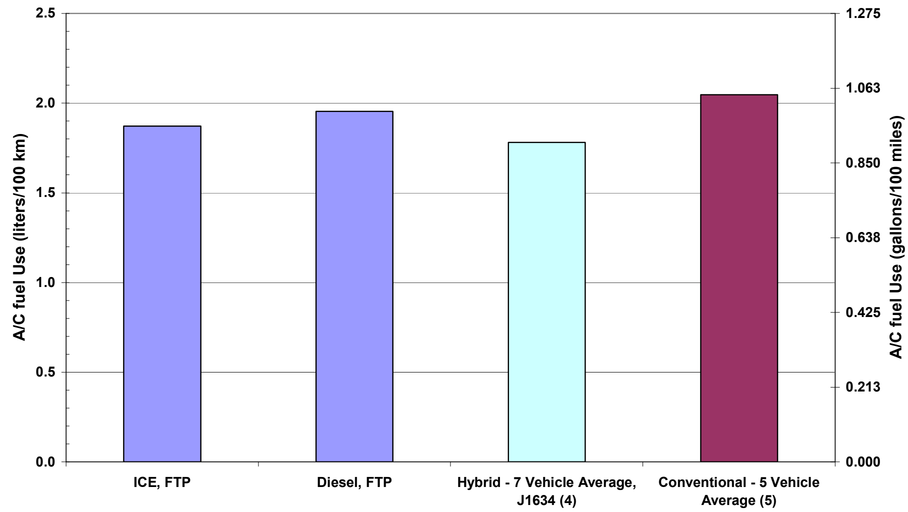

Figure 1. Vehicle A/C fuel use

The A/C system is a baseline R134a configuration controlled to a 5ºC evaporator temperature with ambient conditions of 25ºC and 65% relative humidity. The baseline fuel use for the gasoline and diesel vehicles is 10.2 and 8.6 l/100km (23.1 and 27.2 mpg) respectively.

A/C can also reduce the fuel economy of advanced vehicles by as much as 35%. Testing of a 2000 Honda Insight and 2001 Toyota Prius over the SC03 drive cycle show a 1.9 l/100km increase in fuel consumption due to the operation of the A/C(3). Test results from more recent hybrid vehicles assessed by the U.S. Department of Energy's Idaho National Laboratory are also plotted in Figure 1 and show a similar 1.8 l/100km increase in fuel use over the SAE J1634 drive cycle(4). Data from the U.S Environmental Protection Agency shows similar magnitude of fuel use over the SC03 drive cycle(5)

We have calculated the U.S. national and state-by-state fuel use impact of air conditioning in light-duty vehicles(6,7,8). Our analysis used a bottom-up approach to estimate the fuel used in vehicles for air conditioning per year. A thermal comfort model determined the percentage of time that a driver used the air conditioning based on the premise that people dissatisfied with their thermal environment will turn on the air conditioning. Environmental conditions were an important input to the comfort model. The thermal comfort results were then combined with statistics on when people drive (time of day), where they live (climate including cloud cover), and how far they drive in a year. Finally, vehicle simulations determined the fuel use penalty of using the air conditioning in cars and trucks. This algorithm determined the fuel used for air conditioning in light-duty vehicles.

The analysis showed that the United States uses approximately 7.0 billion gallons of gasoline every year for air conditioning vehicles(8), equivalent to 5.5% of domestic light-duty vehicle petroleum consumption(9). It would take 9.5% of U.S. imported crude oil to produce this much gasoline(10). We expanded the analysis to cover Europe and Japan in 2003 and more recently investigated India, Mexico City, and Australia.

There is currently a great opportunity to reduce A/C fuel use and emissions because the world's attention is focused on mobile air conditioning (MAC) like never before. The European Commission has passed a regulation prohibiting MAC refrigerants with a GWP > 150, which bans the currently used HFC-134a in new cars. Although the regulation does not specifically address MAC fuel use, the Association des Constructeurs Europeens d'Automobile (ACEA) and its members have a voluntary agreement to reduce CO_2 emissions of vehicles sold in the European Union. Reducing the A/C fuel use helps meet the aggressive targets. The California Air Resources Board is rewarding the incorporation of improved efficiency A/C compressors in its 2004 greenhouse gas emissions regulation. In the 2006 proposed U.S. Environmental Protection Agency fuel economy window sticker update, the fuel use from MACs will be incorporated into the new test/calculation methodology for determining miles per gallon.

2 APPROACH TO REDUCE MOBILE AIR-CONDITIONING FUEL USE

While most emphasis is on efficient equipment because suppliers manufacture hardware, the emphasis should begin with reducing the thermal load, such that equipment size is as small as possible. Reducing the cooling thermal load may include reflecting the infrared portion of the solar spectrum through reflective glazing, shades, and/or paint, minimizing conduction into the cabin via body insulation, or rejecting heat to the ambient using active or passive ventilation of the vehicle cabin or heat pipes while it is parked in the sun. In the winter, reducing the cabin heat loss will become increasingly important in advanced vehicles where waste heat is not readily available such as a plug-in hybrid vehicle operating in all-electric mode. Options include increased body insulation and advanced glazings with low-emissivity coatings or multiple layers.

After the load is reduced, then the next logical step is to remove energy as effectively as possible from the occupants. Conditioning the entire cabin can be inefficient when there is only one occupant. Technologies might include occupant sensor, body coolers, and conditioned seats.

The final step is to design efficient equipment. Waste heat should be used when possible, even for cooling using techniques such as thermoacoustic systems, absorption systems, or adsorption systems (such as metal-hydride). Climate-control equipment must be capable of operating without the engine and should minimize fuel cost. Electric energy can be used to operate an electric air-conditioning compressor, perhaps even operating in a heat pump mode to provide heating. However, electric heating can be expensive but might be an effective technique for direct delivery, such as heated seats or heated windshields.

The options are many and include initial as well as operating costs. The barriers are high because an effective solution will involve multiple disciplines (such as seating, glazing, body, engine, etc.) that normally do not collaborate. However, the potential to reduce fuel use for A/C and increase occupant comfort is great.

3 REDUCING THE THERMAL LOAD

3.1 Solar-Reflective Glazing

When a vehicle is parked, typically 50 to 75% of the thermal energy entering the passenger compartment is from the transmitted and absorbed solar energy at the glazings(11). Transmitted energy is primarily absorbed directly by the interior mass. The absorbed energy at the glazing is transferred to the interior by convection and re-radiation in the thermal infrared wavelength range. Reflecting the incident solar radiation at the vehicle glazings is a critical step to making significant reductions in the thermal loads. With lower thermal loads, there is potential to reduce the capacity of the A/C system.

A 3M nonmetallic solar-reflective film was soak tested in two minivans (tan Dodge Grand Caravans) and two sport utility vehicles (black Ford Explorers)(12). The configuration with solar-reflective film on all glazings had the best thermal performance with a 1.8°C (3.2°F) reduction in maximum breath temperature. The maximum instrument panel temperature was reduced by 3.4°C (6.1°F) in this case. These results were not as good as other solar-reflective technologies, but an advantage of the nonmetallic construction is that it does not attenuate electromagnetic transmission/reception from cell phones and other communication devices.

NREL and PPG Industries conducted a test program with Sungate laminated solar-reflective glass installed in a Ford Explorer to quantify improvements in fuel economy and reductions in tailpipe emissions(13). Sungate is a solar-reflective coating consisting of a double stack of silver and dielectric layers. The vehicle with the solar-reflective glazing at all locations had a maximum breath temperature 2.7°C (4.9°F) lower than the baseline vehicle, and the instrument panel was 7.6°C (13.7°F)

More recently, NREL tested a new type of solar-reflective glass that improves reflection of the near-infrared portion of the solar spectrum on a 2005 Cadillac STS as part of the Improved Mobile Air Conditioning Cooperative Research Program (I-MAC)(14). The Sungate EP allows only 3% of the infrared energy to be transmitted through the glass. Figure 2 shows this technology at all glazing locations reduced the average air temperature by 7.1°C (12.8°F), seat temperatures by 8.7°C (15.7°F), windshield temperature by 19.3°C (24.7°F), and the instrument panel surface temperature by 14.6°C (26.3°F). Another way to assess these data is in terms of the maximum possible temperature reduction. For the solar-reflective glass

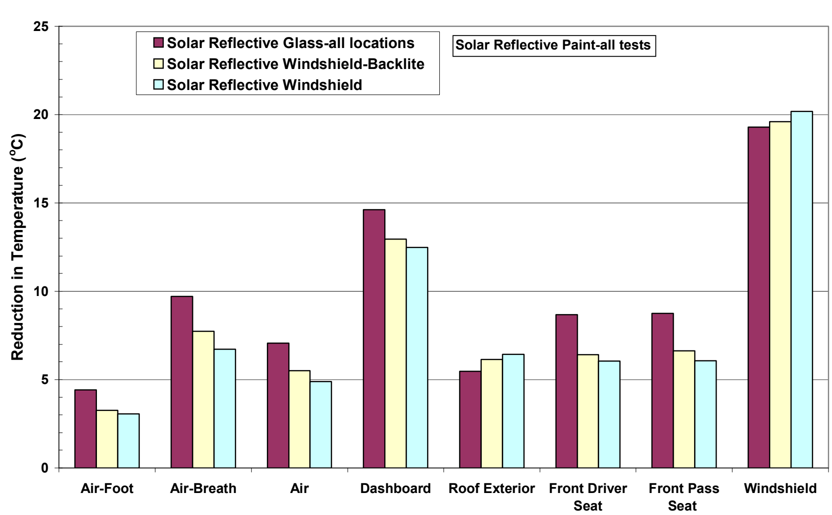

Figure 2. Cadillac STS – reduction in temperature

in all locations, the average air temperature is reduced 34% of the maximum possible while the seat temperature is reduced 35%.

Solar-reflective glass would also reduce the steady state thermal loads when the vehicle is being driven with the A/C on. In cold environments, solar-reflective glass would also reduce the temperature of the interior compared to traditional glazings. In today's vehicles, drivers have grown accustom to a warmer than ambient passenger compartment if the sun is out and it is cold outside. With solar-reflective glazings, the drivers will have to adjust their expectations to a cooler interior in the winter also, but interior temperatures would not be lower than ambient, and it would be no different from entering the car after the sun goes down.

3.2 Parked Car Ventilation

When the solar energy does enter the vehicle, it heats the interior mass of the passenger compartment including the air. Venting the warm air and pulling in cooler ambient air can reduce the temperature of the interior. NREL tested various natural and forced parked car ventilation techniques on a 2000 Jeep Grand Cherokee. The results show natural convection induced flow can be effective with strategically located air inlets and was as effective as forced convection ventilation using the HVAC blower on medium speed. Figure 3 shows the sunroof open 6 cm and floor inlets reducing the cabin air temperature 5.7ºC, 38% of the maximum possible temperature reduction, while the HVAC blower on medium reduces the breath air temperature 6.9ºC. While air entering the vehicle at the foot level enhances the natural convection flow, implementation challenges include preventing the entrance of moisture and contamination including exhaust products, dirt, and animals.

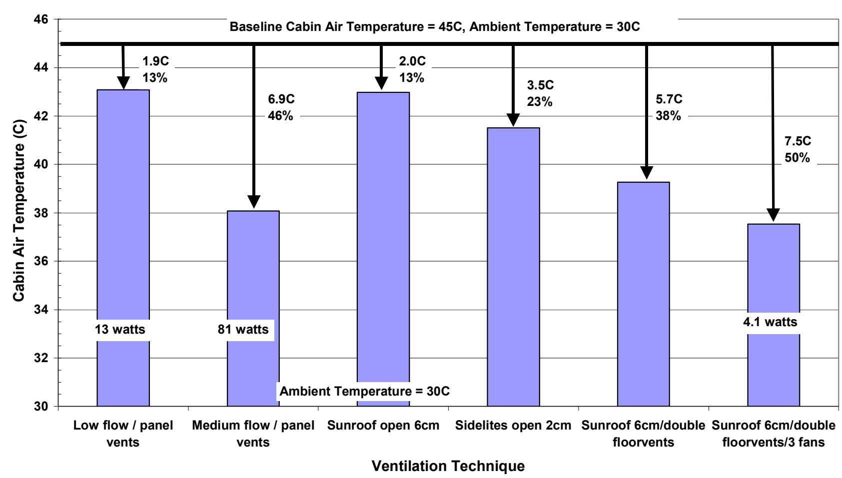

Figure 3. Parked car ventilation in a Jeep Cherokee

As part of the I-MAC thermal soak testing on the Cadillac STS, we tested a solar-powered parked car ventilation system(14). With air being pulled out of the vehicle, the average air temperature was reduced 5.6ºC and the seat temperatures were reduced 5-6ºC. This was 26% and 21% of the maximum possible temperature reduction respectively. Air was being pulled in through the HVAC heater/defroster ducts and the natural vehicle body leakage areas. Even though they don't reduce temperatures as much as solar-reflective glass, parked car ventilation technologies can be used in conjunction with solar-reflective technologies to significantly reduce interior temperatures. This combination in the Cadillac STS reduced the average air temperature 46% and the seat temperature 44% of the maximum possible(14).

3.3 Solar-Reflective Opaque Surface Coatings

If the exterior vehicle skin temperature is warmer than the interior surfaces, the resulting conduction heat transfer will warm the vehicle interior. This is more likely to occur when solar-reflective glazings and/or parked car ventilation are used and the interior is cooler. Using a 2001 Lincoln Navigator, NREL investigated the impact of solar-reflective coatings on interior cabin temperatures on a parked vehicle. We used two identical vehicles: one baseline and the other modified. A 3M visibly reflecting roof film reduced the breath air temperature 12% of the maximum possible temperature reduction, which is defined as the difference between the baseline vehicle breath air temperature and ambient. The exterior surfaces were covered with aluminium foil to determine the largest potential reduction. The breath air temperature was reduced 28% relative to the maximum possible reduction for this case.

As part of the I-MAC project, we soak tested a solar-reflective film on the roof of a stationary Cadillac STS in 2005. The film was an infrared reflecting product (CI-100T) manufactured by 3M. The baseline gray paint had a solar absorptance of 0.78, and the paint with film had a solar absorptance of 0.55. The 6.7ºC cooler roof temperature resulted in a less than 1ºC reduction in the breath air temperature (Figure 4). During the summer of 2006, we tested a prototype solar-reflective paint on the Cadillac STS. The baseline paint had a solar absorptance of 0.89 and the solar-reflective paint had a solar absorptance of 0.82. The exterior surface temperature was 6.0ºC cooler than the baseline. The impact of paint by itself was not tested, but we estimate the results would have been similar to the 2005 data. Ford found that reducing the vehicle soak temperature with solar reflective coatings can reduce the AC system requirements(15).

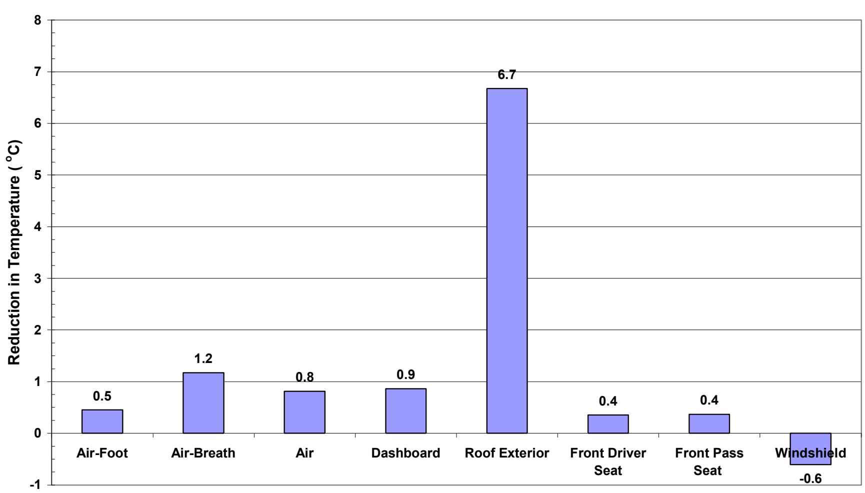

Figure 4. Cadillac STS – reflective roof

While skin temperatures can be significantly reduced with these technologies, the impact on interior temperatures is not that large because 1) the majority of thermal load is entering though the windows, 2) the roof is typically well insulated, and 3) wind reduces the advantage of the lower temperature skin by cooling the hot skin. If the vehicle is moving, the increased convective heat loss further reduces the thermal impact of the solar-reflective coatings.

3.4 Insulation

The benefit of headliner insulation depends on the exterior surface and interior temperatures. If the interior is warmer than the exterior (e.g., white paint with traditional glazings), then increased insulation in the headliner will make the car warmer. However if solar-reflective glazings and/or parked car ventilation are used to cool the car, then insulation may reduce the heat gain of a parked car. A computational fluid dynamics (CFD) analysis of a Jeep Grand Cherokee resulted in only a 0.2ºC reduction in average cabin air temperature due to insulation of the roof. As discussed in Section 3.3, advanced technology insulation on the roof of the Lincoln Navigator reduced the cabin breath air temperature 5% of the maximum possible. In a Cadillac STS, the addition of current technology roof insulation had little impact on the interior soak temperatures.

For reducing the parked car thermal loads in conventional vehicles, insulation was not very effective. If the thermal loads are reduced with solar-reflective glass or ventilation, insulation may become more important. When the vehicle is in use, the case where the interior is cooler (A/C on in a warm environment) is common. In this case, insulation would reduce the thermal loads. Also in winter when the interior is warm and the environment is cold, insulation would help to reduce the heating load. In the United States, cabin heating is not an issue with today's vehicles due to the available waste heat, but will be a challenge for advanced vehicles and small diesels that have less (or no) available waste heat for cabin warming.

3.5 Instrument Panel Heat Pipe Cooling

When a vehicle is parked, the instrument panel can absorb a large amount of heat, attain temperatures approaching 100ºC, and impact driver thermal comfort and cool-down performance. A mock-up of a passenger compartment and instrument panel was built to assess the impact of cooling the instrument panel with heat pipes. Outdoor test results show that heat pipes cooled the instrument panel by nearly 20°C and the air temperature by 9°C to 12°C while maintaining a uniform temperature across the instrument panel during the day. Beside lower surface temperatures, the electronic components in the instrument panel would benefit from the lower temperatures as well as the reduced heat pickup of the A/C ducts. Barriers to incorporating heat pipes in the instrument panel include where to locate of the condensing section outside the cabin and the increased mass/volume of the heat pipes.

4 EFFICIENT DELIVERY OF CONDITIONED AIR

The goal of efficient delivery is to more effectively deliver climate control to each occupant, increasing thermal comfort with little energy cost, thereby reducing fuel use. Automotive seats have potential to improve delivery efficiency because of their large contact area with and close proximity to the occupants. Standard automotive seats thermally insulate the occupant and reduce evaporative cooling of sweat, increasing the occupant/seat contact temperature. Both actively ventilated seats and meshed seats are potentially low-energy approaches to improving thermal comfort and achieving efficient delivery of climate control.

The NREL Vehicle Climate Control Laboratory was developed to simulate the soak and cooldown of a vehicle passenger compartment(16). A compact car passenger compartment was thermally soaked for 3.5 hours using a 963 W/m^2 ± 23% full spectrum solar simulator. The average room environment was controlled to 31.6 °C ± 0.4 °C and

30% ± 5% RH. Both the ADvanced Automotive Thermal Manikin (ADAM) and the subjects were preconditioned in an office environment. ADAM and a subject entered the heat-soaked room, and the subject stood for 30 seconds before doing step exercises for 1 minute. The cooldown was started 45 seconds after cabin entry, allowing time for pre-cooldown votes to be taken.

Ventilated seats provided by W.E.T. Automotive Systems were tested(14). ADAM measured a seat contact temperature reduction of ~ 4.7 °C and an increase in heat loss from the back and bottom of ~ 60 W/m^2 between seat on-and-off cases. This resulted in an overall thermal sensation improvement of 0.28 (on a +4 to -4 scale). The average juror thermal comfort over the cooldown is shown in Figure 5. We estimate that the A/C system capacity could be reduced by 7%. Using NREL's A/C fuel use model(6,7,8), an estimated 522 million gal/year or 7.5% reduction in U.S. A/C fuel use could be achieved.

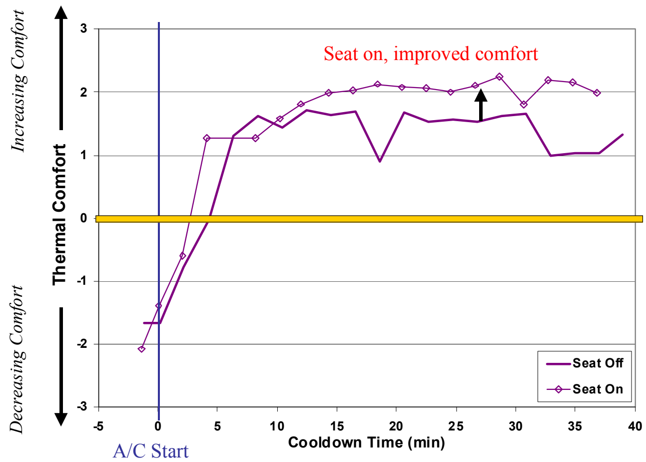

Figure 5. Ventilated seat improved comfort

A prototype meshed backseat was tested and provided encouraging results. With a reduced, 96% heat capacity A/C system, an average seat back and bottom temperature reduction of 4°C and 0.6 °C respectively were observed(16). Assuming that a meshed bottom would provide similar results to the meshed back, much of the thermal benefit gained through ventilation could be achieved using low-mass meshed seats while avoiding energy costs. A lack of thermal control, physical ergonomics, and safety is a significant challenge for mesh seats.

5 EFFICIENT EQUIPMENT

5.1 Improved Mobile Air Conditioning Cooperative Research Program Efficiency Team

As part of the I-MAC project, a team of engineers from automobile manufacturers, suppliers, and the U.S. government have been investigating techniques to improve the efficiency of MACs. The goal of efficiency team is to demonstrate an improvement of 30% in system coefficient of performance over the R134a System used in Phase II of the Alternate Refrigerant Cooperative Research Program. Results of the test and analysis will be available after the completion of the program.

5.2 Waste Heat Utilization - Thermoacoustics

Thermoacoustics is an innovative technology that uses sound to cool the interior of the vehicle or produce electricity. Thermoacoustic effects, which convert heat energy to sound, have been understood for over a hundred years. However, only over the past two decades has substantial improvements been made to the design of thermoacoustic engines and refrigeration cycles. Recent thermoacoustic refrigerators have flown on the space shuttle, cooled electronics in a U.S. Navy destroyer, and cooled Ben and Jerry's ice cream.

Thermoacoustics has many potential advantages over a conventional A/C system. It uses waste heat, is reliable and inexpensive, does not entail the use of an extra energy load on the engine, relies on gases that are environmentally benign, has no moving parts (and thus should have a long lifetime), and requires no lubrication. The downside is, because of its low energy density, the device could take up significant volume. If we can overcome that barrier, it could be one of the cooling technologies in your next-generation car.

During the last quarter of 2004, NREL designed and developed a standing- wave thermoacoustic device that pumps heat using a standing sound wave to take the working fluid (helium) through a thermodynamic cycle. We rely on the heating and cooling that accompany the compression and expansion of a gas in a sound wave to produce the cooling for the interior of a vehicle. The device is modular and allows for different stack designs and heat exchangers to be used in order to assess the most cost-efficient and best-performing components. Modeling efforts show that a thermoacoustic standing- wave engine/heat pump has a heat efficiency of approximately 15% and a heat pump coefficient of performance of approximately 1. The NREL team completed testing of the standing- wave thermoacoustic engine and heat pump during the early part of 2005. The thermoacoustic engine performed within 10% of modeled results. However, the heat pump only provided 20 watts of cooling. The poor performance of the heat pump was attributed to combining the room temperature heat exchanger for both the engine and heat pump into a single unit. It was determined that the pressure wave from the engine needs to be fully developed before it can be utilized for cooling. This problem can be easily rectified by separating the heat engine from the heat pump and utilizing two ambient heat exchangers. Although the standing- wave thermoacoustic system works, the size necessary to generate sufficient cooling power for a light-duty vehicle preludes its use. Therefore NREL researchers concentrated their efforts on developing a smaller travelling-wave thermoacoustic system.

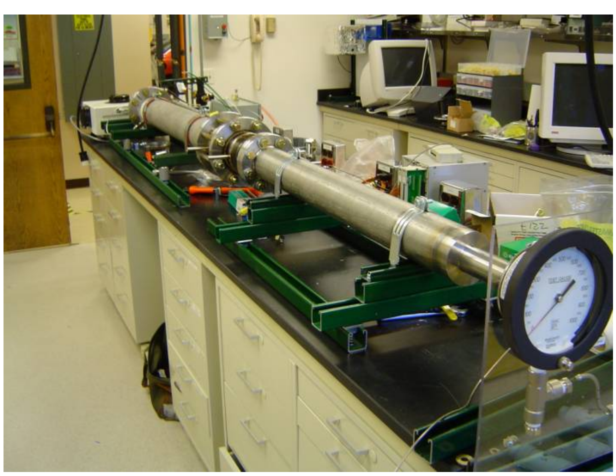

Figure 6. Travelling-wave thermoacoustic prototype

During 2006, the NREL team assembled and tested a travelling-wave thermoacoustic engine (Figure 6). Like the standing- wave prototype, the travelling-wave system was modular and allowed for different components (heat exchangers, regenerators, etc.) to be tested. In particular, we tested a micro-channel regenerator and a copper foam heat exchanger. It was determined from NREL's modeling and test results that a travelling-wave thermoacoustic system for direct vehicle cooling will not be viable for light-duty vehicles—the resonant cavity will be too large. In order to decrease the size of the resonant cavity, a new combination of gases, working fluid, will need to be found that will lower the resonant frequency of the device without lowering the power per unit volume. One way to decrease the length of the resonant cavity is to combine a heavier gas with a lighter gas. Unfortunately, combining gases precipitously reduces the power per unit volume, resulting in an unrealistically large diameter for the device in order to provide the necessary cooling for the vehicle. However, it was determined that a travelling-wave thermoacoustic system could still be used in light-duty vehicles for electricity generation. Electrical power could be produced through the use of a flexible membrane, which would also determine the resonant frequency of the thermoacoustic system and therefore its size. Future work should be concentrated on reducing the cyclical fatigue of such a membrane for eventual integration into light-duty vehicles.

6 TOOLS

6.1 Vehicle Solar Load Estimator

In order to fully understand solar-reflective glazings and their impact on heat load of passenger compartments, a Vehicle Solar Load Estimator was developed(17). The Vehicle Solar Load Estimator or VSOLE is GUI-driven and programmed in the MATLAB environment. The model calculates solar radiation transmitted, absorbed, and reflected by glazings as a function of the optical properties of the glazing, glazing location, vehicle geometry, vehicle orientation, time, and radiation source. The model accounts for the angular dependence of the optical properties for glass. The program can also display glazing properties and comparisons of different glazings under the same solar load and vehicle orientation as a function of time. This software is available to the public upon contacting the authors.

6.2 Integrated Climate-Control Modeling Process

A numerical model was developed to assess the impact of reducing the thermal load on A/C system capacity and vehicle fuel used for A/C. The numerical model of a Cadillac STS vehicle with solar-reflective glass, solar-powered parked car ventilation, and solar-reflective paint was developed using Fluent CFD software and RadTherm thermal analysis software. RadTherm is used to model the solar load on the vehicle, convection losses on the interior and exterior surfaces, and conduction through the surfaces. Fluent CFD

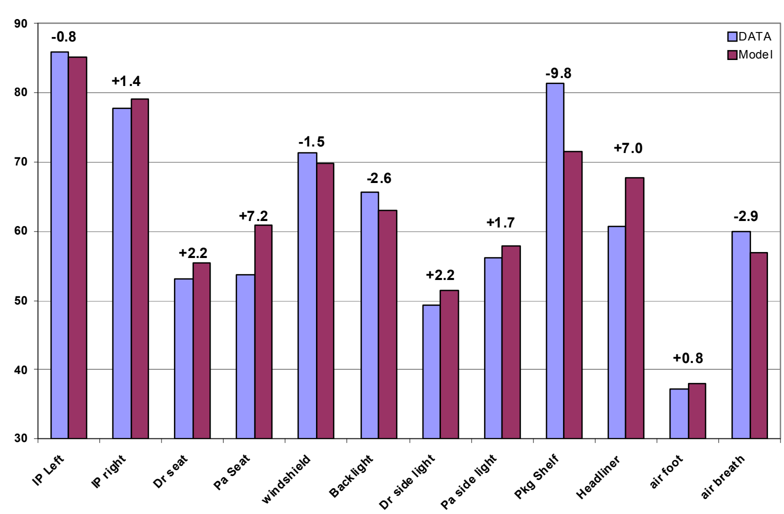

Figure 7. Baseline soak results comparison to test data

software was used to model the convective heat transfer and fluid flow in the cabin. The model was compared to quasi steady-state soak conditions, and Figure 7 shows excellent agreement to the data.

It was found that excessive run times were needed to achieve a cool-down simulation using the full CFD/RadTherm model. Therefore, a simplified model was created for the cool-down simulations, which used only RadTherm. This simplified RadTherm model was compared to STS cool-down data with the vehicle at idle conditions. The baseline model showed agreement with the data when A/C cooling capacity was 5.7 kW. The reduced thermal load model was then run with decreasing A/C capacity until the two models had equal cool-down at 30 minutes (Figure 8). The model showed that the A/C capacity could be decreased to 4.0 kW, a 30% reduction in A/C system capacity.

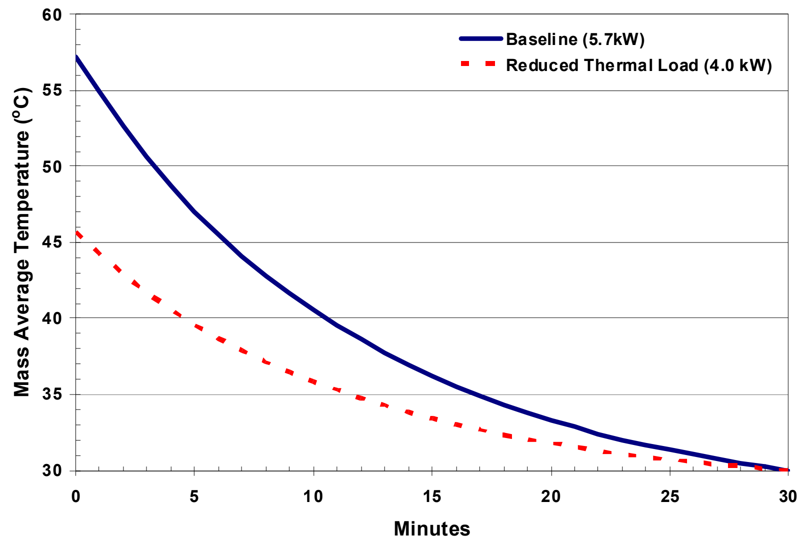

Figure 8. Mass average temperature

These results are consistent with data from Visteon where they tested a mid-sized sedan with insulated solar-reflected glazings and body insulation(18). An average temperature reduction of 3-4ºC during soak resulted in a 4-16% reduction in A/C power. This compares to the 11ºC reduction in mass average temperature for the Cadillac STS and the 30% reduction in A/C power.

Next the STS was simulated using the ADVISOR vehicle simulator to determine the effect of the reduced A/C load on fuel use. The A/C fuel use calculation followed the procedure used in reference 7. For the baseline case, we use a compressor power vs. rpm curve for the STS. For the reduced thermal load case, we reduce the compressor power by the same % reduction as the calculated % reduction in capacity. We are assuming the reduced thermal load A/C system has same COP as the baseline case. The vehicle simulation showed that reducing the A/C load by 30% resulted in a 26% reduction in A/C fuel use.

6.3 Thermal Comfort Tools

Designed to assess human thermal comfort in a transient nonhomogeneous environment, NREL's thermal comfort portfolio includes a manikin or ADAM, a Human Thermal Physiological Model, and a Human Thermal Comfort Empirical Model. The 126 porous metal segments of the manikin allow

Figure 9. ADvanced Automotive Manikin

independent control of surface temperature and sweat rate, and measurement of transient heat flux. The manikin, shown in Figure 9, can be clothed, and is designed for either tethered or wireless operation with an internal battery pack and radio transceiver(19,20).

The Human Thermal Physiological Model is a three-dimensional, finite-element model of the human thermal physiological and thermoregulatory systems. The model consists of bone, muscle, fat, and skin layers, as well as blood circulation. The thermoregulatory system physiological responses of vasodilatation/constriction, sweating, shivering, and variable metabolic or cardiac rates are simulated(21).

The Human Thermal Physiological Model controls the manikin, so the segments have human-like skin temperatures. Validation testing was performed to show the manikin/model respond like a human(22). The Human Thermal Comfort Empirical Model uses temperature data from the physiological model to predict local and global thermal comfort as a function of local skin and core temperatures and their rates of change(23).

7 BARRIERS

A critical barrier to the incorporation of advanced climate-control technologies is the increased vehicle cost. If there were a consumer demand, automobile manufacturers would have a financial incentive to incorporate the technologies discussed in this paper. In many cases, consumers simply do not know the technologies exist. Reduced fuel consumption has not been an important factor in the past; although, this can change quickly. It is clear that additional benefits, such as improved comfort and safety, are critical to the incorporation of advanced climate-control systems

Another barrier is that automobile manufacturers are sometimes hesitant to change. The risk of recalls is an important consideration. Thermal management crosses multiple disciplines at automotive original equipment manufacturers which sometimes makes system-level decisions difficult.

Since the A/C system is not operated during corporate average fuel economy tests, there has not been a fuel economy motivation to reduce the fuel use for MACs. Some have suggested adding an A/C on test to the CAFE tests, but the potential added complexity of a test that accounts for thermal load reduction is a barrier.

Barriers to utilizing waste heat for cooling include: relatively low and variable temperatures, particularly in fuel cell vehicle applications; weight; volume; corrosion; and engine back-pressure requirements.

8 CONCLUSION

NREL is pursuing a variety of avenues in its efforts to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle, while still keeping the passengers "comfortable." Because climate control loads can significantly impact the fuel economy and tailpipe emissions of conventional and hybrid electric automobiles, NREL is working closely with industry to develop techniques to reduce the auxiliary loads, such as climate control, in a vehicle.

Our research shows that technologies, such as solar-reflective glass and parked car ventilation, can significantly reduce the thermal loads and fuel use. Solar-reflective coatings and insulation had less of an impact on interior temperature, but could become increasing important as cabin thermal loads and as engine waste decreases in advanced vehicles. A critical benefit of reducing the soak thermal loads is that the occupants experience lower temperatures upon entering a hot-soaked vehicle and feel less discomfort. Additional energy savings can be realized by cooling the occupants through ventilated, cooled, and low-mass seats. Using waste heat to generate cooling with thermoacoustics was not feasible for light-duty vehicles, but there is potential for using a more compact thermoacoutic system to generate electricity.

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