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ABSTRACT

Based on a recent U.S. Environmental Protection Agency (EPA) study, about 95% of all trips start after a cold-soak period of 16 hours or less. By preserving the heat in the catalyst between trips, exhaust gases could be processed without warm-up delay and without the usual cold-start emissions. Vacuum insulation and phase-change thermal storage have been incorporated into a catalytic converter design to enhance its heat-retention time. Laboratory testing of a bench-scale prototype showed that a "light off" temperature (above 350°C) could be maintained during a 10-hour cold soak. Design improvements currently being tested should increase this heat-retention time to more than 16 hours. The thermal conductance of the vacuum insulation will be made continuously variable to prevent overheating and excessive thermal cycling. This approach to thermal management may be more durable and less costly than quick-heat methods using electric or fuel-fired preheat catalysts.

BACKGROUND

Environmental concerns are pushing us toward changes in our transportation systems. Carbon monoxide (CO), ground-level smog, and particulates are major problems in urban areas worldwide. Vehicle emissions account for 75% of CO and 44% of nitrogen oxides (NO_x) in U.S. urban atmospheres [U.S. DOE, 1992]. Increased vehicle mileage is one reason this issue persists despite significant progress in the treatment of automotive exhaust gases over the past two decades.

Today's catalysts process more than 97% of CO and hydrocarbon (HC) emissions when fully active. Unfortunately, a catalyst is not effective at temperatures below about 250°C for CO or 290°C–340°C for HC emissions. Automakers indicate that more than 50% of all HC emissions during a Federal Test Procedure (FTP) driving cycle can occur during "cold-start" periods while the catalyst is at temperatures below its "light off" temperature [Laing, 1994].

The EPA is currently conducting driver studies and re-evaluating the FTP driving cycle [U.S. EPA, 1993]. Several changes are being considered to make the FTP more accurately reflect typical urban driving conditions. One proposed change is to add moderate-length cold-soak periods. The California Air Resources Board (CARB) estimates that 60% to 80% of emissions from automobiles in Los Angeles originate from these "cold-start" emissions [Sabate and Agrawal, 1993].

The concern over cold-start emissions has led to significant activity by auto manufacturers and suppliers in developing new emissions treatment techniques. Leading approaches include quick-heat of the catalyst electrically [Laing, 1994; Socha et al., 1994] or with a catalyzed-fuel burner [Oser et al., 1994]. These techniques typically require a minimum of 1 kW to 2 kW of power for 10 to 30 seconds in order to reduce (but not totally eliminate) the cold-start emissions. In addition to significant added cost and complexity, these systems also undergo repeated and severe thermal gradients. It is anticipated that these gradients may lead to a reduction in system durability at a time when warranty periods are being extended. Electrically heated catalyst systems also put the battery through repeated deep-discharge cycles and stress the alternators.

Moving the catalyst closer to the engine manifold has also been used (often with an electrically heated precatalyst) to reach light off temperatures more quickly. In many autos, however, this strategy introduces additional unwanted heat into the footwells of the cabin and into the engine compartment, where thermal degradation of engine components (electronics, hoses, wire insulation, and other polymer materials) is already a significant problem. Also, the catalyst is more susceptible to damaging exhaust temperature excursions.

Work has also been reported by General Motors [Moore and Mondt, 1993] and Ford [Hartsock et al., 1994] using insulated catalysts located well downstream of the engine. This can involve double-walled insulating pipe leading from the manifold to the catalyst, as well as high-temperature refractory insulation around the catalyst itself. Sufficient insulation around the catalyst can maintain its temperature above lightoff for several hours after the engine is shut off. Any trip initiated within this time then would start with virtually no cold-start emissions. As with electrically heated and fuel-fired catalysts, some vehicles may require air-injection to fully catalyze the fuel-rich mixture typically present in the first few minutes of engine operation.

Unfortunately, to provide sufficient thermal insulation for holding heat for more than an hour or so, conventional refractory insulation must be extremely bulky and heavy. Also, during steady-state operation of the engine, this insulation may allow the catalyst temperature to exceed safe limits (about 1000°C) and cause thermal degradation and loss of emission conversion efficiency.

Perhaps a better approach to the thermal management of a catalyst would be to use an insulation that could be continuously varied in thermal conductance, providing the low conductivity needed to retain heat between trips, but providing much higher conductivity for heat rejection from the catalyst during engine operation. This is the approach being developed at the National Renewable Energy Laboratory (NREL).

VACUUM INSULATION DEVELOPMENT

Over the past 10 years, NREL, a U.S. Department of Energy national laboratory, has been investigating a number of vacuum insulations for a variety of energy conservation and thermal management applications such as high-performance window glazings, energy efficient refrigerator side-walls and electric vehicle high-temperature battery enclosures.

A recent thermal test with an NREL prototype vacuum-insulated vaccine refrigerator/freezer yielded a measured center-of-panel thermal conductance of 0.07 W/m^2K through the 20-mm-thick wall of the freezer. Freezers of this kind typically have about 51 mm of foamed polymer insulation and a thermal conductance of 0.5 W/m^2K. Conductances as low as 0.15 W/m^2K have been measured through the 15-mm-thick walls of 350°C hot-battery enclosures under development at NREL. Common non-vacuum refractory insulation would have to be more than 500 mm thick for equivalent thermal resistance.

Recently, NREL has studied mechanisms to make a compact vacuum insulation continuously variable in thermal conductance [Benson et al., 1994; Benson and Potter, 1994]. One such mechanism involves introducing hydrogen gas into the vacuum insulation by electrically heating a small amount of metal hydride in the vacuum. The pressure of the hydrogen is a predictable function of the hydride temperature and the gas is readily reabsorbed whenever the hydride is allowed to cool. By controlling the temperature of the hydride, the thermal conductance of the insulation can be continuously adjusted between a minimum value determined by the construction of the insulation and a maximum value bounded roughly by the thermal conductance of the hydrogen gas.

For example, the 15-mm-thick vacuum insulation discussed earlier had a minimum conductance of 0.15 W/m^2K, and by heating an attached hydride and introducing 10 torr of H_2 gas, a conductance of 5 W/m^2K was achieved. This represents a 33:1 control range for the thermal conductance in this Variable Conductance Insulation (VCI).

This VCI applied to automotive catalytic converter thermal management may provide a very compact and effective insulation to hold in heat between trips, while allowing for sufficient heat rejection during trips to avoid overheating of the catalyst.

Two catalytic converter test articles have been fabricated with vacuum insulation and tested at NREL. The first (TA-CC1, Figure 1) included a single cordierite catalyst without precious-metal loading, 152 mm long and 93 mm in diameter. This was secured in a stainless steel pipe with a standard vermiculite tumescent mat. This pipe was covered with 20 layers of copper-foil thermal radiation shielding and placed inside a 127-mm-diameter stainless steel pipe. A vacuum space was formed between these two pipes by welding a flanged metal bellows at each end. Two 51-mm-diameter stainless steel pipes were welded onto each bellows flange to serve as the exhaust gas inlet and outlet. Note that the metal bellows not only reduced heat conduction from the hot inner pipe to the outer pipe, but also from the interior to the inlet and outlet pipes.

A simple lumped-parameter thermal network model was built to predict the cooldown of the test article under typical conditions. Assuming an initial internal (catalyst) temperature of 650°C and an ambient temperature of 20°C, the predicted catalyst temperature versus time is shown as smooth curves in Figure 2. The vacuum insulation should enable the catalyst to remain above 350°C (a conservative lightoff value) for about 2 hours instead of about 20 minutes without vacuum insulation. The model also predicted that for the uninsulated baseline catalytic converter, most of the heat would be lost through the metal "can," whereas for the vacuum-insulated test article, most heat would be lost out the pipe ends. If the radiation and natural convection at the ends were mitigated, the vacuum-insulated test article would have the potential for holding the catalyst above 350°C for more than 3 hours.

These thermal predictions were verified experimentally by instrumenting the test article with thermocouples and heating the interior with electric resistance heaters. The results for both open and fully plugged ends are shown as data points in Figure 2. As predicted, plugging the ends with fibrous ceramic insulation significantly improved the heat retention. Although fully plugged ends are clearly not practical for actual use, they provide a useful check of the thermal model and establish a lower limit for the heat loss.

Thermocouple readings at the ends, as well as infrared thermography images, indicated that even more heat than expected was being lost through the bellows. A more detailed thermal analysis of the bellows, including radiative heat transfer between adjacent convolutions, has been performed and incorporated into the overall thermal model for future use.

INCORPORATION OF PHASE-CHANGE THERMAL STORAGE MATERIALS

Although extending the heat retention time from 20 minutes to 2 hours is significant, much longer times would be required to avoid cold-start emissions for common cold soaks such as work-start to lunch (4 hours), work-start to work-end (9 hours), or overnight (12 hours). Based on a recent Baltimore commuter driving study by the EPA [U.S. EPA, 1993], approximately 89% of all trips are started after a cold soak of 12 hours or less. CARB has also performed a more limited study indicating 82% of auto trips in Los Angeles begin with less than 12 hours of cold-soak.

Due to the heat loss through the bellows and pipes, it is unlikely that hold times of 12 hours or more could be obtained through catalyst insulation alone. However, computer simulations using the thermal model indicated that such hold times would be possible if the vacuum insulation were combined with significant increases in thermal storage. In particular, if the vacuum insulation could cut the heat loss rate to 10% of the baseline (uninsulated) value and the thermal storage could be increased by a factor of three, then hold times of greater than 12 hours should result.

Such a large increase in thermal storage using sensible heat alone would require unacceptably large increases in system mass and volume. Therefore, the use of high-temperature phase-change material (PCM) was investigated. Aluminum and its eutectic alloys were chosen for initial testing as PCMs because of their high thermal conductivity and availability. The thermal model indicated that 2.2 kg of pure aluminum within the vacuum insulation would triple the total thermal storage.

A second vacuum-insulated catalytic converter test article (TA-CC2) was designed to test these predictions. TA-CC2 had vacuum insulation between 127-mm and 103-mm-diameter stainless steel pipes (with metal bellows end seals). In addition, 2.2 kg of aluminum was sealed between the inner wall of a 103-mm-diameter pipe and the outer wall of a 76-mm-diameter pipe (see Figure 3). The PCM volume reduced the space for the non-loaded ceramic catalyst substrate. Therefore, two cylindrical substrates were used, each 152 mm long and 68 mm in diameter, with a 25-mm gap between. Minor improvements in the vacuum insulation radiation shields were also made to further reduce the heat loss rate.

The catalyst cooldown for TA-CC2 is shown in Figure 4. As with the first test article, TA-CC2 was tested with fully unplugged ends and fully plugged ends. In addition, a very open (85% porosity) ceramic material was used in the ends to reduce natural convection and radiation losses yet allow flow of exhaust. As seen in Figure 4, TA-CC2 holds the catalyst above 350°C for 6 hours with unplugged ends, 13 hours with fully plugged ends, and 10 hours with the porous ceramic end plugs.

These results clearly show the thermal benefit of adding 2.2 kg of aluminum phase-change material. They also show that heat loss from the ends can be controlled through fairly simple means.

WORK IN PROGRESS

A third test article (TA-CC3) is currently being fabricated. It will use 2.3 kg of an aluminum/silicon alloy instead of pure aluminum as the PCM thermal storage. This eutectic alloy has a 29% higher specific latent heat of melting. Computer simulation predictions indicate that this should extend the heat hold time with porous ceramic plugs from 10 hours to about 13 hours. Further improvements in the vacuum insulation are also planned, leading to an anticipated hold time of more than 16 hours. According to the EPA study cited earlier [U.S. EPA, 1993], about 95% of all automobile trips start after a cold-soak period of 16 hours or less. This test article will also incorporate the reversible hydrogen source and will be tested for its heat-rejection ability as well as its heat retention.

To verify the expected impact of this catalyst thermal management on engine emissions, TA-CC3 will contain precious-metal-loaded catalysts and will be tested at an engine dynamometer facility capable of measuring CO, HC, and NO_x continuously. Pressure drop versus exhaust flow will also be measured with and without porous ceramic end plugs.

Additional studies and test articles are planned to investigate the benefits of this approach to the treatment of exhausts from alternate fueled vehicles and hybrid vehicles. Engines using methanol and ethanol as fuel generally produce much lower temperature exhaust, further delaying lightoff. Under some extended idle and deceleration driving schedules, the catalyst can actually cool off and "un-light" while the engine is on. This situation is also possible with hybrid vehicle APUs (auxiliary power units). Both "series" and "parallel" hybrid vehicles can have drivetrain control systems that cause the APU to cycle on and off. Without thermal management of the catalyst, these cycles could produce cold-start, or at least "cool-start," emissions.

Another potential benefit of quicker catalyst lightoff is more rapid use of exhaust heat downstream of the converter for supplemental winter heating of the passenger compartment. This additional heat source becomes increasingly important for automobiles with small, efficient engines such as those used in hybrid vehicles.

CONCLUSIONS

Based on thermal analysis and computer modeling, vacuum insulated catalytic converter test articles were designed, built, and tested. Thermal tests demonstrated the ability of vacuum insulation plus 2.2 kg of added phase-change thermal storage to maintain the catalyst temperature above a conservative lightoff temperature (350°C) for 10 hours (compared to 20–30 minutes with typical, conventional catalysts). Planned design enhancements are predicted to provide a 16-hour heat-retention period. An electrically heated metal hydride source of hydrogen gas will also be added to provide control over the conductance through the vacuum insulation so as to prevent overheating.

The 16-hour heat retention period is long enough to prevent cold-start emissions from occurring in about 95% of all trips. This emission-reduction method offers several possible advantages over electrically heated or fuel-fired preheat catalysts including less complexity, lower cost, and reduced thermal strains.

Emissions testing is planned to confirm the merits of this thermal management approach. A follow-up paper will report these findings.

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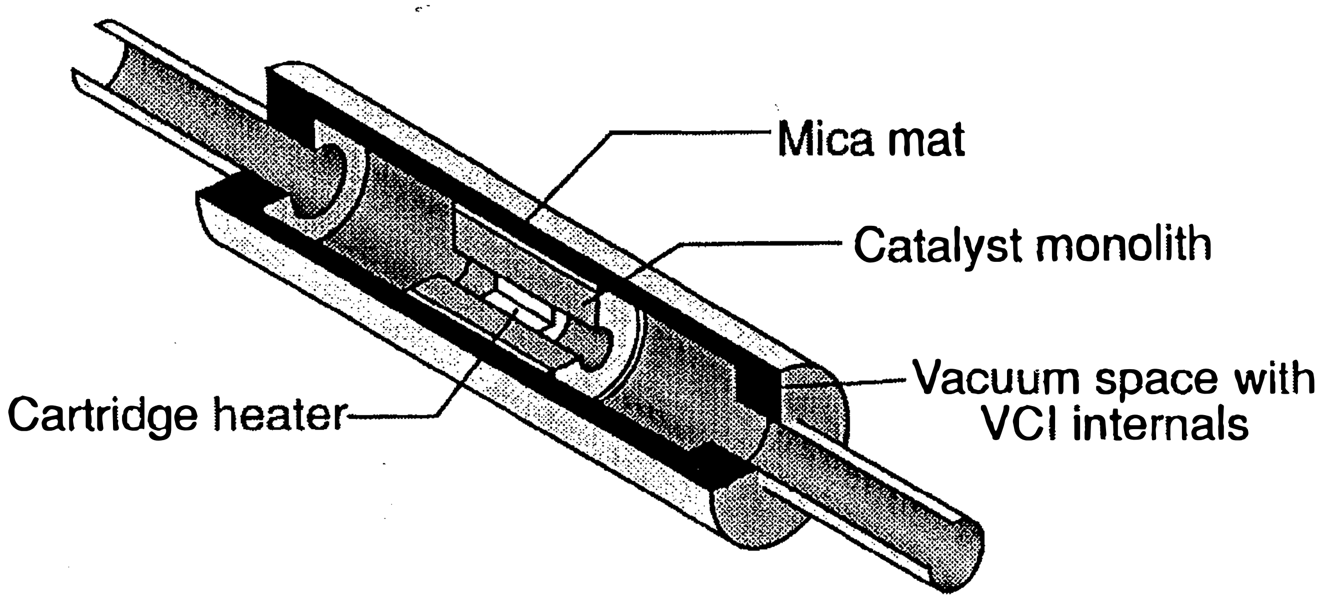

Figure 1 - Cut-Away View of Catalytic Converter Test Article 1 (TA-CC1)

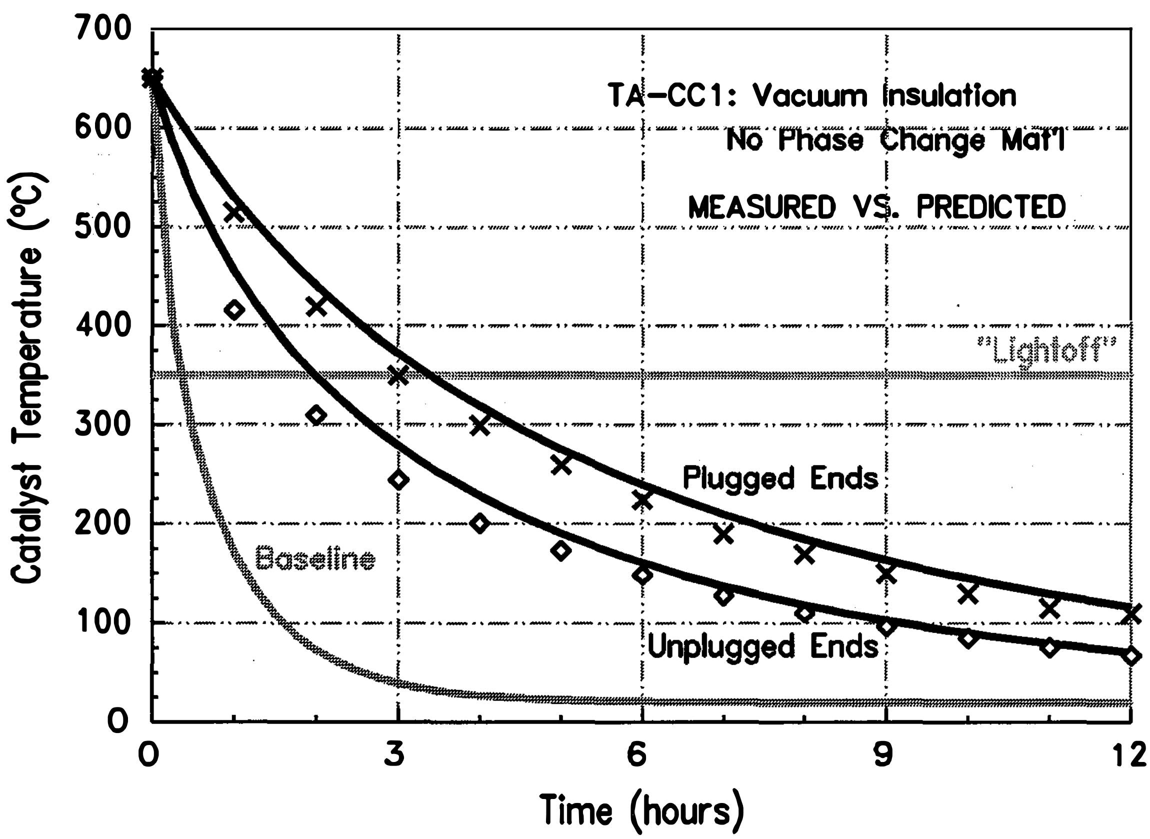

Figure 2 - Predicted (smooth curves) and Measured (data points) Catalyst Cooldown of First Test Article (TA-CC1)

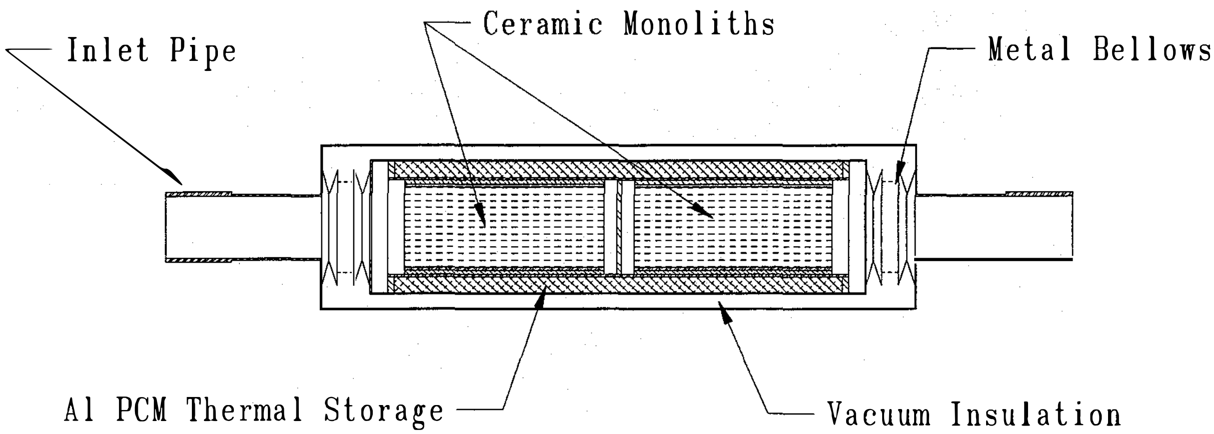

Figure 3 - Sectional View of Second Catalytic Converter Test Article (TA-CC2)

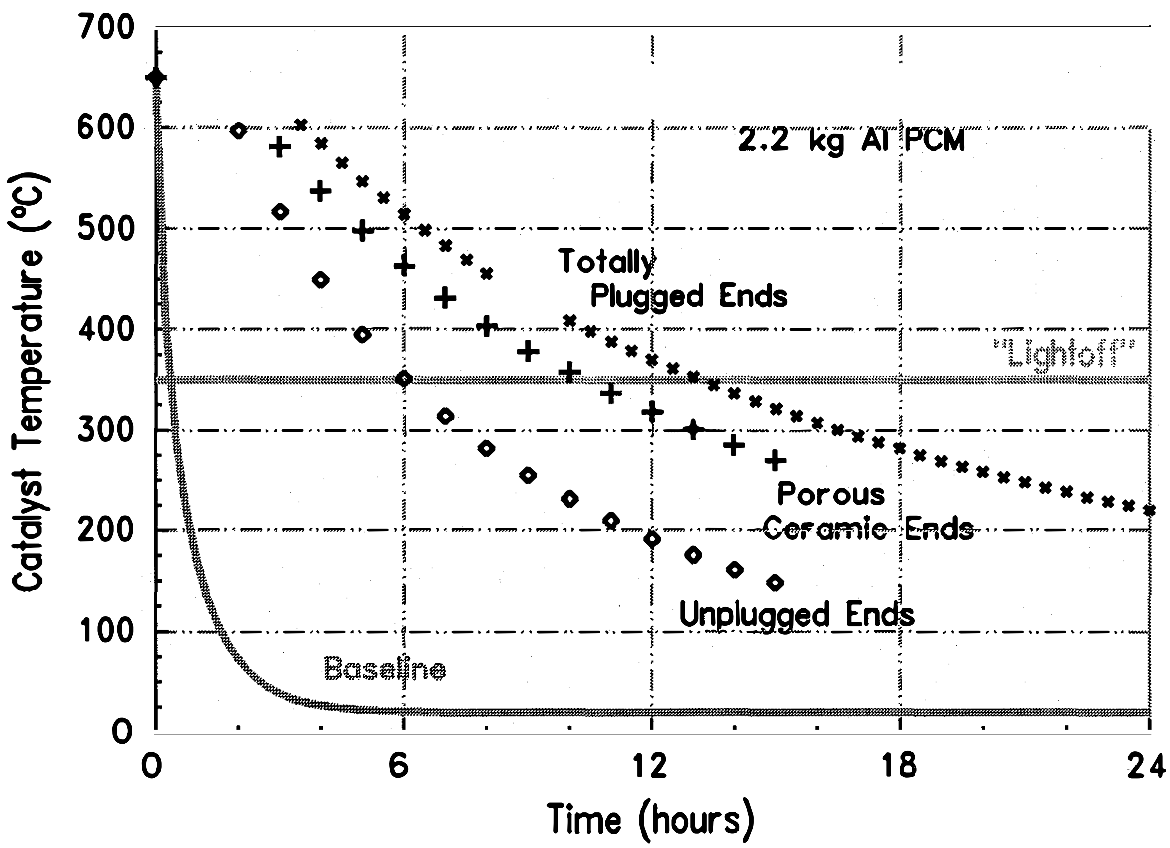

Figure 4 - Measured Catalyst Cooldown of Second Test Article (TA-CC2)