Performance of the 1 kW Thermoelectric Generator for Diesel Engines*

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Abstract

Hi-Z Technology, Inc. (Hi-Z) has been developing a 1 kW thermoelectric generator for class eight Diesel truck engines under U.S. Department of Energy and California Energy Commission funding since 1992. The purpose of this generator is to replace the currently used shaft-driven alternator by converting part of the waste heat in the engine's exhaust directly to electricity. The preliminary design of this generator was reported at the 1992 meeting of the XI-ICT in Arlington, Texas. This paper will report on the final mechanical, thermal and thermoelectric design of this generator.

The generator uses seventy-two of Hi-Z's 13 Watt bismuth-telluride thermoelectric modules for energy conversion. The number of modules and their arrangement has remained constant through the program.

The 1 kW generator was tested on several engines during the development process. Many of the design features were changed during this development as more information was obtained. We have only recently reached our design goal of 1 kW output. The output parameters of the generator are reported.

BACKGROUND

The program to build and test a 1 kW thermo-electric generator for Diesel engines started in 1987 as part of the U.S. Department of Energy's (DOE) Energy Related Inventions Program. This initial program was to design and build a 200 Watt thermoelectric for Diesel engines which was reported [1] at the 1991 Conference in Cardiff, Wales.

The purpose of the thermoelectric generator is to utilized the engine's waste heat to provide auxiliary electric power for the truck instead of using the engine driven alternator. This concept should reduce the shaft horse power by three to five horse power which will save money spent on fuel, decrease maintenance, and reduce emissions such as particulates, NO_x, and So_x.

A phase I design study of a 1 kW generator completed[2] in 1990. A Phase II program supported jointly by the DOE and the California Energy Commission (CEC) was begun in late 1991 and early 1992. The CEC Energy Technology Advancement Program (ETAP) monitored the initial portion of the program and later it was shifted to the CEC's Transportation Technology Advancement Program (TTAP).

Tests of the 1 kW generator started in mid 1993 in the Diesel engine test cell at Golden West College which is located in Newport Beach, California. These tests continued for about a year while various modifications were made to the heat transfer system within the generator. The reason that it took so long was because the modifications and testing had to be alone serially, which required an abnormally high amount of waiting time.

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GENERATOR DESIGN

The generator uses seventy-two Hi-Z 13 bismuth-telluride modules to convert the energy in the engines exhaust directly to electricity. A picture of this module which is 2.1 inches square by 0.2 inch thick and contains 49 active couples in a 10 x 10 element array is shown in Figure 1. Vacuum hot pressed materials are used to make the thermoelements in the module.

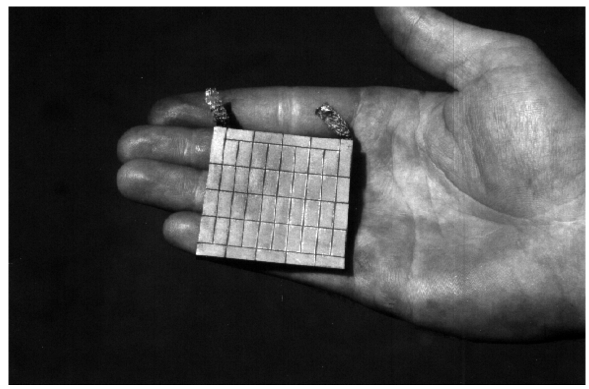

Figure 1. HZ-13 Module

The modules are arranged in eight groups of nine modules. Each group of modules is mounted on a single water cooled heat sink as shown in Figure 2. The module and heat sink assemblies are then positioned on the octagonal outer surface of a cast steel center support structure. This structure was sand cast from Ni Resist steel. The interior surface of the casting is a circle about 5.75 inches in diameter with heat transfer fins on the inside surface.

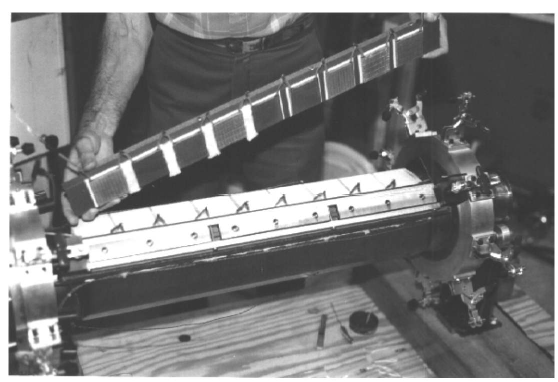

Figure 2. Thermoelectric Modules and Heat Sink Assembly

A hollow displacement body is place in the center of the generator to force the exhaust gas flow close to the surface of the support structure. This displacement body provided a better gas flow distribution within the generator and can be easily changed in size to match the exhaust gas flow rate of engines of various displacements

The ends of the displacement structure were tapered to maintain both a nearly constant gas velocity at the inlet and to minimize the exit expansion losses as the exhaust gas leaves the generator.

The eight aluminum water cooled heat sink assemblies are held against the flat surface of the support structure with a pressure of about 200 lb/in^2. The force required is provided by stack of Bellville springs located at positions which coincide with the center of each thermoelectric module. Each spring stack is individually adjusted to the same load and acts between the back side of the heat sink assembly and one of three floating aluminum support rings which surround the generator.

Figure 3 shows the 1 kW generator mounted on a 14 liter Cummins NTC 350 engine. The generator is coupled directly to the exhaust gas outlet of the engine's turbocharger.

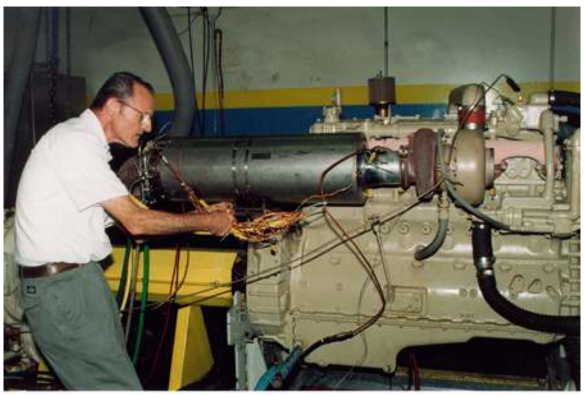

Figure 3. 1 kW Generator Mounted on Cummins Engine

GENERATOR TESTING AND MODIFICATION

Initial generator testing started in the summer of 1993. These tests were conducted using a 14 liter Cummins NTC 275 engine. The initial results, shown in Figure 4, and reported in Reference 3, were quite poor since we were able to achieve a maximum of about 400 watts of output.

It was suspected that there was a boundary layer problem with the heat transfer from the exhaust gas to the support structure. The original heat transfer fin design used 90 fins about 0.25 inches high which were continuous from the inlet to the outlet.

A more detailed picture of the differential temperature distribution than could be obtained from the several thermocouples which were installed along the support structure was required to prove the thesis. A good indication of the heat transfer profile was obtained as shown in Figure 5 by wiring the thermoelectric modules on one heat sink assembly, so that the open circuit voltage of each module could be obtained individually. The profile, which is an analog of the local heat transfer rate, confirmed that the laminar boundary layer was the source of the heat transfer problem.

The design of the casting was modified by reducing the number of fins to 32 and lengthening then to maintain the required heat transfer area. The fins were also made to be discontinuous by placing 0.375 inch gaps at about 1.5 inch intervals to aid in breaking the laminar boundary layer.

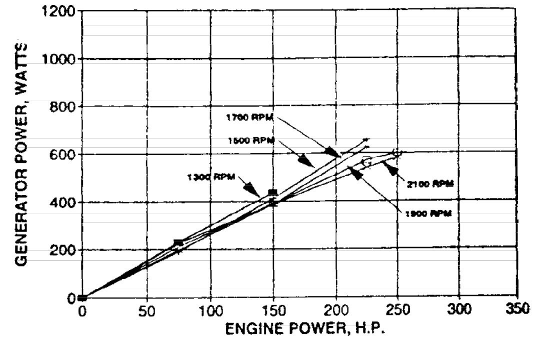

Figure 4. Results of Early Test on Cummins Engine

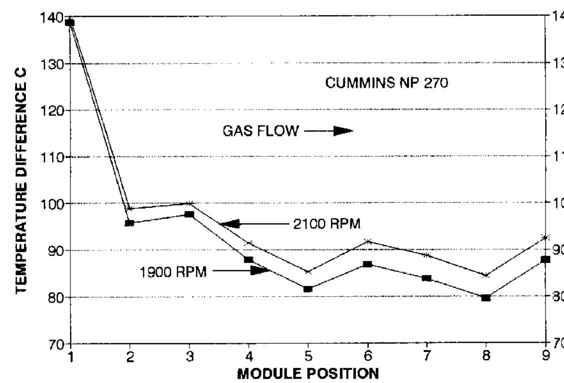

Figure 5. Differential Temperature Profile from Early Test

Testing the modified generator resulted in a marked improvement of power output as shown in Figure 6. The generator output power improved over 600 Watts and the power curves were less erratic than in the previous test.

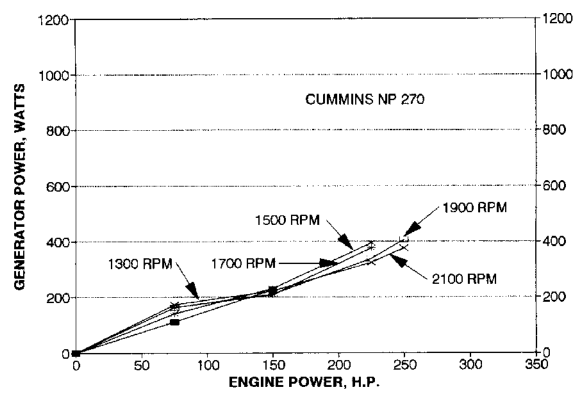

Figure 6: Initial Test Results with New Fin Arrangement

The open circuit voltage temperature profile showed some improvement from the first test series, however, it still indicated that there was a problem with the gas boundary layer and it was suspected that heat transfer problem was associated with lack of turbulence in the exhaust gas as it exited the turbocharger drive turbines.

The heat transfer fins had been made discontinuous, they were placed in line because of both the time required and the cost of changing the casting core mold to offset the fins. It was decided to install swirl fins on the center displacement body to increase the gas turbulence. This was accomplished by welding two types of fins to the shell of the hollow displacement body, the first row was a single set of curved blades to start the swirl and the second type consisted of four rows of angled straight blades to sustain the swirl as shown in Figure 7.

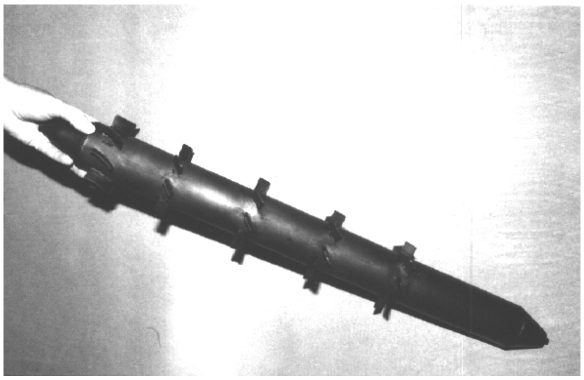

Figure 7: Center Body with Swirl Fins

The generator with the modified displacement body was tested on both Cummins NTC 325 and NTC 30 engines. The results of the final test on the NTC 350 engine is shown in Figure 8. This test was limited to an engine output of 300 h.p., however it is capable of going to 350 h.p. A maximum generator output of 1068 Watts was obtained at 300 h.p. and 1700 RPM.

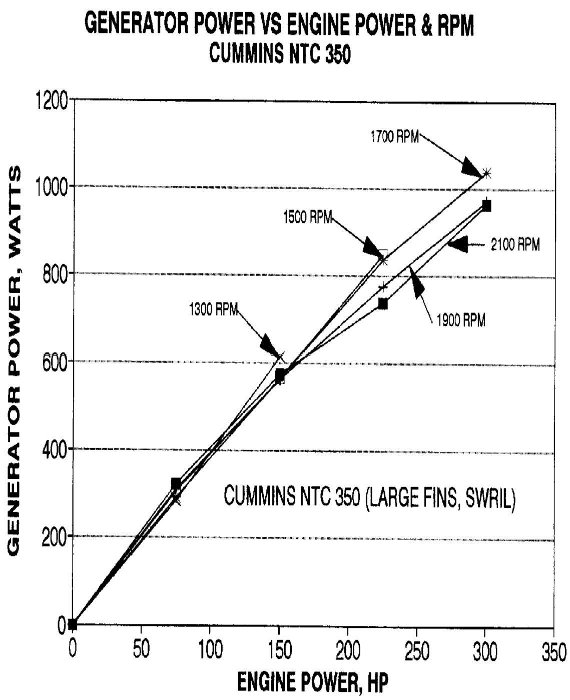

Figure 8. Test Results for Generator with Swirl Fins

A graph of the open differential temperature profile for this last run is shown in Figure 9. One will not that after the high initial temperature at the generator inlet, the remainder of the temperature points are quite flat compared to the early profile.

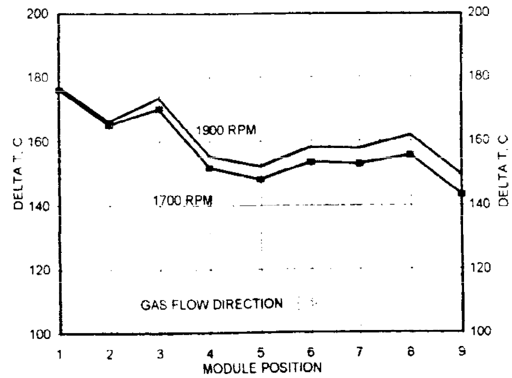

Figure 9: Differential Temperature Profile with Swirl Fins

CONCLUSIONS

A high powered generator to provide electric power for Diesel engines is feasible. Hi-Z has designed and tested such a generator. The design of this generator could be further refined, however, the current design has now met the original design goal for the program of producing 1 kW of electricity directly from the exhaust of a Diesel engine.

The information presented here shows how important the details of the heat transfer design can be. We believe that the need to pay attention to such details is even more important in thermoelectric systems because of the increased sensitivity of such systems to both temperature difference across the elements and average temperature of the elements.

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