Overview of Waste Heat Utilization Systems

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

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Dearborn, Michigan, October 29–November 1, 1984
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ABSTRACT

The heavy truck diesel engine rejects a significant fraction of its fuel energy in the form of waste heat. Historically, the Department of Energy has supported technology efforts for utilization of the diesel exhaust heat. Specifically, the Turbocompound and the Organic Rankine Cycle System (ORCS) have demonstrated that meaningful improvements in highway fuel economy can be realized through waste heat utilization. For heat recovery from the high temperature exhaust of future "adiabatic" diesel engines, the DOE/NASA are investigating a variety of alternatives based on the Rankine, Brayton, and Stirling power cycles. Initial screening results indicate that systems of this type offer a fuel savings advantage over the turbocompound system. Capital and maintenance cost projections, however, indicate that the alternative power cycles are not competitive on an economic payback basis. Plans call for continued analysis in an attempt to identify a cost effective configuration with adequate fuel savings potential.

OBJECTIVES OF THE PROGRAM

FUEL SAVINGS - The objectives of the waste heat utilization program have remained essentially constant throughout approximately a decade of activity. The primary objective, as with other DOE sponsored activities, is fuel savings. A specific goal of 15 percent improvement in engine rated specific fuel consumption (s.f.c.) was established early in the program. Naturally the desire is to see this goal translated into a like improvement in highway fuel economy.

ACCEPTANCE - System acceptance is a second objective, established out of a recognition that the degree of acceptance and use controls the magnitude of total fuel savings. The specific goal is to limit the systems incremental hardware costs such that fuel savings provide economic payback in a period of 2 to 3 years ownership. Early payback of the initial capital outlay allows for an attractive net gain during the balance of the ownership period.

BARRIER REMOVAL - The final, and also a continuing objective, has been to identify any technology barriers associated with specific waste heat system configurations. A technology barrier is defined as a technological problem of such magnitude that it would prevent industry from proceeding with final development of an otherwise attractive system. The Governments' role would be to conduct a technology program appropriate to the removal of such items as barriers.

BACKGROUND

The background era of waste to heat utilization systems spans the decade of 1974-1984. In that time period, the heat recovery efforts were addressing the water-cooled diesel engines with exhaust gas temperatures in the range of 700 to 900 °F. The approach included system buildup, truck installation, and on-highway fuel economy testing. There were two waste heat systems investigated; the turbocompound system and the organic Rankine cycle system.

TURBO COMPOUND - The turbocompound system was developed by Cummins Engine Company and later subjected to on-highway testing (1) and advanced development (2) under DOE sponsorship. The turbocompound system involves a low pressure power turbine downstream of the turbocharger turbine and connected through a gear train to the diesel output shaft. The program results indicated a 6 percent highway fuel economy improvement attributable to the advanced development version of the turbocompound.

Numbers in parentheses designate references at end of paper.
ORGANIC RANKINE CYCLE SYSTEM (ORCS) - The ORCS was a DOE funded development originating out of the Rankine Cycle Automotive Engine program of the early 1970's. The development contractor was Thermo Electron Corporation. The cycle (organic) working fluid was a mixture of trifluoroethanol and water with a peak operating temperature of 550 °F. A single-stage axial flow turbine was used as the prime mover in the system (3). The ORCS was installed in a Mack truck for on-highway testing which subsequently demonstrated a 12 percent fuel economy advantage over a similar truck without waste heat utilization.

Rankine Heat Exchanger Fouling - A prominent feature in the ORCS configuration is the heat recovery heat exchanger (HRHX). The HRHX design used was a shell and finned-tube type with fin spacing of approximately 10-fins/in. A problem which soon became apparent was that of HRHX fouling by the diesel exhaust gasses. The fouling degrades overall system performance in two ways:

1. Increased backpressure on the diesel working fluid
2. Reduced heat transfer to the ORCS working fluid

Dynamometer test cell results indicated that the gas side heat transfer coefficient degrades by as much as 50 percent during a 50 hr test series.

The HRHX fouling problem was considered to be a technology barrier as defined previously under the program objectives. The approach to removal of the barrier was two pronged:

1. Conceptual design study of a fluidized-bed system as an alternative HRHX
2. Experimental evaluation of various cleaning techniques in the existing finned-tube HRHX

The fluidized-bed design involves bare tubes immersed in the bed. The constant agitation of the bed material is expected to produce high heat transfer coefficients; as well as a cleaning action that eliminates any concern for fouling of the bare tube surfaces. Unfortunately, the conceptual design study results indicated that size, weight, and cost factors associated with the fluidized-bed seriously reduce the concepts attractiveness for truck applications.

The experimental evaluation of cleaning techniques for the existing finned-tube HRHX fortunately identified two techniques that appear acceptable for control of the fouling problem in that unit:

1. Water wash with a built-in spray bar
2. High temperature "self-cleaning"

The water wash is accomplished with tap water introduced at a standard hose connection on the HRHX body and connecting to a circular spray bar mounted inside at the top of the HRHX tube bundle. The water wash is completed in approximately 30 min at any truck stop location.

The self-cleaning approach is perhaps more attractive than the water wash because self-cleaning can be accomplished on-highway. The technique involves the temporary shut-down of the Rankine working fluid loop such that the HRHX metal temperature approaches that of the diesel exhaust gas. At the elevated temperatures the accumulated soot dries and flakes off to be carried away in the gas stream. A testing program indicated that a 20 min self-cleaning each day will maintain the HRHX in a clean condition. In practical applications, the self-cleaning technique may be limited to steam (water) Rankine systems since fluid residue may remain in the tubes during the cleaning cycle and the temperatures involved exceed those normally associated with organic fluid stability.

CURRENT PROGRAM

The current program was formulated in 1982. It addresses the "adiabatic" engine of the future, an engine anticipated to have exhaust gas temperatures in excess of 1100 °F. The program is formulated on the assumption that industry accepts and is pursuing on its own the turbocompound system for use with advanced engines. The Government role is to screen the waste heat power cycle alternatives with the objective of identifying economically acceptable systems that offer a fuel savings advantage over the turbocompound system.

SCREENING MATRIX - Figure 1 illustrates the alternative power cycle screening matrix which addresses the Rankine, Brayton, and Stirling cycles. The blocks below the cycle designations represent individual conceptual design studies. As indicated on the figure, the Stirling cycle study is currently underway and scheduled for completion in 1985. The prime contractor is Cummins Engine Company with Mechanical Technology, Inc. and Adiabatics, Inc. as subcontractors.

Completed Studies - The four blocks under the Rankine and Brayton cycle headings in Fig. 1 represent studies that have been completed. In the Rankine cycle area, the Steam Rankine study was completed by Foster-Miller Associates, Inc. The final configuration was a 1000 °F/1000 psia steam system using a two-cylinder piston expander operating at diesel engine speed (4). The RC-1 Organic Rankine study was completed by Thermo-Electron Corp. The RC-1 organic fluid is a mixture pentafluorobenzene and hexafluorobenzene. The final system configuration involved 750 °F/800 psia working fluid conditions with expansion in a single stage, axial flow turbine (5).

Under the Brayton cycle heading, the AGT Adaptation block refers to a study completed at NASA Lewis Research Center involving a minimum cost adaptation of the automotive Advanced Gas Turbine (AGT) hardware for use as a waste heat recovery system. The concept involves use of the AGT (6) rotating regenerator as the HRHX. The motivation was one of minimum hardware cost on the assumption that AGT components might be the subject of high rate production for passenger car use.

The Clean Sheet Brayton block refers to a study completed by United Technologies Research Center of a Brayton system optimized for the waste heat utilization application. The resulting configuration used a plate-fin HRHX design with a turbomachinery arrangement that included two com-
The fuel savings, maintenance costs, and capital costs need to be combined in the appropriate manner to calculate payback time. For this study, the cost estimates were first subjected to a minor scaling adjustment to a 350 hp common size (core plus heat recovery). The comparison was then made to a competing turbo-compound - aftercooled diesel of the same size. An additional assumption was made that all systems will retain a 15 percent salvage value after the 7-yr (700 000 mile) life. The payback equation thus becomes

$$\frac{0.85 (\Delta \text{capital})}{\Delta \text{fuel} - \Delta \text{maintenance}} = \text{payback years}$$

The payback results are illustrated graphically in Fig. 6 as a function of fuel price. Unfortunately, the results indicate that at the reference fuel price the alternative power cycle systems do not meet the payback target. The target would be realized for the Rankine systems if the often discussed $2/gal fuel price became a reality, but only if that fuel price change were not accompanied by a general inflation affecting the system hardware prices. Note in Fig. 6 that the lower capital cost of the Steam Rankine system now "pays off" in terms of payback time. Also, the Clean Sheet Brayton and AGT systems appear not be competitive with the Rankine at any fuel price.

Figure 7 illustrates a second set of payback results, similar to those of Fig. 6 except that now the core diesel is a turbocompound (nonaftercooled) diesel. The hardware arrangement involves the alternative power cycle(s) operating downstream of the turbocompound power turbine. Surprisingly, the difference to the alternative power cycle is a mere 100°F lower gas temperature than that available from the turbocharged diesel core. The payback results (Fig. 7) show significant improvement but still fail to meet the established payback target.

Conclusions - A major conclusion drawn from the power cycle comparative review is that 8 to 10 percent fuel economy improvement over a turbocompound diesel is possible with an appropriate
alternative power cycle system. For this application, the Rankine cycle is superior to the Brayton both in terms of fuel economy improvement and economic payback. The use of a Rankine cycle in combination with turbocompounding appears interesting as a means to provide the maximum fuel economy and economic payback.

The design complexity and resulting high cost of the Rankine cycle systems evaluated are considered to constitute a technology barrier. A 25 to 50 percent reduction in cycle capital cost is needed to produce acceptable economic payback at current fuel price levels.

FUTURE PLANS

The future plans, for the near term at least, are analytical rather than hardware oriented. A study is currently underway at Argonne National Laboratory for modeling and analysis of the Rankine cycle systems in an attempt to further define optimum designs from a combined performance and cost viewpoint. The completed Rankine cycle model will be utilized at NASA Lewis Research Center in conjunction with an appropriate Diesel model and vehicle mission simulation model to continue the optimization process.

Also underway is the Stirling cycle study identified in Fig. 1 as the last item to be completed in the alternative power cycle screening matrix. This study, to be completed by Cummins Engine Company during 1985, will include an engine manufacturing and vehicle integration review of the completed Rankine and Brayton designs.

REFERENCES

Figure 1. - Alternative power cycle screening matrix.

Figure 2. - Common diesel core.
Figure 3. - Horsepower recovery and resulting S.F.C. improvement.

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Figure 4. - Annual maintenance cost estimates.
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*HIGH RATE PRODUCTION

Figure 5. - Capital cost estimates.

Figure 6. - Payback results using turbocharged diesel core.
Figure 7. - Payback results using turbocompound diesel core.
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### Key Words (Suggested by Author(s))
- Diesel technology
- Waste heat utilization
- Brayton cycle
- Rankine cycle
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