

Waste Heat Recovery Concept to Reduce Fuel Consumption and Heat Rejection from a Diesel Engine

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ABSTRACT

Fuel economy is critical for heavy-duty line haul applications. As fuel prices rise and impending fuel economy regulations are implemented, new ways to improve heavy vehicle fuel economy will be in high demand. AVL Powertrain Engineering has undertaken a research and development project to demonstrate the feasibility of a Rankine Cycle Waste Heat Recovery (WHR) system. The goals of the project were to reduce the overall engine heat rejection, specific emissions and fuel consumption (CO_2 emissions) of heavy-duty diesel engines by converting heat that is typically wasted to the exhaust stack and through the EGR cooler to useable mechanical energy. A detailed thermodynamic analysis was conducted which laid the groundwork for working fluid selection and proper sizing of the WHR components. Based on the system specifications, a prototype WHR system was designed and built. The performance of the system was evaluated on a 10.8 liter heavy-duty on-highway diesel engine.

INTRODUCTION

The concept of recovering excess or wasted heat from a primary thermodynamic process via a bottoming cycle is nothing new. On a large scale, power plant and industrial process cogeneration using steam Rankine cycle systems have been utilized for decades to improve the overall efficiency of the facility. Similarly, waste heat recovery from very large diesel engines in marine applications has been in practice since the early 1980's. This technology has been developed to the point where 10% fuel efficiency improvements are the industry standard for marine applications [1]. Despite the success and acceptance of waste heat recovery technology in industrial and marine application, there remains a gap when applying the technology to smaller

transportation applications. The cost and complexity of waste heat recovery systems are generally considered to be prohibitive to developing systems for small vehicles. Light duty passenger vehicle present the biggest challenge for waste heat recovery due to tight packaging constraints and the relatively low duty cycle of the combustion engine. The best opportunity for successful application of waste heat recovery technology is for engines that operate steadily at high load for sustained periods; similar to a power plant or marine vessel. The class-8 line haul truck fits this criteria. The last time this technology was investigated seriously by the trucking industry was during the energy crisis of the 1970's when high fuel prices tipped the cost-benefit tradeoff in favor of waste heat recovery [2, 3, 4]. Given the recent emphasis on fuel efficiency in the heavy-duty truck market, there may be an emerging opportunity for waste heat recovery in this sector [5].

Fuel energy is used in the diesel engine to create mechanical work. Most modern heavy-duty diesel engines are achieving a maximum of 40-42% thermal efficiency. The remaining energy is lost through several routes.

Table 1 shows the energy balance of a typical heavy duty diesel engine when operating at high load near the point of highest thermal efficiency [6].

Analysis has suggested that up to a 5% improvement in engine fuel efficiency is possible by utilizing an organic Rankine cycle that taps energy from the EGR cooler alone [6]. In this investigation, a waste heat recovery system was designed, built and applied to a 2006MY Cummins ISM 10.8L diesel engine. The goal of the project was to demonstrate a functional system capable of delivering up to 3% improvement in engine fuel consumption. During the course of the project, the system was configured to recover

heat from the EGR cooler alone, the exhaust gas alone and a combination of both sources. The system configuration showing the working fluid flow path is illustrated in [Figure 1](#). The working fluid plumbing remained unchanged for the entire project as the focus was on determining the best routing for the exhaust gases through the system.

Table 1. An example of engine energy balance [5]

Energy Flow Path	% of Total Fuel Energy	Temperature (°C)
Mechanical Energy (Shaft Work)	40-42	N/A
Exhaust Energy	19-21	400
Coolant Energy	17-19	90
EGR Cooler Energy	10-12	540
Charge Air Cooler Energy	8-10	170
Other (Radiant)	1-3	varies

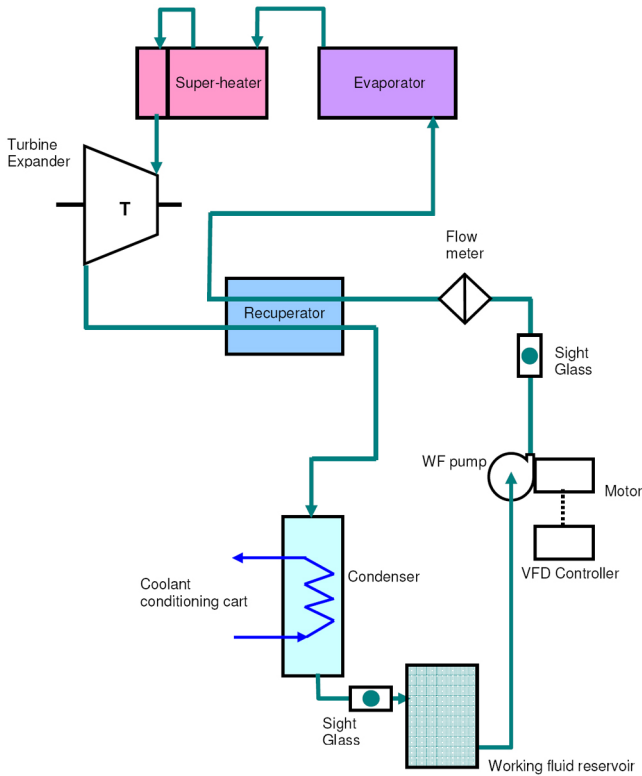


Figure 1. Waste heat recovery system diagram

WORKING FLUID SELECTION

The efficiency of the WHR Rankine cycle is governed by the thermodynamic properties of the working fluid. A proper selection of the working fluid for the WHR system at the given waste heat conditions is the key to achieving high WHR efficiency. For a WHR system with the EGR cooler integrated in the system, the working fluid temperature in the evaporator should be close to that of the engine coolant in

order to achieve a similar level of the EGR cooling. The basic requirements for the working fluid are:

- High thermal stability temperature, i.e., high superheating temperature;
- Large specific enthalpy drop over the expander, i.e., good utilization of recovered useful energy;
- Appropriate evaporation temperature for the EGR cooling;
- Relatively low evaporation pressure thus low system pressure and pumping work;
- Condensation pressure close to or higher than the ambient pressure to prevent the ambient air from entering the WHR system during system operation;
- Low dryness for the working fluid state after the expander to minimize the size of the recuperator;
- Low freezing point and flammability; and
- Environmentally friendly.

Three working fluids, R245fa (C₃H₃F₅), water and ethanol, were selected as candidates from more than 30 working fluids reported in the literature. From the consideration of the working fluid temperature required for the EGR cooling, the target evaporation temperature and condensation temperature are set to be 120°C (which is appropriate for EGR cooling) and 70°C respectively. Corresponding vapor pressures for the three candidates at these temperatures are listed in [Table 2](#).

Table 2. Properties of candidate working fluids

	R245fa	Water	Ethanol
P vapor @120°C [bar-a]	19.3	2.0	4.3
P vapor @70°C [bar-a]	6.1	0.3	0.7
Potential expander deltaP [bar]	13.2	1.7	3.6
Boiling Point @ 1 atm [°C]	15	100	78
Thermal Stability [°C]	350	>600	350
Recuperator size	large	no need	medium
Companies using for WHR	Cummins CAT	BMW Honda	BMW

Water as a working fluid for WHR was used by BMW and Honda for passenger car applications [7, 8]. In the BMW and Honda systems, the waste heat source is the engine exhaust and the evaporation temperatures of the working fluid are much higher than the engine coolant temperature and therefore not appropriate for the EGR cooling. Based on the thermodynamic properties presented in [Table 2](#), water is eliminated from the candidate list due to having insufficient condensation pressure (0.3 bar) and insufficient differential pressure across the expander (1.7 bar).

R245fa was used as a working fluid in the WHR systems of Cummins and Caterpillar [9, 10]. [Figure 2](#) and [Figure 3](#) show

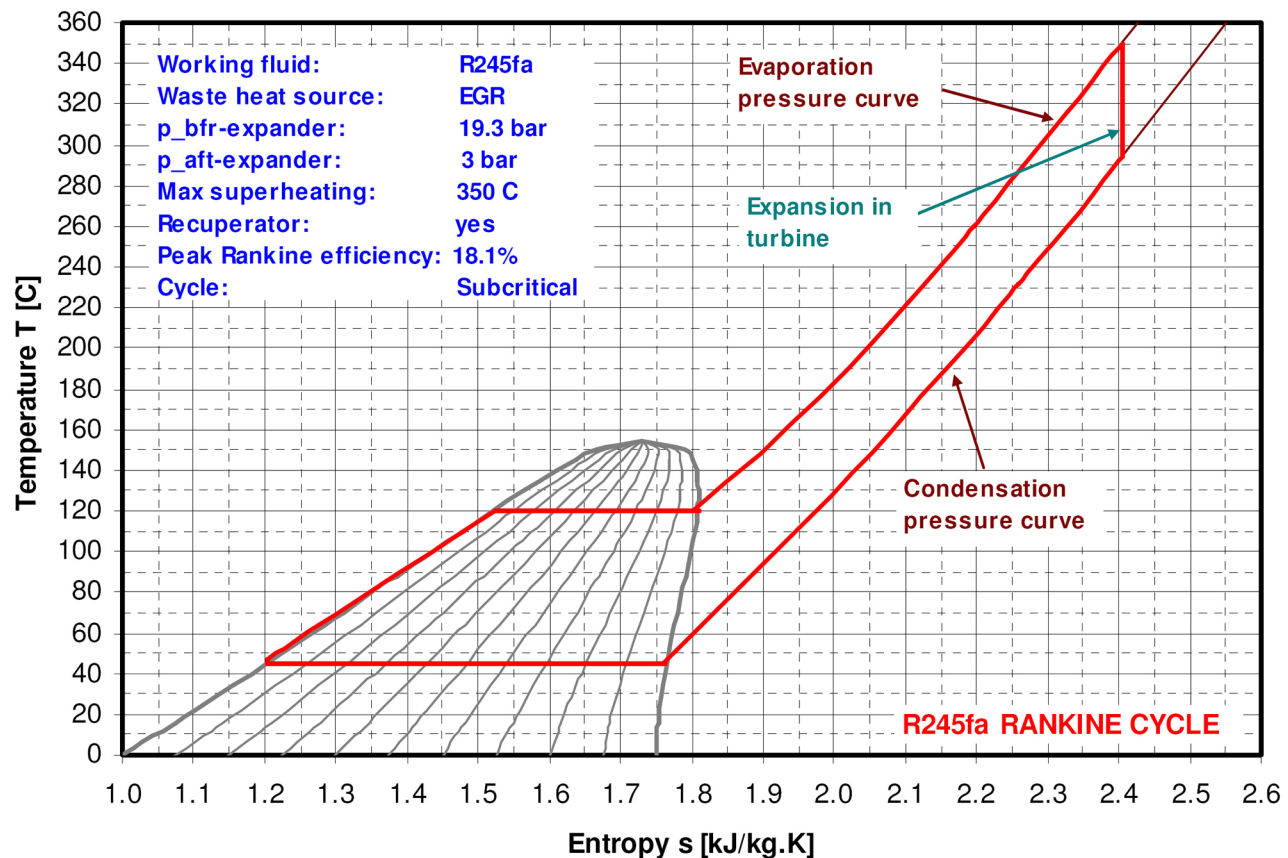


Figure 2. T-s Diagram for R245fa

Temperature-Entropy diagrams for the R245fa and Ethanol Rankine cycles respectively under the same evaporation/superheating temperatures and cycle efficiency.

The comparison of the two working fluids shows that ethanol has advantages over R245fa in the system pressure and the size of the recuperator. The system pressure has significant impact to the cost of the WHR system for mobile applications because the costs of the working fluid pump and the heat exchangers increase with increasing system pressure. Also, it is difficult for a single-stage rotary pump to reach a head pressure > 10 bar because of the low pump volumetric efficiency as a result of the low viscosity of the working fluid. Based on the above considerations, ethanol was selected as the working fluid for this R&D project.

HEAT EXCHANGER DESIGN

The purpose of this project is to demonstrate the waste heat recovery concept and not to demonstrate packageability. For this reason, the heat exchangers were all chosen to be tube-shell style for low cost, fast delivery, flexibility and safety. The waste heat recovery system is illustrated in Figure 4.

EVAPORATOR

Working fluid is routed from the pump, through the shell side of the recuperator for preheating and then runs to the inlet of the shell side of the evaporator. Exhaust gases are routed from the superheater through the evaporator on the tube side and then back to the intake of the diesel engine. The layout of the evaporator consists of a 203 mm diameter, 304 stainless steel shell, with a 101 tube bundle of 1275 mm in length. The tubes are 9.5 mm ID stainless steel with 0.5 mm wall thickness. The evaporator was built with no internal baffles or fins and is mounted on the test stand at a 5 degree oblique angle. This allows for better utilization of heat transfer surface area as ethanol changes state from liquid to gas and it reduces the resistance to the vapor outflow. The tube bundle was laid out with a minimum distance of 4 mm between tube surfaces so as to avoid vapor bubbles of the boiling ethanol being trapped between the tubes due to surface tension.

SUPERHEATER

The superheater is manufactured in two sections. The first and shorter section, designated the shock absorber, was designed to take the hottest exhaust gas from the test engine. Should there be a heat related failure of the heat exchanger, this shock absorber section would be easiest to replace. Working fluid is routed from the evaporator to the inlet of the