

Validation and Design of Heavy Vehicle Cooling System with Waste Heat Recovery Condenser

Jon Dickson
Cummins Inc

Matthew Ellis
Exa Corporation

Tony Rousseau
Modine Manufacturing Company Inc

Jeff Smith
Peterbilt Motors Company

ABSTRACT

Fuel efficiency for tractor/trailer combinations continues to be a key area of focus for manufacturers and suppliers in the commercial vehicle industry. Improved fuel economy of vehicles in transit can be achieved through reductions in aerodynamic drag, tire rolling resistance, and driveline losses. Fuel economy can also be increased by improving the efficiency of the thermal to mechanical energy conversion of the engine. One specific approach to improving the thermal efficiency of the engine is to implement a waste heat recovery (WHR) system that captures engine exhaust heat and converts this heat into useful mechanical power through use of a power fluid turbine expander.

Several heat exchangers are required for this Rankine-based WHR system to collect and reject the waste heat before and after the turbine expander. The WHR condenser, which is the heat rejection component of this system, can be an additional part of the front-end cooling module. Packaging this WHR condenser as part of the front-end cooling module can be an engineering challenge given the tight underhood environment where the current powertrain cooling components are already near system-capable thermal limits.

This paper shows how Lattice Boltzmann Method based simulations using highly-detailed vehicle geometry were utilized in the development of the heat exchanger architecture used to meet peak cooling needs as well as provide sufficient cooling airflow to the WHR condenser under all operating conditions. Heat exchanger results from the simulations are shown to compare well to cooling test measurements in a fully-climatic vehicular wind tunnel.

CITATION: Dickson, J., Ellis, M., Rousseau, T., and Smith, J., "Validation and Design of Heavy Vehicle Cooling System with Waste Heat Recovery Condenser," *SAE Int. J. Commer. Veh.* 7(2):2014, doi:10.4271/2014-01-2339.

INTRODUCTION

The Extension of Rankine Cycle Waste Heat Recovery into On-Road, Linehaul Applications

The idea of recovering waste heat, and using it for some useful purpose, is certainly not new. Within vehicular applications, most people are aware, perhaps unknowingly, of some form of waste heat recovery technology. The simplest of these forms is most-likely the utilization of engine waste heat for the purpose of cabin heating. In this instance, the waste heat engine coolant stream simply transfers heat to the cabin, instead of outside air, in order to provide the desired level of passenger

comfort. Another common, and more complex, form of waste heat recovery is the use of a turbocharger. In this instance, some of the waste heat from the exhaust stream is used to drive a compressor, via an exhaust-driven turbine, for the purpose of increasing the aerobic potential of an internal combustion engine, which in turn increases its power output.

This evolution of waste heat recovery technology from simple thermal waste heat utilization, to thermal mechanical waste heat utilization with the automotive industry is an evolutionary path not unique to this industry, and has since found a place in other areas outside of on-road applications. Of

principal interest, and applicability to the work presented here, is the use of waste heat to vaporize a power fluid for the purpose of providing motive energy to a thermal-mechanical device: typically a power turbine. Since the power turbine of a waste heat recovery (WHR) system needs to be appropriately sized in relation to the amount of usable waste heat available and the desired rate of WHR power production, the applications best suited to the use of WHR technology are those where a consistent amount of energy, at a consistent level of thermal availability, is available within the applicable waste heat stream.



Figure 1. ECHOGEN industrial process Waste Heat Recovery System with power outputs ranging from 6MWe to 32MWe [1]. The 8MWe system has a total estimated mass of 114,000kg (Process Skid + Power Skid + Control House) [2].

Such applications experience relatively infrequent changes within their waste energy streams and allow for the effective, and economical, use of a WHR system in order to provide greater levels of energy efficiency.

One of the more common, and commercially available, forms of mechanical WHR is the use of a Rankine Cycle WHR system to recover energy from the waste heat streams of industrial processes. These processes can vary widely and range from recovering flue gas energy, to recovering some of the waste energy present in the process streams present in other industrial processes, such as chemical processing, cement production, or oil refining operations. Another current WHR application involves recovering mechanical energy from the waste heat energy of large marine engines: an application well suited to WHR because of the consistent energy available within the waste heat stream (limited engine load changes), the large amounts of fuel consumed within a single installation, the space available for a WHR system, a large and efficient heat sink (seawater), and the straightforward calculations involved in determining the economics of the WHR system installation. Similar to large marine WHR systems, commercial-scale power generation systems show strong potential toward leveraging the benefits of a WHR system due to presence of many similar factors. Of principal importance is a known, and consistent, energy level within the waste heat stream. This allows for the appropriate sizing of the WHR system in order to provide the end-user of the technology with a WHR system having easily-determined economic benefits.

The lessons learned from the successful, and economical, application of thermal-mechanical WHR systems to large-scale off-road applications lends valuable insights toward achieving similar efficiency and economic benefits for on-road applications, noting that on-road applications have added challenges such as a more dynamic operating range, increased system integration constraints, and a more complex and codependent, waste-heat to environmental-heat-sink, heat rejection path. With this in mind, the architects of on-road WHR systems cannot simply examine the closed-cycle thermodynamics of their WHR system, and must be mindful of both the integration challenges, and vehicular perturbations caused by the use of a WHR system, as all of these elements will determine the overall installed-efficiency, and subsequent economic value of the WHR system. A significant amount of the effort expended on the Cummins/Peterbilt SuperTruck program was dedicated to the successful, and economical, installation of a thermo-mechanical WHR system into a Class 8 vehicle and this effort drove vehicular changes for this purpose while aiming to minimize impacts to other vehicle attributes, such as the aerodynamic drag.

SuperTruck Program

The Cummins-Peterbilt SuperTruck Project was awarded in March 2010 as a 50% cost shared project with the US Department of Energy. The combined project objectives were as follows:

- **Objective 1:** Engine system demonstration of 50% or greater BTE in a test cell at an operating condition indicative of a vehicle traveling on a level road at 65 mph.
- **Objective 2A:** Tractor-trailer vehicle demonstration of 50% or greater freight efficiency improvement (freightton-miles per gallon) over a defined drive cycle utilizing the engine developed in Objective 1. The demonstration vehicle is designated as Demo 1.
- **Objective 2B:** Tractor-trailer vehicle demonstration of 68% or greater freight efficiency improvement (freightton-miles per gallon) over a defined 24 hour duty cycle (above drive cycle + extended idle) representative of real world, line haul applications. The demonstration vehicle is designated as Demo 2.
- **Objective 3:** Technology scoping and demonstration of a 55% BTE engine system. Engine tests, component technologies, and model/analysis will be developed to a sufficient level to validate 55% BTE

The discussion contained within this paper describes the design, validation, and testing of the vehicle cooling system to integrate the Waste Heat Recovery (WHR) Cooling System that was selected to assist with achieving Objectives 2A and 2B. [3]

Cummins/Peterbilt Approach - Motivation for WHR

The approach utilized for the project was to perform an energy assessment of 2009 vintage vehicles in order to identify opportunities for improvement. A significant opportunity identified was the exhaust and coolant heat energy that would traditionally be rejected to ambient. This led to a decision to employ the Cummins WHR system which captures energy via usage of a working fluid. This fluid is then expanded across a turbine which is coupled to the engine crankshaft in order to generate shaft power.

The top-level breakdown for SuperTruck improvement areas is shown in [Figure 1](#) below. The WHR opportunity is identified as a portion of the Engine opportunity section.

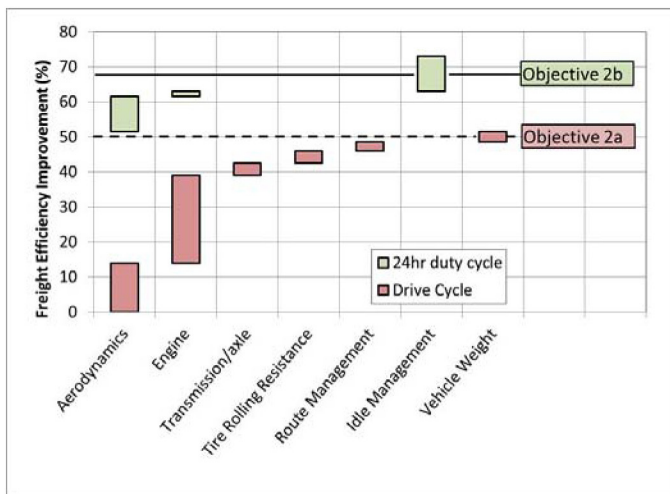


Figure 2. System Breakdown of SuperTruck Opportunities

Waste Heat Recovery in SuperTruck Program

The use of a thermo-mechanical Rankine Cycle WHR system in any scenario requires a low-temperature heat sink, into which thermal energy from the low-temperature side of the Rankine cycle power cycle can flow. In the case of a Class 8 vehicle, or any other on-road vehicle, that low-temperature sink is the atmosphere, and this heat sink is ultimately shared, either directly or indirectly, by all other heat exchangers on the vehicle. The design chosen for this effort was to have the bulk of these heat exchangers reside within the air path between the vehicle's grill opening, and engine-driven fan. These heat exchangers typically consume most, if not all, of the available space within this envelope, making the integration of the requisite low-temperature side heat exchanger for the Rankine cycle WHR system, in this case an air-cooled condenser, challenging.

In addition to space constraints, the WHR Condenser dissipates a significant amount of thermal energy. Increasing the heat that the WHR condenser can reject to the ambient will increase the mechanical power added to the drivetrain. System logic was put in place to make sure that the engine would not overheat during taxing cooling periods by throttling the amount of heat rejected by the WHR condenser. Alternatively, logic

could also be added to engage the engine driven fan to increase cooling airflow through the front mounted heat exchangers including the WHR condenser. However, the additional power draw from fan engagement was determined to counteract any additional mechanical power from the WHR system. A goal was to design the heat exchanger architecture to minimize this throttling time and maximize power addition by the WHR system. Two main operating conditions were considered in the design of the WHR system. The first was a 50 mile per hour vehicle speed with an engine heat rejection 50% greater than a typical cruise condition, which represented a hill climb system load, specified as an A75 condition. The second was a full load cooling case which was defined as the C100 condition.

The A75 condition represents a high total front end heat rejection at highway speeds, with the WHR condenser rejection on the order of 70 kW. Minimizing the WHR condenser throttling and minimizing fan engagement time at this condition will increase the total efficiency of the dynamic vehicle operation. In keeping with traditional Class 8 design requirements, the heat exchanger architecture must also be able to meet cooling needs at high engine power conditions, such as peak power, but with the added WHR condenser heat rejection burden of at least 100 kW for an un-throttled WHR system operating at this condition.

Minimizing the airside inlet temperatures to the WHR Condenser is valuable, as is maximizing the amount of airflow particularly passive, fan-off airflow. Poor WHR Condenser installations have the ability to significantly compromise the efficiency, and economics of a WHR system, therefore careful, and well thought-out, system-level design practices need to be leveraged when integrating a WHR Condenser into the powertrain cooling module space.

This effort can be challenging since most powertrain cooling module arrangements are not conducive to effective WHR Condenser integration. Their component arrangements are typically in series with the airflow path, with the sequential component arrangement, starting at the vehicle's grill, as follows: AC Condenser, Charge Air Cooler (CAC), and main engine Radiator [4]. Naturally, other arrangements for these components exist, as does arrangements where additional heat exchanger types, such as low-temperature radiators and oil coolers, are used, but the general integration practice is essentially the same, especially for high-heat-rejection components like the CAC and Radiator. The addition of the WHR Condenser complicates the installation in several ways. The WHR Condenser adds a significant amount of heat rejection to the cooling module. It competes for cool, fresh air with the CAC and both have operational targets. The CAC must meet intake manifold temperature differential (IMTD) requirements and WHR Condenser needs to minimize low-side pressure. The available heat exchanger frontal area limits mass air flow to both the CAC and WHR Condenser due to fresh-air-competition and the available package depth limits the ability to stack heat exchangers in the fore-aft direction.