

Waste Heat Recovery: The Next Challenge for Commercial Vehicle Thermomanagement

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ABSTRACT

A significant driver for the development of future commercial vehicles is likely to be the introduction of fuel consumption related legislation in various regions around the world. The application of a waste heat recovery system to the powertrain of such vehicles is seen as a possible step, amongst many, to help them achieve the required fuel economy. In particular, the Rankine Cycle (a closed steam cycle) is often proposed as a potential means for deriving work from the engine exhaust heat.

Rankine Cycle systems are already in use in off-highway applications, such as stationary engines or marine power-packs. However, the technical and commercial viability of these systems for on-highway, principally long haul truck application is as yet unproven. Aspects such as the in-use economy benefits, the system performance density, the component robustness and all interactions with the other vehicle systems have to be evaluated. These aspects translate into new challenges for suppliers of vehicle thermal management components and modules.

In this paper, the simulation the Rankine Cycle system together with the complete vehicle infrastructure using in-house developed tools, in order to predict the actual likely fuel consumption benefit, is presented. Results are shown in relation to the use of alternative system layouts for a long haul vehicle application. The validation of the simulation results is also presented.

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INTRODUCTION

Over the past twenty years, achieving ever more stringent emissions legislation has been the focus for commercial vehicle engine development. On the other hand, the commercial vehicle operational profitability has always been dependent upon the vehicle-payload fuel efficiency. These two aspects will converge in the future with the introduction of commercial vehicle fuel consumption (CO₂ emissions) legislation (plus the manufacturer's and operator's own commitments), which will come into force around the world from the middle of the decade. This legislation will, most probably, consider the complete vehicle CO₂ emissions on the equivalent to a g/tonne.mile basis. As such, the contribution to fuel efficiency improvement from vehicle operational logistics, the vehicle design and from the vehicle powertrain will be considered: it is likely that each aspect will

contribute a roughly similar amount to the CO₂ emissions reduction.

Within the powertrain, thermal management will play an important role in helping to achieve future fuel consumption reduction targets. It is estimated that improved thermal management could offer up to a 10% reduction in vehicle fuel consumption [1]. Of this reduction the largest single measure appears to be waste heat recovery (WHR), which, it is hoped, could save up to 5% of the fuel consumption of a heavy duty long haul truck.

Waste heat recovery is a well known technology for stationary engine operations: the discussion about WHR systems for vehicle applications has, therefore, intensified over the past years, for example [2, 3, 4, 5, 6]. The most promising in-vehicle bottoming cycle is the Rankine Cycle. However, before the cycle can be applied to commercial vehicles, the challenges of the integration of the WHR system into the existing vehicle infrastructure and in the development

of the necessary new components for on-highway application need to be addressed. In this paper, Behr's success to date in addressing these challenges is reported.

ASPECTS TO CONSIDER FOR ON-HIGHWAY APPLICATIONS

HEAT SOURCES OF DIFFERENT QUANTITY AND QUALITY

In a commercial vehicle several waste heat sources could be used separately or in combination, for example the tailpipe exhaust gas, the recirculated exhaust gas (EGR) or the charge air. These alternative sources have different quantities (amount of heat available) and qualities (temperature level (exergy), thermal inertia, impact on cooling needs and engine efficiency), which can vary with different engine calibrations and throughout the engine and vehicle transient operation. This brings challenges for the system architecture, the expansion machine and the control of the on-highway Rankine Cycle.

HEAT SINK OF LIMITED CAPACITY AND ENERGTIC EFFECTIVENESS

In a commercial vehicle the only viable heat sink is the vehicle cooling system: this will be more highly loaded than in an existing vehicle if, for example, the tailpipe exhaust gas is used as a heat source. During operation this aspect can limit the amount of waste heat that can be converted into useful work or lead to increased fan power consumption, which could cancel any fuel saving due to the WHR. Whether such situations arise is dependent upon many factors, for example the vehicle speed or the ambient conditions. As such, complete system analysis is necessary to find the optimum compromise between the WHR system layout plus component design and the cooling system, in both steady state and transient conditions.

IMPACT OF WHR ON ENGINE PERFORMANCE AND EMISSIONS

The commercial vehicle's engine and its operation will be influenced by the introduction of the WHR system; hence WHR is performance and emissions relevant. For example, heat exchangers in the tailpipe will increase the back pressure on the engine. Additionally, since the WHR system will share the vehicle cooling system with the charge air and EGR cooling, there will be an interaction with the inlet manifold temperatures thus the engine emissions and fuel economy trade-off. Furthermore, at constant vehicle power, the introduction of WHR will move the engine operating point or be an enabler for engine downsizing. These interactions, between the engine and the WHR, need to be understood and optimized at a vehicle system level.

THE RIGHT CHOICE OF WORKING FLUID

A Rankine Cycle working fluid for a stationary application is not necessarily ideal for a commercial vehicle application. The aspects of fluid degradation, toxicity, flammability, global warming potential and freezing all have to be considered. Similarly, the different possible working fluids lead to different WHR system layouts, component designs, operating strategies and fuel economy benefits. To date no single ideal fluid for on-highway applications has been identified.

WHR COMPONENT DESIGN AND PRODUCTION

The commercial vehicle application of a Rankine Cycle presents new constraints on the component design when compared to a stationary application. In the first place packaging space and payload is at a premium; therefore the volume specific performance density of the components, particularly the evaporators and super heaters, must be maximized. Yet, the components must also fulfill the durability requirements of a long haul truck, which places particular emphasis on the pressure and thermal cycle robustness of the heat exchanger designs, not to mention the vibration and corrosion resistance capabilities. Each of these constraints must be achieved whilst also satisfying the service and safety needs for commercial vehicles and, of course not forgetting, the cost pressures inherent within the automotive industry, which necessitate designs compatible with mass production techniques.

1D MODELING OF THE SYSTEM INTEGRATED INTO THE VEHICLE

The key to the successful development and commercial vehicle market introduction of WHR will be the right choice of system architecture, working fluid and an early knowledge about the cost to benefit ratio. It is, however, impossible to understand the complexities described above without a means of simulation that covers both the overall process as well as the detailed physical mechanisms. Today, vehicle thermal management systems are simulated in a 1D tool that has been developed for engine cooling and vehicle air conditioning systems [7]. This Behr Integrated System Simulation (BISS) has been extended to include WHR systems [8]: a BISS topology for an engine cooling system plus a Rankine Cycle WHR system is shown in [Figure 1](#).

The Rankine Cycle alone is modeled as shown in [Figure 2](#) (by way of example using water as the working fluid): superheated steam is expanded in a machine to the condensation pressure. In the expansion machine the heat is transformed into mechanical work. During condensation of the working fluid, heat is rejected into the vehicle cooling system. Thereafter, the working fluid is pumped into the evaporator at higher pressure. The heat, for example from the

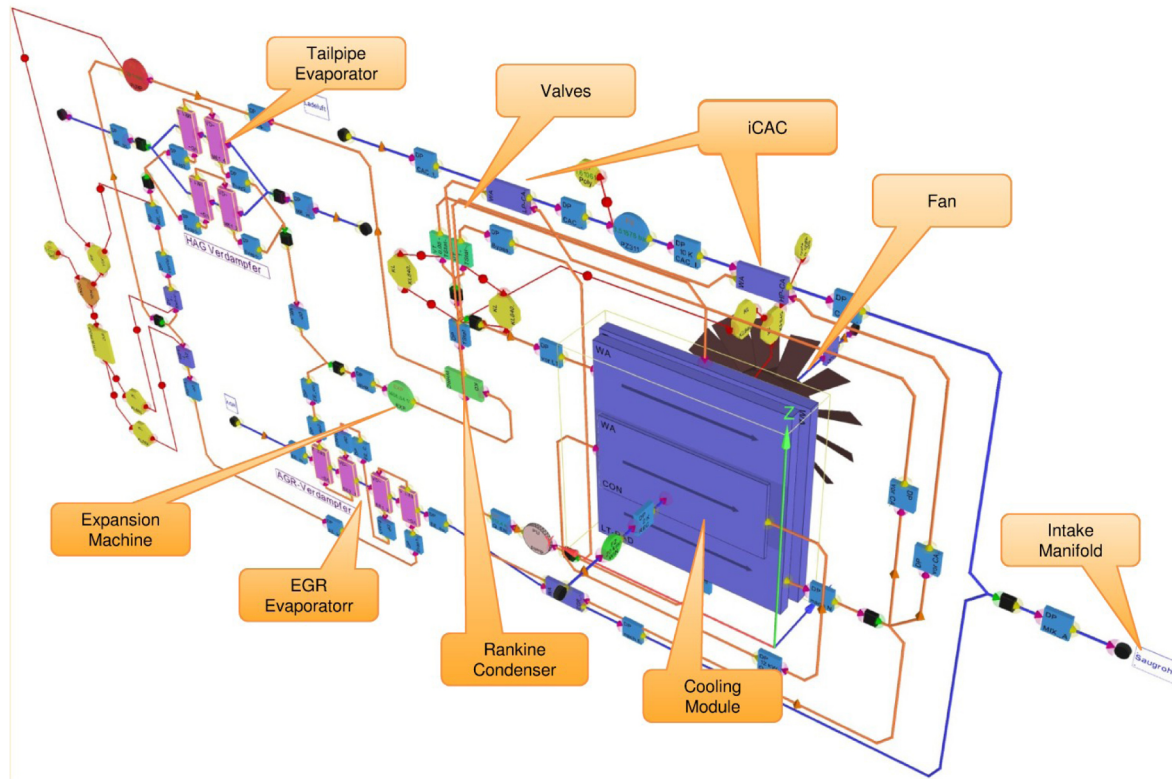


Figure 1. BISS topology for a complete commercial vehicle thermal management system, including the engine, with EGR, its cooling system and a Rankine Cycle WHR system [10].

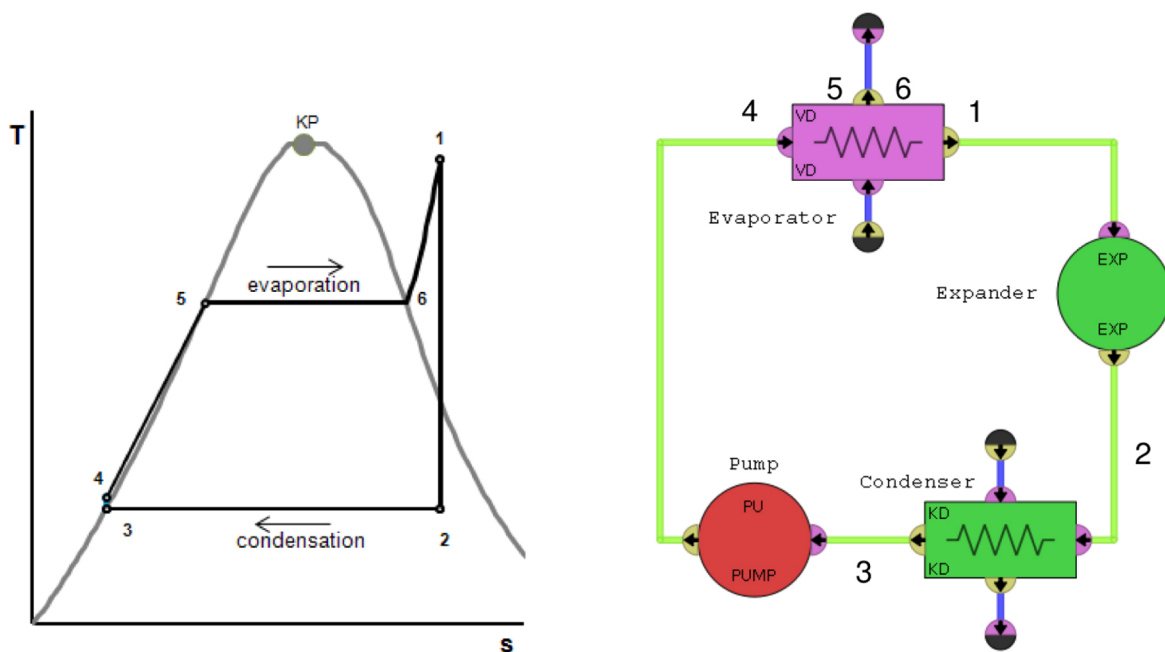


Figure 2. The T-s diagram and the related BISS topology for a simple Rankine Cycle for a wet fluid such as water [8].

exhaust gas, is supplied to the working fluid in the evaporator in three regions: at first the liquid fluid is warmed, then

evaporation takes place before the fluid is, finally, superheated.

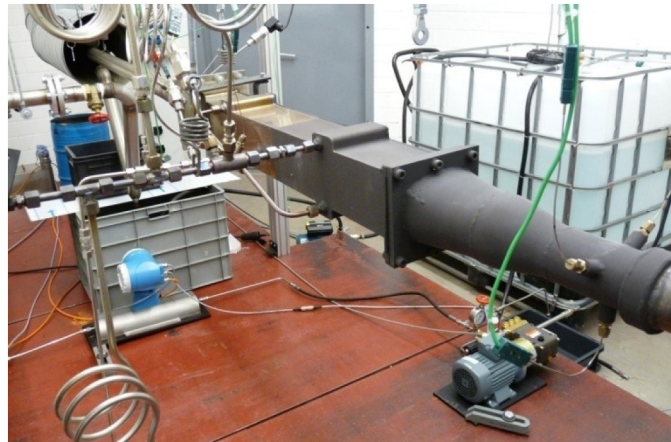


Figure 3. An evaporator (shown without insulation) installed in a hot gas test rig for performance characterization

A prerequisite of the simulation is that the geometrical details of the components as well as the operational conditions are given. The arrangement of the cycle is variable to some degree: at least those components shown in [Figure 2](#) must be included, but multiple arrangements of components, for example evaporators in parallel, and other components, such as a recuperator, are also possible. Of particular importance is the modeling of the evaporator, where a detailed knowledge of the thermo-hydraulic processes in the complex two phase flow structure is indispensable: it is necessary to model the heat transfer and pressure drop in the different flow regimes in a detailed and reliable manner. This becomes increasingly complex with different working fluids, especially with mixtures of fluids. A more thorough description of the Rankine Cycle modeling features in BISS is given in [8].

VALIDATION OF THE COMPONENT MODELLING RESULTS

THE EVAPORATOR

Alongside the development of the modeling tools, the development of Rankine Cycle heat exchangers has made significant progress over the last two years. Of primary importance for the effectiveness of WHR is the pre-heater plus boiler plus superheater, known as the evaporator, two of which can be used, one fitted into EGR circuit and one in the exhaust tailpipe. These components, which are naturally designed to the performance density, durability and manufacturability requirements of commercial vehicle applications, are similar to an EGR cooler on the exhaust gas side but have complicated flow paths and flow channel geometries on the working fluid side. The performance testing of such a component is shown in [Figure 3](#): here the evaporator (shown without insulation) is installed into a hot gas test rig to provide the engine exhaust like thermodynamic conditions and is coupled to a working fluid supply and condensing circuit suitable to vary the mass flows over a

wide range. This test installation allows the characterization of the evaporator, for example the working fluid outlet temperature as a function of the fluid mass flow rate over a range of exhaust gas temperature and mass flow conditions. The results from such a test are shown in [Figure 4](#), along with the results of the equivalent component simulation within BISS. It is seen that as the working fluid mass flow rate is reduced at constant exhaust gas conditions, the working fluid outlet temperature varies rapidly between that related to a wet vapor and a superheated fluid: it is this transition that must be characterized in order to ensure good performance and control of the evaporator operation within the WHR system. The simulation results are in good agreement with the test measurement results, the remaining differences are mostly a result of external heat losses and non-1D flow distributions in the test rig.

THE INDIRECT CONDENSER

In a similar manner to the exhaust gas evaporators, so the development of the condenser for the WHR system has made significant progress. Depending upon the working fluid being used, the condenser in the Rankine cycle can either be direct, that is air cooled, or indirect, that is coolant cooled (where the coolant comes from either the vehicle high temperature cooling circuit or a secondary low temperature cooling circuit). For the majority of the commercial vehicle applications under consideration with either water or ethanol as the working fluid, an indirect condenser is applicable: such a component is shown on an in-house performance test rig in [Figure 5](#). The results from such a test are shown in [Figure 6](#), along with the results of the component simulation within BISS. The simulation results are in excellent agreement with the test measurement results.