

Rankine Cycle for Waste Heat Recovery of IC Engines

J. Ringler, M. Seifert, V. Guyotot and W. Hübner

BMW Group Research and Technology

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ABSTRACT

This paper deals with an analysis of the potential of the Rankine cycle as an additional power generation process, which uses the waste heat of a car engine. A review of different heat recovery technologies leads to the identification of the steam process as a favorable solution for automotive applications.

Two basic configurations (exhaust gas only; exhaust gas plus coolant) are selected from numerous illustrated Rankine cycle layouts for a detailed evaluation of heat recovery based on a four-cylinder internal combustion engine (ICE). Furthermore, the impact of different working fluids is studied. A parametric analysis of the efficiency of two selected systems is accomplished with the Dymola simulation tool, followed by a direct comparison between both configurations for different engine technologies and vehicle speeds.

Finally, test bench measurements of the applied engine coupled with a heat recovery device are carried out. It can be demonstrated that waste heat recovery can produce an additional power output of about 10% at typical highway cruising speeds.

INTRODUCTION

In recent years the automobile industry has made great progress in improving engine efficiency. So far, the corresponding R&D activities have mainly focused on the optimization of fuel/air mixture preparation and the combustion process [1; 2]. Nevertheless, today's engine

efficiency is reaching its technical limit and will not be sufficient enough to meet future fuel economy targets without additional measures.

Electrical hybrid concepts are one well-known approach [3]. A relatively new perspective is to take a closer look at the "periphery" around the engine with all its units for converting energy. The application of an optimized energy management system can also contribute to the reduction of fuel consumption [4]. But what about the biggest and, as yet, untapped source of energy in the car: engine waste heat? Even modern combustion engines achieve a maximum efficiency of approximately 40%. Hence, at least 60% of the energy in the fuel is lost via exhaust gas and engine coolant. In this study the issue of heat recovery of combustion engines is addressed for automotive applications.

REVIEW ON HEAT RECOVERY SYSTEMS

Several physical effects can be used to recover energy from the waste heat of a combustion engine (Figure 1). The utilization of the waste energy is the first determining key factor for the overall efficiency of each technology illustrated. While turbo-machines (e.g. turbochargers) can only use pressure gradients and/or kinetic energy fractions of the exhaust gas, other technologies are tapping the much bigger amount: waste heat (Figure 1).

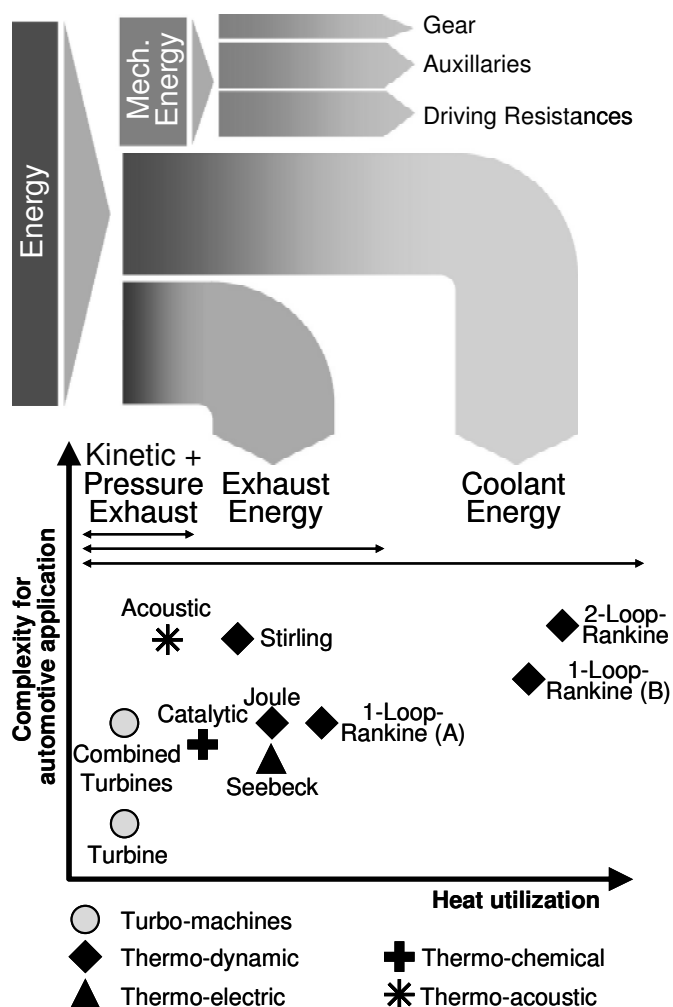


Figure 1 Energy utilization vs. complexity of different heat recovery systems

The differences in the thermal processes in heat utilization are mainly caused by the ability to use the temperature difference. Chemical reactions have to run within a required temperature range ($>400\text{--}500^\circ\text{C}$) and can therefore only utilize heat above this temperature level. Due to the process management, the realization of a high heat input is much more critical for devices based on the thermo-acoustic effect or the Stirling cycle. The heat transfer by gas-to-gas of the Joule process and by gas-to-material of a thermoelectric device makes the heat utilization for a given heat exchanger surface more difficult in comparison to the evaporation procedure of a Rankine cycle. Moreover, the latter approach offers the possibility to recover the released heat of both the exhaust gas and the coolant system. In general, system complexity (e.g. size, weight, system integration) is increasing with growing heat utilization. But the complexity of some technologies (Stirling, thermo-acoustic) is disproportionally high in comparison to the heat recovery achievable for automotive applications. For this reason these systems are excluded in the following evaluation.

In addition to the heat utilization, the efficiency of the process itself plays an important role. Turbo-machines and thermo-chemical technologies are not considered, because their efficiency benefits are strongly linked to the combustion engine and, hence, hard to assess. Furthermore, turbo-machines, and in particular turbochargers, can be applied in combination with the thermal processes illustrated in Figure 1. Current efficiencies of thermo-electrical devices are lower than those of thermo-dynamic processes, but future material development could offer the chance to efficiently generate electrical power directly on-board [5]. The two remaining thermo-dynamic processes (Joule, Rankine) are well-established in gas and steam cogeneration plants. Due to its better efficiency the steam cycle is used for lower temperature levels ($300\text{--}900^\circ\text{C}$) as found in the exhaust gas of an IC engine. To summarize the Rankine steam cycle can be identified as a favorable approach for the recuperation of waste heat.

POSSIBLE SYSTEM CONFIGURATIONS OF THE RANKINE STEAM CYCLE

As shown in Figure 2 the underlying ideal Rankine steam cycle can be divided into four processes, each associated with a change of state of the working fluid:

- **Process 1-2:** The isentropic compression of the liquid working fluid.
- **Process 2-3:** The isobaric heating, evaporation and superheating of the medium ($2\rightarrow3$) $Q_{\text{med,in}}$ by supplying the thermal loss energy.
- **Process 3-4:** The isentropic expansion of the vaporous medium ($3\rightarrow4$) in an expansion machine, generating mechanical power.
- **Process 4-1:** The isobaric condensation of the medium back into the liquid phase ($4\rightarrow1$) along with dissipation of heat $Q_{\text{med,out}}$ into the environment.

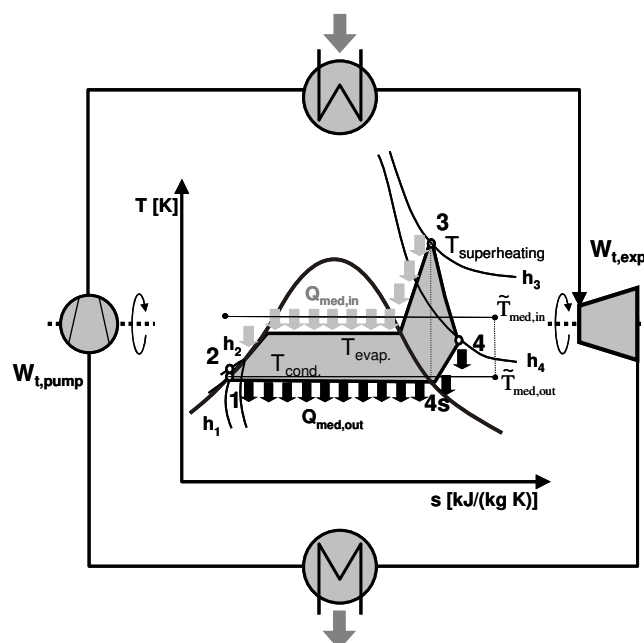


Figure 2 Fundamentals of the Rankine cycle

Assuming an ideal process, the thermal efficiency of the Rankine process is as follows:

$$\eta_{\text{Rankine, ideal}} = \frac{W_{t, \text{exp}} - W_{t, \text{pump}}}{Q_{\text{med, in}}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)} \quad (1)$$

$$\eta_{\text{Rankine, ideal}} = 1 - \frac{Q_{\text{med, out}}}{Q_{\text{med, in}}} = 1 - \frac{\tilde{T}_{\text{med, out}}}{\tilde{T}_{\text{med, in}}} \quad (2)$$

The thermal efficiency as given in equation (1) gauges the extent to which energy input to the working fluid passing through the heat exchanger is converted to the net work output. The values for technical work of the pump ($W_{t, \text{pump}}$) and the expander ($W_{t, \text{exp}}$) can be calculated from the differences in the enthalpy of the working fluid (Figure 2), whereas $Q_{\text{med, in}}$ gives the heat transferred from the loss energy of the engine to the process (2→3). The thermal efficiency can be also expressed in terms of heat transfers as shown in equation (2) where $Q_{\text{med, out}}$ gives the heat released during the condensation process (4→1). As illustrated in Figure 2 the mean lower and upper process temperature correspond to $\tilde{T}_{\text{med, out}}$ and $\tilde{T}_{\text{med, in}}$, respectively.

Based on this fundamental cycle, various designs can be identified to recover engine waste heat. These configurations differ in the utilization of the heat source (coolant system and/or exhaust gas) and the number of system components (e.g. heat exchangers, expanders), as well as in the number of separate loops (Figure 3). In a dual or multiple loop system the working fluid of each sub-system is not exchanged. For example, layout 1 illustrates a dual-loop apparatus which combines a high temperature (HT) loop and a low temperature (LT) loop. The HT loop only recovers the heat of the exhaust gas. The LT loop recovers the residual HT heat, the coolant heat and the remaining exhaust gas heat. The two separate loops are coupled with a heat exchanger. Information on this configuration can be found in [6] where, besides the additional power, other automotive aspects such as the geometrical integration in a passenger car are also discussed.

A complete system evaluation of all the configurations displayed, including the package requirements as well as cost effectiveness would exceed the framework of this paper. Hence, in order to access the potential of heat recovery for automotive application we will only focus on the additional power. Furthermore, the evaluation is restricted to two basic single loop systems which are studied in detail in the following section:

- **System A:** Utilization only of exhaust gas
- **System B:** Utilization of exhaust gas and coolant

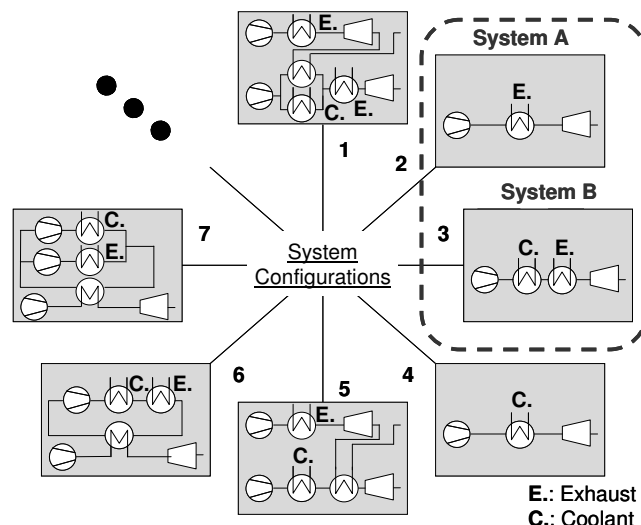


Figure 3 Conceivable designs for the heat recovery of the engine waste heat with steam cycles

Using the example of the two selected system configurations the role of the heat source as well as the impact of the operating parameters on the heat recovery potential were analyzed. The presented simulations, calculations and experimental investigations were performed for the most common engine design, a four-cylinder engine with a stoichiometric combustion [2].

WASTE HEAT FLOWS

For every Rankine cycle knowledge of the temperature level of the heat sources is essential for the selection of a working fluid and the optimization of the operating conditions. Hence, the temperature of the coolant and exhaust is needed. Furthermore, the ratio of the corresponding heat flows is required for the comparison of the net output of system A and B. This ratio is given by:

$$q = \frac{\dot{Q}_{\text{coolant}}}{\dot{Q}_{\text{exhaust}}} \quad (3)$$

Test bench measurements of heat flows were carried out for the studied engine. First, the temperature level of the coolant was raised to ~115°C and kept constant in order to optimize the utilization of this heat source. It is important to point out that no negative effects on the engine efficiency could be observed. The exhaust gas temperature sensors were positioned behind the catalyst, where the inlet of the exhaust gas heat exchanger was placed. Figure 4 shows the measured data together with the road resistance curve for the top gear. Changing the vehicle speed from 45 to 80 mph causes the exhaust gas temperature to increase from ~500 to ~800°C. As indicated by the isolines, engine load has also a significant influence on the temperature level of the exhaust gas. Nevertheless, the road resistance curve for the top gear will be the focus in the following evaluation, bearing in mind that heat flows might be very different for highly dynamic driving profiles.