Development of Exhaust Gas Evaporators for Rankine Waste Heat Recovery Systems

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Introduction
The utilization of the waste heat of combustion engines is a very promising technology to reduce the CO₂ emissions of future vehicles and promises fuel consumption savings up to more than 10% [1, 2, 3, 4, 5, 6].

Figure 1 shows an abstract overview of different technologies to utilize automotive waste heat, either directly or by conversion to other energy forms. TheSys GmbH, as a highly specialized engineering company on the field of research and development of mobile cooling systems and heat exchangers, has a specific project focus on the development of waste heat recovery systems based on

- Rankine process
- Thermo electric generators
- Joule process and
- Thermal heat management.

![Figure 1: Overview of automotive waste heat recovery technologies](image-url)
This paper focuses on the development of evaporators for Rankine waste recovery systems, the thermodynamic system and component simulation and the development of various designs of evaporators to serve different customer applications.

1. Cooling System Integration of a Rankine Waste Heat Recovery System (WHRS)

In a Rankine Waste Heat Recovery Process, a working fluid is being compressed in a feeding pump to a high pressure level, vaporized and overheated in an evaporator. The overheated steam will then be expanded in an expander providing mechanical energy. The expanded fluid will then be condensed in a condenser and by passing a collecting tank be led back to the pump.

For a principal design and dimensioning of a WHRS, the interactions with the cooling system have to be considered in an early development stage. Taking a series vehicle with a cooled exhaust gas recirculation as a basis, it is obvious to replace the exhaust gas recirculation cooler (EGRC) by an exhaust gas recirculation evaporator (EGR-evaporator), figure 2. This leads to an increase in engine power by app. 3%. Additionally, the overall heat load of the engine cooling system is reduced by app. 3%. As the EGR-evaporator is only operated when the exhaust gas recirculation is activated, the control strategy of the EGR-valve has a significant impact on the WHRS efficiency. As a second aspect, the temperature level of a low temperature cooling circuit serving the condenser influences the efficiency of the WHRS but also the energy demand of the cooling system and has to be balanced out.

![Energy flow diagram](image)

Figure 2: Energy flow of a Rankine-WHRS with an EGR-evaporator compared to series
Adding a main exhaust gas evaporator (MEG-evaporator) into the exhaust gas duct, e.g. downflow of the exhaust gas aftertreatment system, leads to a permanent heat input for the WHRS. Therefore, the engine power will be increased by app. 7% or more. On the other side, the additional heat load leads to a significant increase in overall cooling system heat load by 23%. This may be acceptable at uncritical cooling system operating conditions as e.g. at engine part load or at low ambient temperatures and needs an intelligent control strategy which needs to be developed, figure 3.

![Diagram showing energy flow of a Rankine-WHR with and without an EGR-evaporator and main exhaust gas evaporator.](image)

**Conventional Vehicle**

**Vehicle with Rankine-WHR-System**

**EGR- & Exhaust-Evaporator**

Figure 3: Energy flow of a Rankine-WHR with an EGR-evaporator and main exhaust gas evaporator

2. Thermodynamic System Simulation

A 1d-simulation model for a truck was build up in GT-Suite to enable principal thermodynamic studies and optimizations, figure 4. The EGR-evaporator and the MEG-evaporator are modeled in detail based on measurement data. The condenser, expander and feeding pump are described by efficiency characteristics and assumptions. The WHRS-condenser is integrated into a low temperature cooling circuit.

The thermodynamic description of evaporators is done with the home made simulation tool “TheSim”. The 0d-evaporator model allows the separation in different sections representing the one phase areas (liquid, overheated steam) as well as the two phase area. Each section can again be divided into subsections to represent local changes of the flow duct geometries.
Based on calorimeter measurements done at prototypes, the heat transfer coefficients, the heat transfer resistance in the separation walls and the efficiency of primary and secondary heat transfer surfaces are modeled for each section. The thermodynamic correlations are specifically defined for every zone of the evaporator and are gained by regression of the measurement results. The evaporator-specific two-phase heat transfer correlations are based on suitable modified two-phase literature correlations with regressed parameters. Also the pressure drop characteristics of the flow ducts and the characteristics of fluids and materials are implemented.

The resulting thermodynamic evaporator models allows a detailed local analysis of the Nusselt and Reynolds numbers along the working fluid flow path and is therefore a valuable tool for optimizing the local fluid path geometries. Over all, a prediction of evaporator performance and pressure drop can be done for different operating conditions as well as a variation of the evaporator dimensions, figure 5.

The thermodynamic model developed in TheSim is transferred to the system simulation model by using user functions, i.e. a replication of the heat transfer coefficient correlation in a Fortran subroutine that is accessed by GT Suite.
As an example, figure 6 shows the link of the 0d- and 1d-simulation tools to enable simulations for a given route histogram of the truck, figure 6. For the given system architecture, boundary conditions and control strategy it can be seen, that the exhaust gas evaporator has to be bypassed at engine loads exceeding app. 70% to avoid the engagement of the fan at high engine speeds. Otherwise, the power demand of the fan would overcompensate the power benefit of the WHRS. At low engine speeds an engagement of the fan is acceptable and still leads to a positive energy balance. As one exemplary result of the route histogram simulations, it can be seen that the maximum performance of the WHRS (no limitations by the cooling system) can’t be utilized due to the limitations of the engine cooling system, mainly be activation of the fan. After an optimization of the control strategy for the given cooling system limitations, a reduction by 20% compared to the maximum possible WHRS performance could be achieved.
3. Evaporator Development

For the series application of a mobile Waste Heat Recovery System, the necessary evaporators have to be developed, meeting the high requirements regarding power, packaging, weight, reliability and price. Depending on the specific requirements and the place of installation as an EGR-Evaporator or MEG-Evaporator, different evaporator designs will be necessary [7].

The principle design of a bar and plate evaporator for a truck is shown in figure 7. Scope for the development is a design being compatible in terms of packaging as well as media connection positions to replace the series EGR-cooler. A bar and plate design enables maximum flexibility in the geometrical design of the fluid ducts. Therefore, the evaporator can be optimally designed to meet the hydraulic and thermodynamic requirements leading to good stability of evaporation and to a high performance density. Nevertheless this design requires a high material usage and high volume automation is limited due to the quantity of different parts. For high series volumes this design will therefore be transferred into a layered cooler design.
For an off-road application two prototypes of EGR-evaporators were built up showing differences in the design of the working fluid ducts (P1, P2). For both prototypes thermodynamic performance measurements were done. The measurement results are the basis for the 0d-evaporator model in TheSim as described before.

For an automotive application, figure 8 shows a bar and plate design with U-flow of the exhaust gas and working fluid duct. For high volume series production, this design will be transferred into a shell type or layered cooler design, leading to high performance densities and low production costs per unit. Disadvantages are high tooling costs and a limited flexibility to cope with different packaging requirements.

To serve as an alternative for the bar and plate design for high production volumes, a twin round tube evaporator design is under development. This evaporator is built up as a tube bundle with twin tubes as shown in figure 9.

Each twin tube consists of two concentric round tubes with the hot exhaust gas inside the inner tube. The annular gap between inner and outer tube serves as the working fluid duct.
Figure 8: Bar and plate evaporator for passenger cars

Figure 9: EGR-evaporator in Twin Round Tube design
The geometry of the working fluid duct is designed to cope with different local fluid densities and velocities. One or both tubes will be manufactured as twisted tubes, similar as they have been in series for EGR coolers for years. A twist of the inner tube provides the additional advantage of inducing turbulence and therefore increasing the heat transfer performance on the exhaust gas side. Enhanced capabilities in working fluid duct design provide twisted outer tubes. The usage of twisted tubes provides the additional benefit of reducing material stresses, especially under the demands of temperature cycle operation due to the elasticity of the tubes.

Due to the usage of standardized parts and manufacturing processes, this design is applicable for high production volumes. Additionally, a Twin Round Tube Evaporator is a very robust design for the high inner pressure, pressure cycle, and thermal cycle loads are handled by round tubes which can be provided with the required pressure strength and elasticity by appropriate dimensioning of material gage and twist geometry.

Motivation for the development of the Twin Flat Tube Evaporator is the creation of a design which is capable of a high volume series production and meets the high performance density of a plate and bar design by using turbulators or fins on the exhaust gas and working fluid side. Here flat tubes are stapled to a flat tube bundle, provided with fluid headers, and brazed, figure 10.

Figure 10: Twin Flat Tube Evaporator

Design base is the usage of flat tubes with fins being used in series EGR coolers. These flat tubes are wrapped by fins and finally by one or two bended metal sheets. The result is a double
wall flat tube ducting the hot exhaust gas inside and the working fluid in the annular gap channel.

4. Summary

TheSys GmbH develops Rankine waste heat recovery systems for mobile applications. Based on prototype measurements, the thermodynamic performance correlations of evaporators were modeled and integrated into the simulation platform TheSim. A 1d-simulation model was built up to simulate a Rankine WHRS integrated into the engine cooling system. Targeting a given route histogram, system architectures and control strategies were optimized to utilize the potential WHR system power best possible.

On the field of evaporator design development, there are three different designs under development. Twin Round Tube Evaporators and Twin Flat Tube Evaporators are appropriate for high series production volumes and provide a high performance density. For lower production volumes the bar and plate design is preferable, as a robust design providing high manufacturing flexibility. Prototype evaporators in bar and plate design and Twin Round Tube Design were built up and successfully measured on test benches. For evaporators in Twin Flat Tube Design, manufacturing tests are ongoing.

References

[6] BMW Abwärmenutzung, ATZonline, 09./2011

TheSys Home Page: www.thesys-engineering.de