Thesys develops evaporators for Waste Heat Recovery Systems for mobile and stationary applications. These evaporators utilize the enthalpy availability of hot exhaust gas both in the cooled exhaust gas recirculation duct as well as in the main exhaust gas for example in the muffler. At present there are three different designs for evaporators under development. Prototype measurements have already partially proved their function and performance.
The utilization of the waste heat of combustion engines on the basis of a Rankine process is a promising technology to reduce the CO₂ emissions of future vehicles and for e.g. trucks provides a fuel consumption saving potential of app. 5 to 8 % [1, 2, 3, 4, 5].

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 the series application of a mobile Waste Heat Recovery System the necessary components have to be developed, meeting the high requirements regarding power, packaging, weight, reliability and price. In addition to the expander, key components are the evaporators, which have a dominant impact on the efficiency of the Waste Heat Recovery System. In this paper, evaporators are described using the enthalpy supply of the hot exhaust gas of the engine. For integrating these evaporators into the vehicle, two locations are prioritized:

- Exhaust-Gas-Recirculation-Evaporator (EGR-Evaporator): As a substitute of today’s series exhaust gas recirculation cooler (EGRC), the EGR-evaporator is provided with exhaust gas on a maximum temperature level. Additionally the engine cooling system is relieved by outsourcing of the EGRC-heat load.

- Main-Exhaust-Gas-Evaporator (MEG-Evaporator): Integrating the MEG-evaporator into the exhaust gas duct down flow of the after-treatment system provides the MEG-evaporator with a high exhaust gas flow rate but on a lower temperature level.

**MALFUNCTION RISKS OF EVAPORATORS**

The concept finding and design of evaporators needs over and above the challenging performance requirements to meet significant structural mechanical challenges and also faces the risk of instable operation. Due to the gas-to-gas-heat transfer, evaporators are exposed to material temperatures of up to 550 °C. In parallel, there are pressures up to 60 bar with the additional risk of corrosion and blockages in the working fluid duct. Other than conventional heat exchangers without phase change, evaporators face the risk of instable operation, e.g. [6]:

- statical instability
- aperiodic instability
- periodic instability
- pressure drop instability induced by large steam bubbles (slug flow)
- oscillatoric instability of parallel evaporation ducts.

**THERMODYNAMIC SIMULATION OF EVAPORATORS**

The thermodynamic dimensioning of evaporators is done with the home made simulation tool TheSim. In detailed thermodynamic models the geometry-specific heat transfer coefficients and the heat transfer resistance in the separation walls as well as the efficiency of primary and secondary heat transfer surfaces and surface heat losses are taken into consideration. Furthermore, the pressure drop characteristics of the flow ducts and the characteristics of fluids and materials are implemented. The resulting thermodynamic models allow reliable dimensioning as well as variation and optimization of heat exchangers.

In TheSim an evaporator is divided into a minimum of three zones. This allows the modelling and simulation of different geometrical structures inside the evaporator by using the correlating heat transfer characteristics.
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 modified Shah-correlations with regressed parameters.

**BAR AND PLATE EVAPORATOR**

The principle design of a bar and plate evaporator for a passenger car series application is shown in Fig. 2. 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 higher 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 on an evaporator test bench, Fig. 3.

For the measurements, the exhaust gas flow rate was kept constant at 150 g/s and the fluid side working pressure at 40 bar. For different exhaust gas inlet temperatures, the fluid flow rate was controlled to a constant steam outlet temperature.

The measurement results show a stable evaporation and overheating of both evaporator designs P1, P2. The measured performance increases significantly with the exhaust gas inlet temperature and meets 40 kW at inlet temperatures of 500 °C. The thermodynamic performance simulation using Thesim for the specification indicates values of 62 kW at 650 °C. With the available test bench, it was not possible to validate this prognosis.

**TWIN ROUND TUBE EVAPORATOR (TRT)**

To serve as an alternative for the bar and plate design for high production volumes a new twin round tube evaporator design is under development. This evaporator is built up as a tube bundle with twin tubes as shown in Fig. 4. 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.

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.

To validate the performance of a TRT evaporator, a single twin tube prototype was built up and measured on a calorimeter. The comparison of the measurement results with the thermodynamic simulation are shown in Fig. 5 [7].

The measured heat flows on the exhaust gas and working fluid side show a deviation of 16 to 20 %, mainly caused by a non-optimized insulation on the test bench. There is a heat flow output of 2.3 / 2.9 kW from the hot exhaust gas and a heat flow input into the working fluid of 1.9 / 2.4 kW.
Substituting the off-road EGR evaporator in ③ with a package-compatible TRT evaporator with 33 twin tubes, the thermodynamic simulation with Thesim predicts a performance of 48 kW.

Due to the usage of standardized parts and manufacturing processes, this design is applicable for higher production volumes. Additionally, the TRT 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.

**TWIN FLAT TUBE EVAPORATOR (TFT)**

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, ❻.

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. The main manufacturing risks result from the bending of the working fluid fin and the requirement of a leak-proof brazing between adjacent tubes. For evaluation of these risks there are ongoing manufacturing tests.

**SUMMARY**

Thesys develops evaporators for Waste Heat Recovery Systems for mobile and stationary applications. These evaporators utilize the enthalpy availability of hot exhaust gas both in the cooled exhaust gas recirculation duct as well as in the main exhaust gas e.g. in the muffler. At present there are three different designs for evaporators under development. Prototype measurements have already partially proved their function and performance.

For utilization of the exhaust gas recirculation heat and series volumes higher than app. 1000 pc/a, the designs of twin round tube evaporators or twin flat tube evaporators are appropriate. These designs are applicable for high series production and provide a high performance density. Nevertheless, for a series application a high investment in development and series production equipment is needed. For lower production volumes the bar and plate design is preferable, as a robust design providing high manufacturing flexibility.

For utilization of energy in the main exhaust gas in the muffler, the Twin Round Tube Design is appropriate as it provides a high packaging flexibility due to flexible design of the outer tube bundle surface. Additionally, due to the existing muffler housing, the exhaust gas flow can be divided into an inner and outer flow, providing an energy input into the working fluid inside and outside the tubes. Furthermore the exhaust gas side pressure drop will be significantly reduced.

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.

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