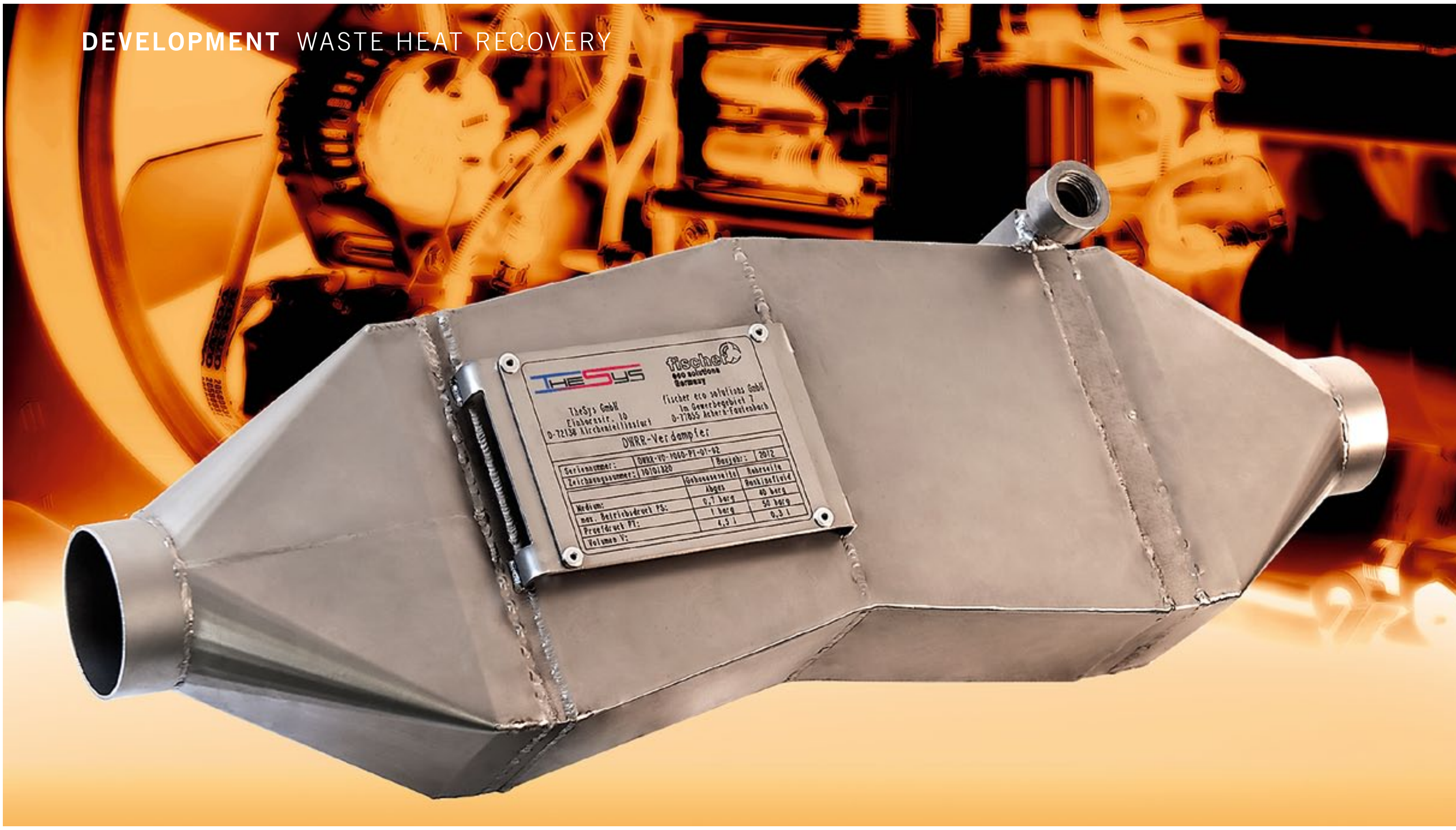

WASTE HEAT RECOVERY

The development of motor vehicles is more than ever driven by the objective of minimising energy consumption and pollutant emissions. The thermal management of the vehicle, i.e. a demand-driven and resource-optimised temperature control of engine, drive train, passenger compartment and ancillary units, already makes an essential contribution. A major focus of current development is the use of waste heat, which is nowadays conducted into the environment unutilised.

A promising technical solution to use the available heat is the application of a thermodynamic cycle based on the Rankine principle. Within various studies and projects the CO_2 reduction potential of a Rankine cycle has been analysed and evaluated. Under real on-road operation conditions an improvement in fuel economy of up to 5 % is expected [1, 2, 3, 4, 5].

TheSys develops evaporators for the series implementation of Rankine cycles, which are either integrated to the main exhaust gas duct or substitute the exhaust gas recirculation cooler. Goal is to develop an evaporator design suitable for different applications in passenger cars and commercial vehicles, but also combined heat and power plants, rail and marine as well as industry applications. Great importance was attached to a simple design of the evaporator, in order to being able to produce them in series with high process reliability and cost efficiency. In addition the design is aimed at being robust and, by using standardised component parts, adaptable to various installation space requirements and operating conditions [6, 7].

DESIGN

The twin-round-tube evaporator is designed as a tube bundle exchanger. Here, tube pairs consisting of two concentric tubes, the inner and outer tubes, are applied. Within the annular passage between both tubes the working fluid to be evaporated is guided. The hot exhaust gas goes through the inner tubes in counter flow and simultaneously flows around the outer tubes. Hence the annular passage is heated double-sided by inner and outer tubes which makes for large heat transfer areas.

The working fluid being under high pressure reaches very high temperatures at the steam outlet. At the same time only small flow areas are required to guide the fluid, which ideally adjust over flow length according to the phase change. The flow areas have to be small at the inlet, where the fluid is in liquid state, and should increase during the evaporation and superheating zone.

The twin-round-tube design has the advantage that the high fluid pressures are supported by cylindrical inner and outer tubes, so that the required wall thicknesses and thus the use of material are minimal. Using twisted tubes the geometry of the annular passage can be adjusted to any boundary condition. In terms of manufacturing technology twisted tubes are used, for they are actually produced in high series number and

❶ Assembled pair of tubes consisting of an outer tube with variable helix and a twisted inner tube

TWIN-ROUND-TUBE EVAPORATOR FOR WASTE HEAT RECOVERY

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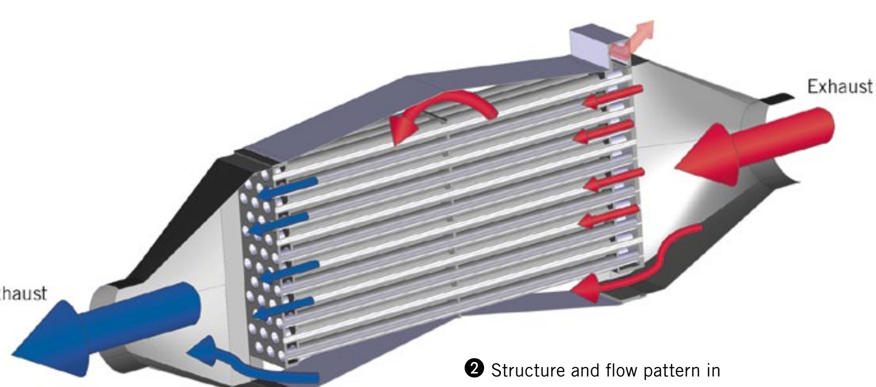
Concepts for waste heat recovery based on the Rankine cycle offer the potential to make use of the energy in the exhaust gas of an internal combustion engine. TheSys develops evaporators for these systems that are either integrated into the main exhaust gas flow or are used to replace the exhaust gas recirculation cooler. The evaporators have a simple design and can therefore be mass-produced at low cost.

operated successfully in exhaust gas recirculation coolers.

❶ shows an assembled pair of tubes consisting of an inner and an outer tube. The outer tube is equipped with a variable helix providing a continuously increasing flow area for the working fluid. The inner tube can be chosen to be a smooth or also a twisted tube in order to improve the heat transfer performance particularly on the exhaust gas side. The twisted tubes are manufactured on available tooling equipment where the variable helix only requires an adjustment of the machine control software. So the core parts of the design can be produced cost-efficiently in large quantities.

The twisted tubes are on both sides mounted to tube plates which build the fluid headers, ❷. The inlet header distributes the working fluid to all parallel annular passages. At the outlet the vapour is collected und guided to the outside by the steam outlet.

Due to apertures in the inlet and outlet headers the exhaust gas is split into a flow portion through the inner tubes and a flow portion around the outer tubes, while in the outlet diffusor both paths are reunited. Due to the division of the exhaust gas flow into two branches a significantly larger flow area is provided. This reduces the pressure drop on the exhaust gas side considerably. The exhaust gas path surrounding the tube bundle can be deflected by baffles, which, within the pressure drop requirements, increases the flow velocities and so the heat transfer performance.



❷ Structure and flow pattern in the twin-round-tube evaporator

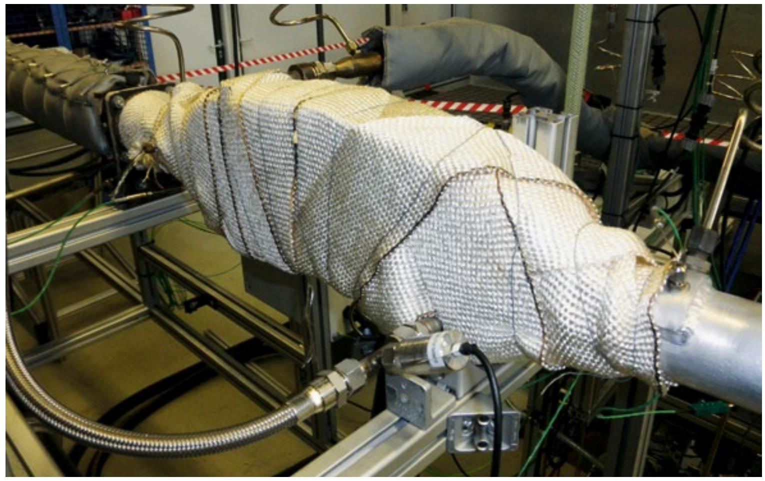
The layout of the twist geometry is primarily done due to the thermodynamic requirements, but also with regard to the structural and mechanical strains. Depending on the type of working fluid, operation pressure and the superheating different flow cross-sections are required. If the twist geometry is performed more distinctively, the tubes behave similar to compensators and bellows, with an increasing elasticity in longitudinal direction. Accordingly, thermal expansions between adjacent tubes, but also between tube bundle and casing can be compensated. In addition, due to the bidirectional support of inner and outer tube the tubes are resistant against vibrations. Besides guiding the outer flow, the baffle plate, ②, performs as a tube positioner and damping device by coupling the tube vibrations. Furthermore it supports the casing against the internal exhaust gas pressure.

TEST SPECIMEN AND MEASUREMENT SETUP

❸ shows an evaporator for passenger cars, which has been built for measurements on a test rig as well as in the car. For testing the thermodynamic behaviour of inner and outer exhaust gas flow separately, the evaporator has been modified at the connections. Using exhaust gas flaps it was possible to adjust the exhaust gas flow at the test rig, so that any ratio of inner flow and flow around the tube bundle could be achieved.

Target of the measurements has been to determine the optimum ratio of inner versus outer flow, the quantification of heat transfer performance and pressure drop as well as the verification of a stable evaporation within a wide operating range. Additionally the measurements should be used as a base to calibrate and validate the thermodynamic simulation model and should give hints for a design optimisation.

❸ Twin-round-tube evaporator for a passenger car application on the hot gas test rig

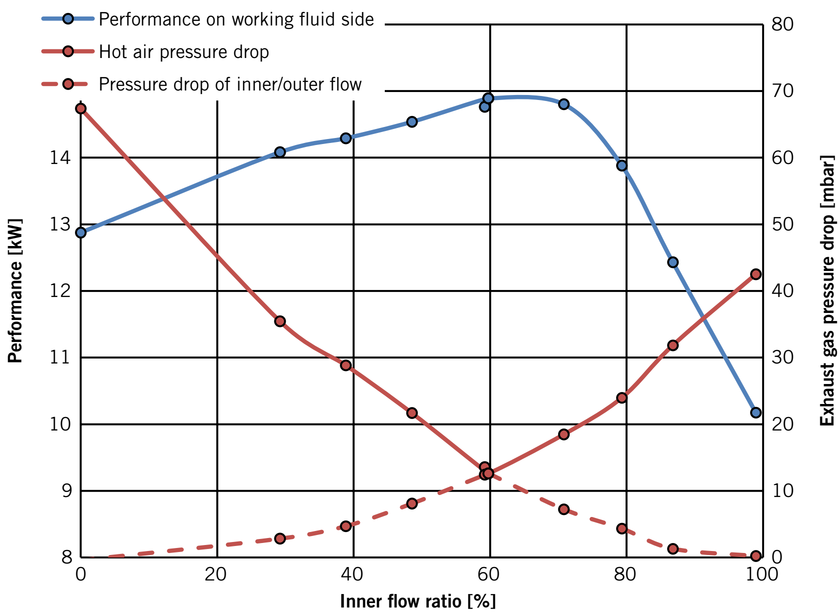


MEASUREMENT RESULTS

❹ shows the measured evaporator performance while varying the inner and outer flow ratio at the nominal operating point. Additionally the corresponding exhaust gas pressure drop is shown. Coming from a pure exhaust gas flow around the tube bundle (inner flow ratio 0 %), the heat exchanger performance can be enhanced by increasing the inner exhaust gas flow. At the same time the pressure drop decreases significantly. It can be seen that the maximum performance is at an inner flow ratio between 60 and 70 %. Increasing the inner flow rate above 70 % leads to a significant performance decrease. At pure inner flow the performance is in the range of 80 % of pure outer tube bundle flow. At the same time the pressure drop on the exhaust gas side again increases.

Evaluating the measurement results of a twin-round-tube evaporator with double-sided heat input to the working fluid, compared to a conventional tube bundle heat exchanger with longitudinal or transversal flow, the result is that in comparison to

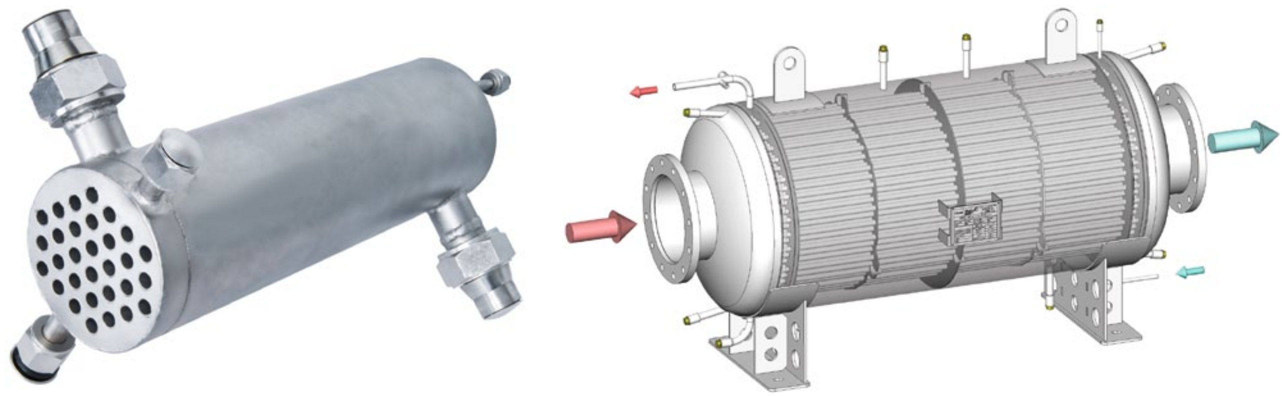
- a tube bundle with pure surrounding flow the performance increases about +15 %, while at the same time the exhaust gas pressure drop is reduced by about 80 %
- a tube bundle with pure inner flow the performance increases about >40 %, while at the same time the exhaust gas pressure drop is reduced by about 70 %.



❹ Measured evaporator performance and exhaust gas pressure drop

THERMODYNAMIC SIMULATION

TheSys develops software for the layout of heat exchangers and evaluates the heat exchangers in the complete system environment [8, 9]. For the twin-round-tube evaporator a two-step regression method has been used to derive accurate thermodynamic correlations from the measurements of one- and two-phase operating points. Out of that a detailed, spatially discretised simulation model has been developed which is able to calculate the simultaneous heat input from exhaust gas from inner and outer flow to the working fluid. This model enables a deep insight to the local heat transfer mechanisms and temperature profiles. It appears, for example, that the so called "pinch point" problem – the point, where the temperature difference between exhaust gas and working fluid is at its minimum – has been considerably mitigated with the twin-round-tube evaporator design, because the exhaust gas features different local temperatures in the inner and surrounding flow, respectively.



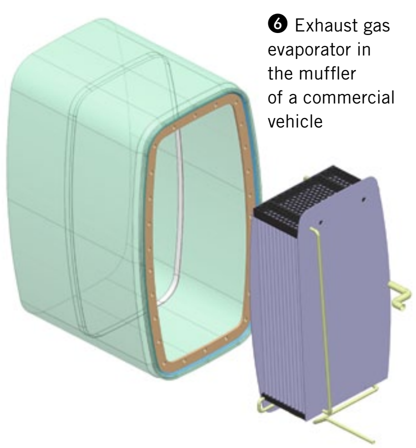
❺ Methanol evaporator in the thermal oil circuit of a fuel cell (left) and evaporator for a combined heat and power plant with a power of 380 kW_{el} (right)

APPLICATIONS

Up to now, twin-round-tube evaporators have been designed, built and measured for different working fluids and applications in different markets. ❺ (left) shows a methanol/water evaporator, used for a fuel cell with a power of 5 kW_{el}. Using hot thermal oil the methanol/water-mixture is evaporated and guided to the downstream fuel cell reformer.

For application in a 380 kW_{el} combined heat and power plant, an evaporator is being assembled, ⑤ (right). The dimensions of the evaporator are about 1.7 m x 0.65 m. Regulatory requirements lead to a cylindrical design with an axial exhaust gas flow. This evaporator will be assembled to the CHP and put into operation in spring 2014 [10].

❻ shows a twin-round-tube evaporator integrated into the muffler of a commercial vehicle. Since the complete main exhaust gas flow rate is guided through the evaporator, a deflection of the flow is forbidden by reasons of exhaust gas pressure drop. Instead, the working fluid flow is deflected in both headers, so that the working fluid is guided in a cross counter flow pattern using the principle of a riser pipe evaporator.



❻ Exhaust gas evaporator in the muffler of a commercial vehicle

THANKS

The authors would like to thank fischer eco solutions GmbH for their support and the manufacturing of evaporators.

SUMMARY

The TheSys GmbH develops evaporators to recover waste heat from vehicles, combined heat and power plants and industrial applications which is converted to mechanical power in a Rankine cycle. For various applications and working fluids prototypes have been manufactured and measured on test rigs successfully.

The twin-round-tube design is characterised by a simple and very robust construction. The assembly to a tube bundle from standardised twisted tubes allows a simple application to any installation space and operating conditions. Due to the simultaneous heat input to the working fluid from both sides of the channel the evaporator is very compact what saves installation space. Nevertheless the exhaust gas pressure drop can be kept very low.

In measurements on a hot gas test rig it has been proven that, compared to a tube bundle with pure outer flow around the tubes, the heat exchanger performance can be increased by 15 % while at the same time reducing the exhaust gas pressure drop by 80 %. Compared to a tube bundle with pure inner exhaust gas flow the increase of heat exchanger performance by more than 40 % is even more distinct. Here the exhaust gas pressure drop can at the same time be reduced by 70 %.

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