COMPACT AND HIGH EFFICIENT RANKINE-EVAPORATOR FOLLOWING ECONOMICAL TARGETS

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ABSTRACT

Within the public funded project "KompACT", Rankine cycle evaporators for Waste Heat Recovery systems are under development. Target for the evaporator development is the selection of designs being capable for future economical operations under real world industrial conditions. Therefore, specific focus was set on providing the best economic key values under consideration of earnings based on heat transfer performance and correlated total costs of ownership. The evaluation of different evaporator designs and the selection of the final design are guided by a utility analysis methodology developed within the project. Two conventional steam boilers serve as a component benchmark.

Currently, two evaporator designs based on the Twin-Round-Tube-principle were selected: The Twin-Round-Tube-Box-Design B1 is extremely compact, light, flexible and targets applications for low and medium heat performance ranges up to approx. 350 kW_{th}. Due to the compact size, installation and operation costs are significantly reduced, offering the best economic values.
The Twin-Round-Tube-Cylinder-Design Z3 provides maximum performance and can easily be adapted to different customer requirements. From an economic perspective, the design seems promising to serve a power range of 200 kW_{th} up to 1,000 kW_{th} as industrial target applications.

In 2021, thermal tests will be done on a prototype test bench at TH Nuernberg to validate thermal simulations, prove thermal function and guide the final manufacturing design work. In 2022, it is planned to build up a full scale 250 kW_{th}-prototype providing 40 kW_{el} to be installed and operated at the 526 kW_{el} - MicroRankine pilot plant in Nuernberg.

Figure 1: MicroRankine pilot plant of the TH Nuernberg

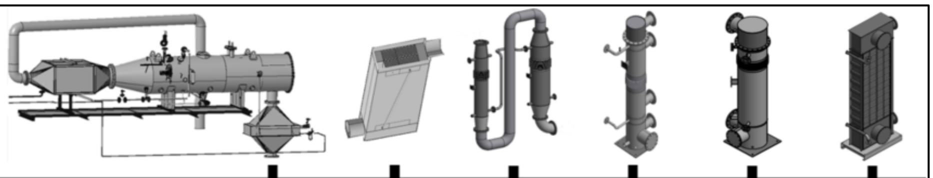
1 INTRODUCTION

With partners from industry and applied research, the TH Nuernberg is investigating high-temperature Waste Heat Recovery (WHR) in current research projects. Although organic fluids achieve maximum efficiencies in the conversion of heat at low and medium temperature levels, according to previous studies, water is an efficient and at the same time sustainable alternative to organic fluids in Organic Rankine Cycles (ORCs) at high waste heat temperatures (Vankeirsblick *et al.*, 2011, Zhang *et al.*, 2016). The state of the art in distributed WHR with water as the working fluid was demonstrated with the Steam Rankine Cycle (SRC) pilot plant called MicroRankine (Figure 1), which converts 250 kW_{th} of thermal power into electric power of 40 kW_{el} (Raab *et al.*, 2021).

The MicroRankine pilot plant is operated by a 526 kW_{el} Jenbacher JMS 312 Internal Combustion Engine (ICE) providing an exhaust gas flow rate of 2,797 kg/h at 451 °C. The steam is produced with a steam generator consisting of economizer, steam boiler and superheater, as it is standard for supplying industrial steam networks. The total net weight of the steam generator is almost four tons and the filling volume in operation is around 1,400 dm^3. The steam is fed at 16.5 bar(a) and 430 °C to a two-stage Curtis turbine. (Kraus *et al.*, 2016). The steam is then condensed via a river water cooling system to a temperature of 60 °C and brought back to operating pressure via a piston membrane-type pump. In addition to system tests and water quality investigations, the MicroRankine test facility enables testing of new components under real operating conditions.

Since the MicroRankine pilot plant was not setup for an economically profitable operation, a three-year research project called KompACT was launched in 2019 to develop a techno-economically optimized, compact, scalable and low-maintenance plant design. KompACT is partnered by five companies and two universities of applied sciences to develop a WHR-plant meeting economic targets for industrial operation. Like the turbine, the steam generator has a significant influence on the overall efficiency but also on the Total Costs of Ownership (TCO) and additionally impacts the overall plant dimensions the most.

2 EVAPORATOR DEVELOPMENT



#	Utility Analysis Method - Project: WHR of a 526 kWel ICE		am boiler MicroRank		DWRR - B1		DWRR - Z3		DWRR - Z1		vertical shell and tube		Water-tube boiler	
#	Evaluation criteria	Weighting main criteria [%]	Rating [0 .. 10]	Utility	Rating [0 .. 10]	Utility	Rating [0 .. 10]	Utility	Rating [0 .. 10]	Utility	Rating [0 .. 10]	Utility	Rating [0 .. 10]	Utility
1.0	**Performance**	**25%**												
1.1	Thermal Output		9,8	1,72	6,9	1,21	8,4	1,47	8,8	1,55	8,3	1,45	9,1	1,59
1.2	superheating (Δϑ)		10,0	0,13	10,0	0,13	10,0	0,13	10,0	0,13	10,0	0,13	10,0	0,13
1.3	relative heat loss (Q_Loss/Q_Exhaust)		8,0	0,06	10,0	0,08	8,0	0,06	9,0	0,07	9,0	0,07	8,0	0,06
1.4	Pressure loss exhaust side		1,9	0,10	7,8	0,39	6,4	0,32	6,0	0,30	6,4	0,32	8,2	0,41
1.5	Pressure loss fluide side		5,5	0,03	10,0	0,05	10,0	0,05	10,0	0,05	10,1	0,05	10,7	0,05
2.0	**Equipment properties**	**17%**												
2.1	Empty weight		1,3	0,01	9,0	0,07	8,4	0,07	9,0	0,07	8,6	0,07	7,7	0,06
2.2	Volume		2,2	0,17	10,0	0,75	9,7	0,73	10,0	0,75	9,9	0,75	9,7	0,73
2.3	Operating weight		2,1	0,02	9,2	0,08	8,6	0,07	9,2	0,08	8,9	0,07	8,3	0,07
2.4	Volumetric power density		2,1	0,02	9,8	0,08	9,5	0,08	9,8	0,08	9,8	0,08	9,5	0,08
2.5	PED Category		1,0	0,01	4,0	0,03	1,0	0,01	4,0	0,03	1,0	0,01	1,0	0,01
2.6	Temperature resistance		10,0	0,08	10,0	0,08	10,0	0,08	10,0	0,08	10,0	0,08	10,0	0,08
2.7	Cleanability		6	0,10	6	0,10	6	0,10	7	0,12	8	0,13	7	0,12
2.8	Fouling impact on pressure drop and thermal performance		1,0	0,02	1,0	0,02	1,0	0,02	1,0	0,02	1,0	0,02	1,0	0,02
2.9	Coverage range of market requirements		5,5	0,09	7,3	0,12	7,3	0,12	6,4	0,11	4,6	0,08	5	0,08
3.0	**Manufacturing**	**8%**												
3.1	Manufacturing complexity		7	0,41	7	0,41	7	0,41	7	0,41	7	0,41	7	0,41
3.2	Risk & Quality		7	0,18	7	0,18	7	0,18	7	0,18	7	0,18	7	0,18
4.0	**Operation**	**42%**												
4.1	Steam quality (stationary) -> droplets (M_droplets/M_steam)		10	0,25	10	0,25	10	0,25	5	0,13	10	0,25	10	0,25
4.2	Steam stability (stationary) -> temperature		8,3	0,17	8,3	0,17	8,3	0,17	8,3	0,17	8,3	0,17	8,3	0,17
4.3	Steam quality (transient) -> droplets (M_droplets/M_steam)		10,0	0,17	10,0	0,17	10,0	0,17	10,0	0,17	10,0	0,17	10,0	0,17
4.4	Steam stability (transient) -> temperature		4,7	0,02	6,5	0,03	6,5	0,03	6,5	0,03	4,7	0,02	6,5	0,03
4.5	Width operating range (stationary) (ΔQ_max/Q_max)		5	0,15	5	0,15	5	0,15	5	0,15	5	0,15	5	0,15
4.6	Wide operating range (transient) (ΔQ_max/Q_max)		5	0,15	5	0,15	5	0,15		0,00	5	0,15	5	0,15
4.7	Service life (stationary)		4,0	0,83	4,0	0,83	4,0	0,83	4,0	0,83	4,0	0,83	4,0	0,83
4.8	Service life (transient - starts)		1,0	0,08	1,0	0,08	1,0	0,08	1,0	0,08	1,0	0,08	1,0	0,08
5.0	**Scalability to customer requirements**	**8%**												
5.1	Scalability and modularity to cover a wide range of market requirements		4,0	0,17	10,0	0,42	8,5	0,35	7,0	0,29	4,0	0,17	8,5	0,35
5.2	Development effort: design&construction		8	0,23	2	0,06	8	0,23	7	0,20	8	0,23	7	0,20
5.3	Adaptation of manufacturing to design		8	0,10	7	0,09	7	0,09	7	0,09	8	0,10	7	0,09
	Total UAM	**100,00%**		**5,44**		**6,16**		**6,39**		**6,14**		**6,21**		**6,54**
7.0	**Earnings**													
	Economic Indicator over Lifetime	**100,00%**		**1,0**		**0,7**		**1,2**		**2,7**		**2,3**		**2,1**

Figure 2: Utility Analysis Method for evaporator design decision

Within KompACT, several evaporator-designs are under development. Evaporator design decisions are currently to be made based on primary thermal dimensioning, CAD-design studies accompanied by manufacturing concepts and cost calculations. The guideline for this process is a definition of component specific and functional criteria combined with an evaluation method. Criteria and evaluation values were implemented into a Utility Analysis Method (UAM) as can be seen in Figure 2.

2.1 Evaporator Development Targets and Utility Analysis Method (UAM)

The partners developed an evaluation method called UAM as a holistic approach to consider performance, component and operation criteria in combination with ownership costs and earnings. Target of the UAM is to identify the optimal design for given customer application targets.

As for principal requirements, the evaporator has to be able to handle different gaseous waste heat sources of ICEs and industrial applications within a thermal range of 100 kW_{th} up to 2,000 kW_{th}.
Criteria-classes were defined as following.
<u>Performance criteria</u> were defined to characterize e.g. heat transfer performance and pressure losses. Dimensions, component weight and fluid volume are reflected by <u>Equipment criteria.</u> <u>Operation criteria</u> cover evaporation stability, fouling tendency of the heat transfer surfaces with special focus on exhaust gas side, and service aspects. Criteria were also set for <u>Scalability to Customer requirements</u> to evaluate adaptability of evaporator design and manufacturing processes to the heat source power, but also to handle different working fluids in case of ORC-applications.

Overall, approx. 40 criteria have been set. Each criterion was classified within a minimum and maximum value and given an individual weighting factor. Summing up the single values provides the value of the criteria-class which, - also based on a weighting factor -, leads to an over-all rating of the design investigated.

The construction and operation of direct evaporators for Rankine cycle power plants are also subject to local directives and laws. Examples include the German Ordinance on Industrial Safety and Health (Betriebssicherheitsverordnung) and the European Pressure Equipment Directive. Expenses for the corresponding approvals and monitoring of operation are considered. In particular, exceeding limits of the heat exchanger volume can increase the monitoring effort and regulatory requirements.

To include the economic perspective, an equation for an economic indicator was defined. Expenses are reflected by definition of a Total Costs of Ownership value TCO*, covering expenses for investment, installation, service and maintenance during operation. “Non-design-dependent-costs” as e.g. costs of infrastructure and overhead are neglected. Therefore, only cost criteria have been considered, having an individual impact on TCO* depending on the different designs.

On the savings side, the different efficiencies of the evaporators provide different electricity production rates to cover the energy demand of the plant and therefore reduce electricity costs to be paid otherwise.

Economic Indicator [€] = TCO* minus Savings (over operation time)

TCO* [€] = Investment + Installation + Initial Filling + Operation approval + Operation x Lifetime
Savings [€] = Savings of electricity costs due to own consumption of WHR - electricity generated

<u>Whereas:</u>

Investment [€]	= evaporator market prize
Installation [€]	= costs for assembly
Initial filling [€]	= Rankine fluid costs (relevant in case of ORC-fluids)
Operation Approval [€]	= costs for safety acceptance
Operation [€/a]	= costs for service, maintenance and material
Lifetime [a]	= Lifetime of Rankine system (10/20/30)

Savings [€]	= Q_{th} x $\eta_{Rankine}$ x Annual operation hours x Lifetime x Electricity value
Q_{th} [kW]	= Evaporator fluid side heat flow rate
$\eta_{Rankine}$ [%]	= Rankine overall net efficiency (P_{el} / Q_{th}) = 15
Annual operation hours [h/a]	= 8.000
Electricity value [€/kWh]	= 0.15

2.2 Evaporator Designs

Based on literature studies, long-time development and operation experiences of TheSys and APROVIS, the Twin-Round-Tube-Design was selected for further consideration. This layout offers the greatest potential for further development within the KompACT project because of its modular structure and the many possibilities for adaptation to a wide range of industrial applications. The specifics of this design are explained below.

Twin-Round-Tube-Evaporator

The Twin-Round-Tube-Evaporator-Design (TRT) was developed for automotive and commercial vehicle applications. The principle design consists of a bundle of concentric double-tube-pairs, where the Rankine fluid passes the gap between inner and outer tubes. Looking at one double-tube-pair, part of the exhaust gas passes inside of the inner tube (flow through) and the other exhaust gas passes outside of the outer tube (flow around) providing a two-sided heat transfer input to the working fluid in the gap between the both concentric tubes. The design was published by Ambros, Fezer and Orso in 2011 to 2014. In each tube-pair, preheating, evaporation and superheating takes place. To ensure evaporation stability, special measures have been taken, such as providing variable cross flow areas inside the fluid channel between the tubes to counteract local changes in density due to evaporation. Otherwise, local hotspots or excessive pressure loss increases on the fluid side would occur. Therefore, structured tubes are installed with different and/or variable local fluid duct geometries. In the tanks of the evaporator the hot gas flow is divided into two flow paths: Path 1 flows through the inner tubes (flow through), path 2 passes the outer tubes (flow around). Therefore, the gas side pressure drop is minimized as heat transfer is increased due to simultaneous heat input into the Rankine fluid from the inner tubes and from the outer tubes, see Figure 3.

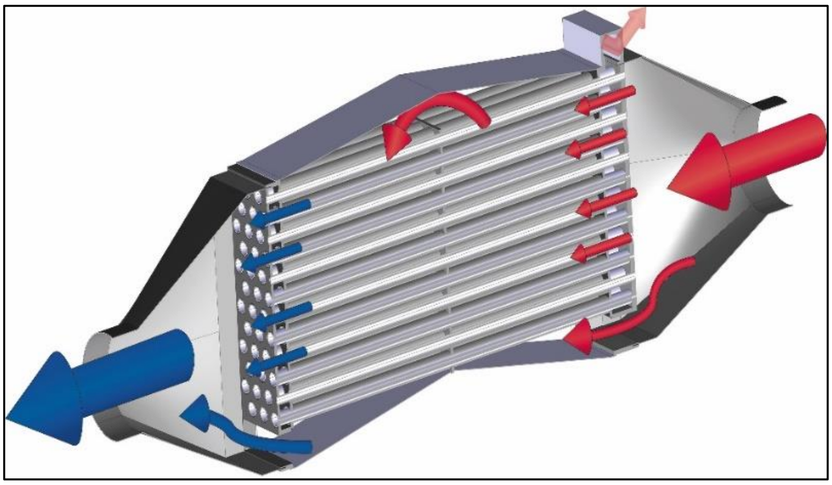


Figure 3a: Design principle of the Twin-Round-Tube-Evaporator with visualization of hot gas flows
Figure 3b: Twin-Round-Tube-Evaporator for trucks

Having proved performance and functionality for vehicle applications, within the KompACT project this design principle was adapted for industrial applications. The design offers a wide range of potential design modifications and by modifying the flow paths on the hot gas and fluid side (in parallel/in series), by separating the whole core into subsections and by preventing or enabling hot gas side mixing inside the heat exchanger, some 15 different TRT-design modifications were considered. Finally, following the UAM methodology described above, two TRT-Designs were selected as shown in Figure 4.

TRT-Box-Design B1 is a very compact cuboid shape design with pre-heating, evaporation and superheating housed in the same enclosure. New is the separation of the core bundle into three subsections for pre-heating, evaporating and superheating. The size of the subsections can be perfectly adjusted to the conditions of the fluid aggregate status, depending on whether it is a boiling 2-phase flow or a single-phase gas or liquid flow. Exhaust gas flow and Rankine fluid flows are guided in series and parallel flow paths around and through these different heat exchange sections. In the preferred setting (Design B1), the outside hot gas flow (flow around) is ducted from subsection "superheating" to "evaporation" to "pre-heating" in series, following the temperature levels in a cross flow heat transfer setting. The inside hot gas flow (flow through) passes all inner tubes in parallel and provides a counter flow heat transfer to the working fluid inside the annular gaps. The working fluid enters the subsection "pre-heater" and therefrom is guided to the inlet of the subsection "evaporation" and to the subsection "superheating" in series via external piping.

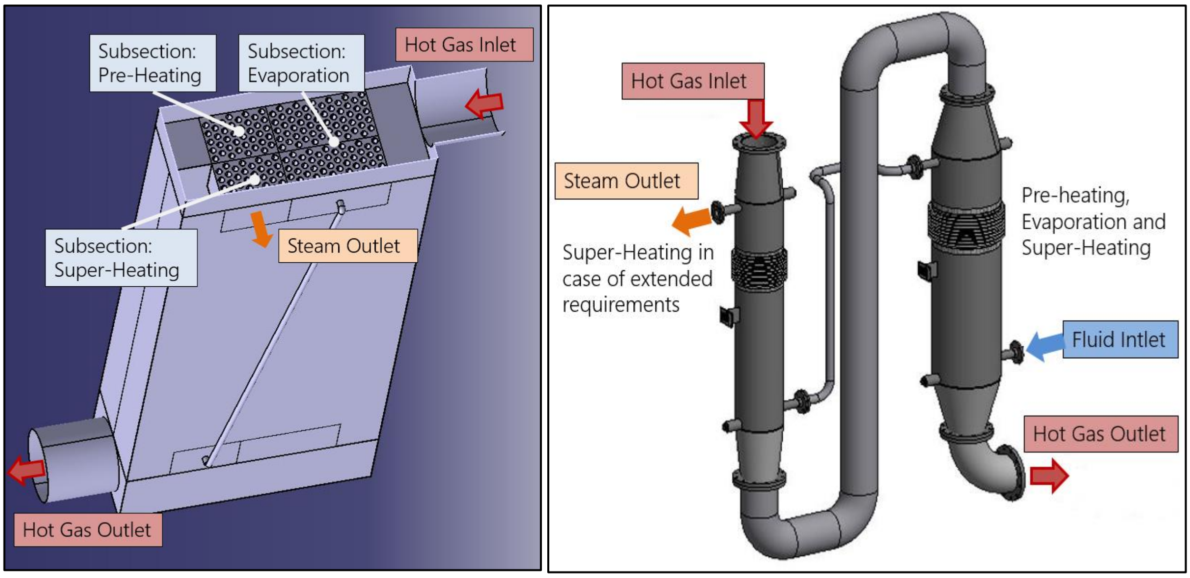


Figure 4a: Industrial Twin-Round-Tube-Evaporator – TRT-Box-Design B1
Figure 4b: Industrial Twin-Round-Tube-Evaporator – TRT-Cylinder-Design Z3

A main advantage of this design B is the possibility to easily change the flow regimes on the hot gas and fluid side by applying or removing the separation walls inside the vessels or changing the fluid flow paths by external piping. Therefore, this Design B can easily be adapted to meet different application requirements, still keeping the identical heat exchanger core.

TRT-Cylinder-Design Z3 is a Twin-Round-Tube evaporator in a cylindrical shell. The design refers to industry-standard manufacturing processes and standard purchasing parts as housings, headers and tanks. Preheating, evaporation and superheating are provided within one single heat exchanger (without sub-sections). A separate superheater can be added for extended superheating requirements, as is the case with WHR utilizing water as working fluid. In this case, the first heat exchanger performs the task of preheating and evaporation, while the second serves as superheater. For costs reasons, the superheater will be based on the identical design principal, utilizing identical double tubes and fluid header designs.

A thermal simulation model was built up to calculate evaporator performance for the investigated designs. The main challenges were to handle the two-sided-heat transfer in cross-flow, counter-flow and parallel-flow settings. The simulation results show, that for both designs, performance increases by increasing numbers of tubes. In parallel, exhaust gas side pressure drop decreases as shown in Figure 5.

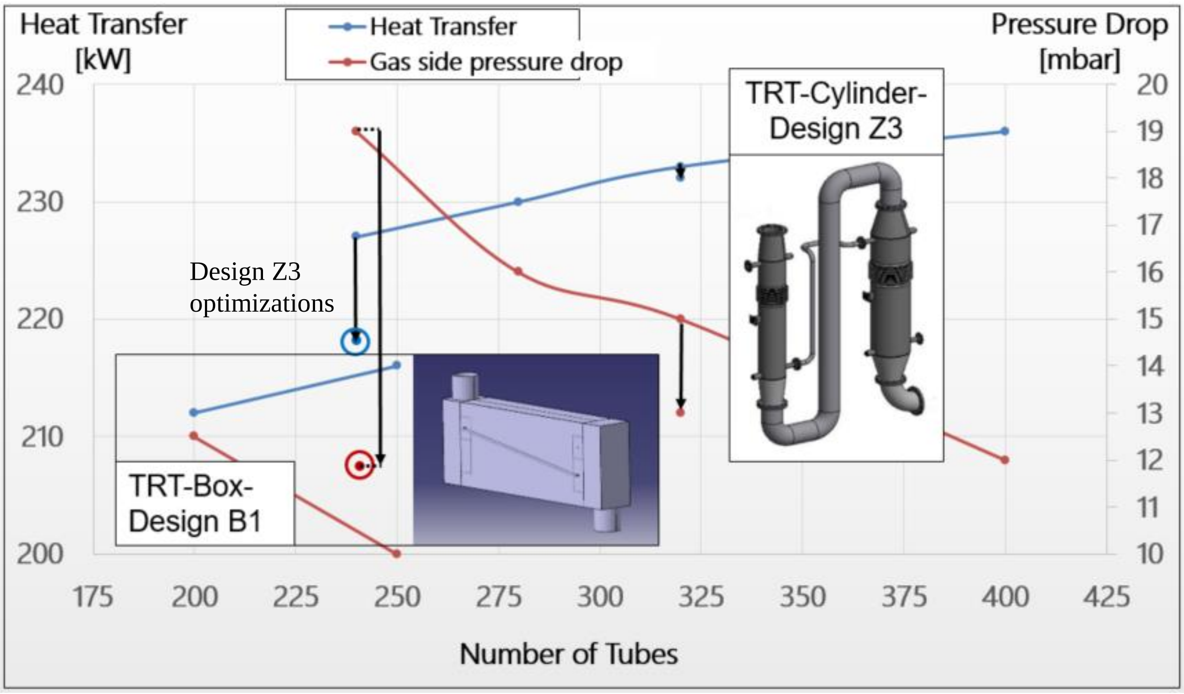


Figure 5: Performance comparison between TRT-Box-Design B1 and TRT-Cylinder-Design Z3

It can additionally be seen that performance and also air side pressure drop of the Z3-designs exceeds B1-Design values. Fine-tuning of Design Z3 was made to reach the B1-design pressure drop level. Finally, comparing both designs shows a principal performance advantage of Cylinder-Design Z3.

Two Benchmarking Designs: MicroRankine-Steam Generator and Water-Tube Boiler

The steam generator installed in the MicroRankine pilot plant in Nuernberg (Figure 1) serves as a first reference application and was taken as a functional benchmark.

Figure 6: Water-tube-boiler prior to manufacturing quality control at APROVIS

To serve as commercial benchmark, a water-tube-boiler was selected. The water-tube-boiler represents a common design for vapor generation in distributed thermal power plants, mainly for ORC and high power steam applications. As shown in Figure 6, the boiler consists of parallel U-tubes or serpentines in a flue gas duct. The flue gas passes through the housing while the working fluid flows inside the tubes. The number, size and arrangement of the rows of the tubes can be individually adapted to the fluid and to the waste heat source.

2.3 Evaluation of Evaporator-Designs

The comparison of the evaporator designs based on the UAM method, see chapter 1, leads to the following conclusions:

The TRT-Box-Design B1 is an extremely compact design, preferable for integration into tight packaging spaces. Due to the cuboid shape, preferred applications may be container CHP plants, marine and industrial buildings. Package space demand is reduced to 5% - 40% and the overall component weight of approx. 600 kg is far below the both benchmark designs by 20% - 50%. With respect to manufacturability, the maximum design dimensions may be limited. Therefore, the TRT-Box-Design B1 targets industrial applications for low and medium range heat performances up to approx. 350 kW_{th}. The design offers a very low gas side pressure drop and can be retrofitted to existing plants and industrial heat sources.

The compactness provides significant advantages for reducing component and installation costs. The internal working fluid volume is minimized to 50 dm^3, far below the benchmark designs. Taking water as working fluid, the filling costs do not affect overall cost. As for ORC-applications, the working fluid impacts expenses in terms of fluid costs, security approval and maintenance costs.

The TRT-Cylinder-Design Z3 provides maximum performance, coming close to the thermo-physical limits. It almost reaches the thermal performance of the MicroRankine steam generator despite the fact that packaging volume drops to approx. 10%, overall operation weight drops to 20%. Due to the flexibility of scaling the core geometries of the preheater/evaporator-unit as well as super-heater-unit separately, it also fits to applications of heat transfer performances of approx. 200 kW_{th}, but shows it' s benefits with increasing thermal power. The Z3-evaporator will be pre-mounted and requires a similar packaging space compared to the water-boiler. Gas side pressure drop is higher than B1-design and needs to be adjusted by a bypass flow around the superheater.

Due to the need of building up two separate heat exchangers in the Z3-design, manufacturing costs don't pay off when it comes to customer applications with low thermal power requirements. To meet the high MicroRankine plant specification, compared to the water-tube-boiler there are similar expenses for component investment, installation costs and expenses during operation. Thus, for bigger and more powerful customer applications, the TRT-Design Z3 promises economic benefits coming along with the modular design capability to fit to the customer requirements.

In case of lower super-heating requirements of the target application, the superheater-unit may be omitted. WHR can be provided with a single evaporator-unit of the basic-twin-round-tube-evaporator-design-type at significantly reduces investment costs.

3 CONCLUSIONS

The evaluation of the component characteristics and the associated economic values leads to the following industrial application scenarios for the different evaporator designs under consideration:

Preferred applications of the TRT-Box-Design B1 will be WHR-systems of low and medium thermal performance for e.g. container-integrated CHP or mobile applications, appreciating a highly compact design, see Figure 7. Due to the very low gas side pressure drop, it can be retrofitted to existing plants and industrial heat sources.

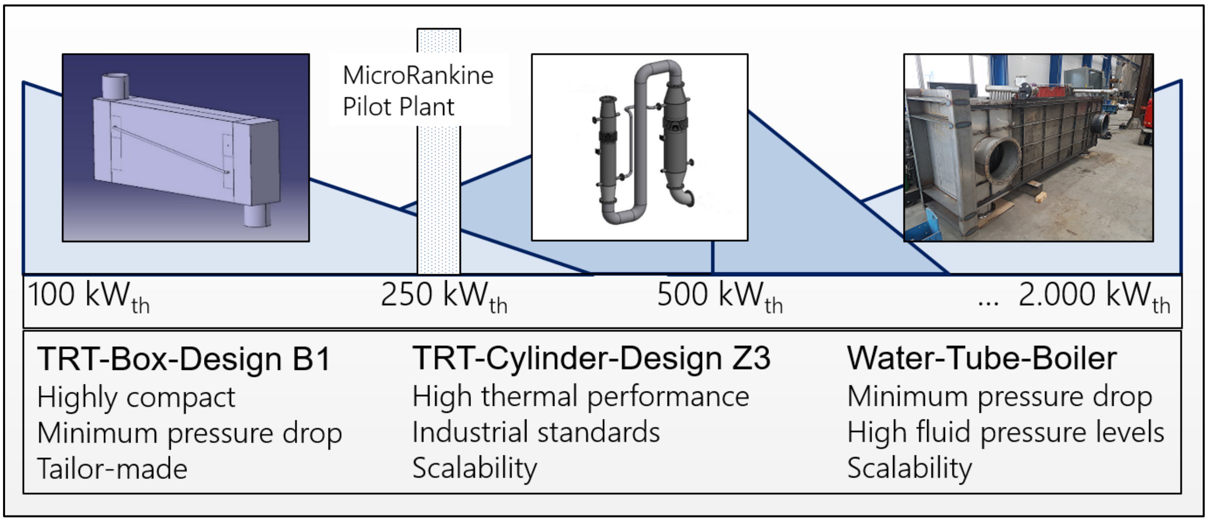


Figure 7: Preferred application scenarios according to the results of the UAM presented

The TRT-Cylinder-Design Z3 provides a maximum performance and will serve for power ranges from 200 kW_{th} to 1,000 kW_{th} and beyond. The design provides additional value due to its scalability to meet specific application needs.

For large capacity applications, there are often less stringent compactness requirements. On the other hand, the demands for low exhaust gas pressure losses and the possibility to realize higher Rankine cycle fluid pressures are increasing. Here, the water-tube-boiler design offers the best compromise.
For thermal testing of tubes, evaporation stability and for selection of series purchase parts an evaporator test stand was built at the TH Nuernberg. The project partners will provide prototype double-tubes and evaporator test specimens. Finally, small scale samples of the final evaporator design will be evaluated for their technical function in the test stand. In 2022, a full-scale steam generator will be built up to be installed and operated at the MicroRankine pilot plant at the TH Nuernberg. The results from this real-size application will be published in further papers.

For commercialization of the evaporator in future customer projects, the UAM will be used in the quotation and project planning phase. Characterizing the customer specific priorities by individual weighting factors for the 40 criteria defined will provide a guideline for the selection and dimensioning of an economically profitable total evaporator.

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