STEAM RANKINE CYCLE INSTEAD OF ORGANIC RANKINE CYCLE FOR DISTRIBUTED WASTE HEAT RECOVERY – PROS AND CONS

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ABSTRACT

The Rankine Cycle for Waste Heat Recovery (WHR) can be operated with various working fluids, all of which have different advantages and disadvantages. This paper compares the pros and cons of a Steam Rankine Cycle (SRC) using water as working fluid to an Organic Rankine Cycle (ORC) using an organic fluid as working fluid for distributed, high-temperature WHR of a stationary Internal Combustion Engine (ICE) in the lower power range. The comparison in this paper is made on the basis of thermodynamic, safety, plant engineering and operational aspects. While organic liquids have disadvantages in the areas of occupational safety, environmental protection and thermal stability, water in Rankine Cycle systems only reaches a comparable efficiency at higher heat source temperatures, and thus at higher live steam temperatures. Additionally, water poses apparatus-technical challenges in the steam generator and the turbine due to the comparatively high evaporation enthalpy and the volume change during phase transition. The thermodynamic parameters within the SRC, the internal consumption and the effects of the integration of an Internal Heat Exchanger (IHX) are compared with ORC plants, depending on the heat source temperature. Differences in the operation of these cycles as well as influences of the fluids on the plant design and costs are described. Finally, industrial applications are discussed in which the SRC could be preferred to the ORC taking into account all relevant aspects. To support these analyses, the thermodynamic design parameters, measurements, experience in apparatus design, as well as operating experience from the SRC pilot plant "MicroRankine" of the TH Nürnberg are applied.

1 INTRODUCTION

The ORC is legitimately state of the art in distributed low and medium temperature WHR. Due to its favorable thermodynamic properties with a wide variety of approx. 100 (Macchi and Astolfi, 2017) well-known pure fluids and mixtures, the energy from different waste heat sources can be economically converted into flexible and transportable electrical power. The SRC on the other hand, which is significantly involved in the majority of electricity generation worldwide, is used in large power plants of over 1,000 MW electrical power and achieves the highest efficiencies in converting heat from fossil and renewable fuels into electricity with the help of advanced technologies. However, even for smaller power ranges, the use of water as a working fluid for WHR is possible and in certain applications may be preferable to ORC in the sum of the arguments. This paper provides an overview of the arguments for and against the use of a SRC compared to an ORC for distributed high temperature WHR.
Several previous publications have compared the thermodynamic properties of various working fluids including water. Vankeirsbilck *et al.* (2011) investigate the advantages of an ORC with several hydrocarbons, refrigerants and siloxanes as working fluids to a SRC as a function of live steam temperature up to 350 °C. Water would need to have an extrapolated live steam temperature of over 425 °C in this case to become more efficient than the investigated ORCs. From Zhang *et al.* (2016), it can be derived a waste heat temperature of more than 400 °C, above which a SRC is thermodynamically

preferable to an ORC with different refrigerants. The heat flows in both studies are over 4 and, respectively, 6 MW, so the assumptions of the calculations are not necessarily comparable to smaller plants in every case. Extrapolating Rettig's (2011) studies, also a live steam temperature higher than 400 °C can be determined, above which SRC has advantages over ORC with different refrigerants, hydrocarbons and siloxanes, without assigning it to a specific power range. Gewald *et al.* (2010) investigate power generation from large ICEs of up to over 18 MW_{el}. From a waste heat temperature of over 300 °C, they always recommend a SRC instead of an ORC. A 2011 publication by Gewald *et al.* theoretically compares the use of a SRC with an ORC for the WHR of two ICEs with 3,688 kW_{el} in total and an average waste heat temperature of 460 °C. Under the assumptions made, a minimal thermodynamic advantage of the SRC was identified. In the following economic analysis, it was also determined that the same level of power generation cost is obtained. In a comparison of alkanes as working fluids to water at a waste heat temperature of 500 °C and 235.8 kW_{th}, Shu *et al.* (2014) conclude that although water would achieve a higher thermodynamic efficiency at full load, alkanes appear more attractive due to partial load behavior and thus lower temperatures and higher required turbine and evaporator size for water. Weith *et al.* (2013) theoretically compare the SRC with ORCs and conclude that toluene is more suitable for the WHR of an ICE with 1,416 kW_{el} and 448 °C waste heat temperature, although water seems to be an efficient alternative. Yamamoto *et al.* (2001) compare a SRC with an HCFC-123 ORC at waste heat temperatures of 60 to 200 °C and electrical powers up to 1 kW theoretically and practically. At these conditions, the ORC is superior to the SRC. The SRC and ORC have often been compared not only in stationary high-temperature applications with ICEs, but also in mobile and solar applications. Chammas and Clodic (2005) investigate the use of SRC or ORC for hybrid vehicles. Since with an ORC, engine cooling can be used in addition to the exhaust gases of up to 900 °C, higher overall efficiencies could be achieved with an ORC. For a waste heat temperature above 300 °C, according to Ringler *et al.* (2009), n SRC is preferable to an ORC even for the small power ratings if only the waste gas is used. When engine cooling is included, ethanol is suggested as working fluid. Katsanos *et al.* (2012) compare a SRC with an R245ca ORC for a truck engine at full and part load from 383.4 to 581.0 °C and conclude that the ORC achieves a 13 % higher performance. Facao *et al.* (2008) investigate the conversion of heat from solar collectors to electricity in countries with high levels of solar radiation. Water would achieve similar efficiencies to organic media, but because of the low live steam temperatures, wet fluids do not seem to be suitable for the turbine used.

ORC working fluids for WHR have been widely investigated in recent years. In addition to refrigerants for low temperature applications, hydrocarbons and siloxanes have proven favorable for medium and high temperature waste heat. Vélez *et al.* (2012) suggest refrigerants at waste heat temperatures below 180 °C, hydrocarbons from 180 °C to 250 °C and siloxanes above 250 °C. Nevertheless, even at temperatures above 250 °C, some studies conclude that certain hydrocarbons are more suitable than siloxanes, depending on the constraints and evaluation criteria. Among others, Ng *et al.* (2020) conclude that cyclopentane is most suitable for ORC-WHR of an offshore service vessel engine up to 392 °C at 1,950 kW mechanical power. In the studies of Lai *et al.* (2010), cyclopentane was also found to be the most suitable working fluid for WHR using ORC for high-temperature waste heat up to 350 °C. In contrast, Grob (2013) determines hexamethyldisiloxane (MM) as the most suitable ORC medium for the WHR of a 1,063 kW_{el} ICE with 450 °C exhaust gas temperature. Petrollese *et al.* (2018) also conclude MM as the most suitable ORC working fluid at live steam temperatures of 250 °C and a desired power output of 630 kW_{el}. Therefore, the SRC will be compared with cyclopentane and MM as high temperature ORC fluids in the thermodynamic consideration of the present work.

2 COMPARISON OF SRC AND ORC FOR HIGH TEMPERATURE WHR

As can be seen from the literature review, studies with different theoretical assumptions, constraints and applications come to different conclusions whether or not the SRC is preferable to an ORC at high temperature WHR. For this reason, constraints and design parameters of an existing SRC and ORC plants as well as a realistic waste heat source are used for the following investigations in order to obtain a reliable result.

The practical application considered in this paper is the WHR of the thermal energy contained in the exhaust gas of a Jenbacher 312 GS-B.L ICE. The exhaust gas has a temperature of 451 °C at full load with a mass flow of 2,797 kg/h. The change in specific enthalpy in the exhaust gas under consideration in the range between 170 °C and 451°C is further calculated using REFPROP (Lemmon *et al.*, 2007), correspondingly the maximum waste heat is 247.6 kW_{th}.

The design process data of the SRC are based on a pilot plant of the TH Nürnberg at the local sewage treatment plant, which converts the thermal energy of the exhaust gas of a Jenbacher 312 GS-B.L ICE into electricity. The water in the circuit is preheated by the exhaust gas at 16 bar, evaporated and superheated up to 431 °C. The superheated steam expands in a Siemens micro steam turbine prototype (Kraus *et al.*, 2016) with a design isentropic efficiency of 53.2 % and generates a power of up to 40 kW_{el}. In the plate condenser cooled by a river water system, the water condenses at variable pressure of minimum 0.060 bar. A membrane-type pump returns the water to operating pressure after the feedwater tank.
Grob (2013) describes a comparable ORC plant in his dissertation with design and real measurement parameters, where MM serves as working fluid and the waste heat of a 1,063 kW_{el} ICE at 450 °C is converted to electricity. The live vapor pressure of the realized ORC plant at maximum load is 17.23 bar, the turbine inlet temperature is 248 °C. The isentropic ORC turbine design efficiency is 70 %, the isentropic efficiency in all measured operating points is lower. For further calculations, the design efficiency of this exemplary example is used because it represents the system exactly designed for the appropriate application. The condensation temperature in the plant is 50 °C. The isentropic pump efficiency is 65 %, the degree of desuperheating is 80 %. The working fluid side pressure drop of the evaporator and IHX is 200 mbar and 50 mbar, respectively. In current literature, parameter optimization with cyclopentane as working fluid often concludes that live steam pressures over 30 bar provide maximum efficiency (Huster *et al.*, 2020), but in realized plants the maximum pressure is usually limited to 30 bar in order to reduce the complexity of the plant (Quoilin *et al.*, 2013). Although even this value is not always utilized in distributed plants with cyclopentane in the medium and small power range due to the low flash point, 30 bar is used in the following calculations as live steam pressure of an ORC plant with cyclopentane. In addition to these design parameters of the SRC and ORC plants, Table 1 lists the further relevant constraints that are necessary for the cycle calculations. According to Vaja and Gambarotta (2010), the minimum pinch point in the economizer can be set to 30 K.

Table 1: Constraints of the thermodynamic evaluation

Constraints	**Value**	**Unit**
Isentropic pump efficiency	65	%
Electrical pump efficiency	90	%
Temperature exhaust gas	451	°C
Minimal exhaust gas temperature	170	°C
Mass flow exhaust gas	2,797	kg/h
Minimal pinch point of the economizer	30	K
Pressure loss evaporator exhaust gas	20	mbar
Pressure loss evaporator working fluid	200	mbar
Level of superheating in the ORC	10	K
Electrical turbine efficiency	95	%
Isentropic SRC turbine efficiency	53.2	%
Isentropic ORC turbine efficiency	70	%
Pressure loss IHX vapor-side	50	mbar
Pressure loss IHX liquid-side	100	mbar
Degree of desuperheating IHX	80	%
Condensation temperature	50	°C
Condenser subcooling	10	K

The efficiency used to evaluate the different systems, displayed in Equation (1), is defined by the power of the generator minus the power of the pump, related to the maximum heat flow that can be transferred when the exhaust gas is cooled to 170 °C. This combines the exploitation efficiency of the evaporator with the actual cycle efficiency.

$$\eta = \frac{P_{el,gen} - P_{el,pump}}{Q_{G,max}} \tag{1}$$

The process parameters calculated using the constraints from Table 1, the heat fluxes transferred, the electrical powers of the turbine and pump and the defined efficiency of the ORC with MM (a), with cyclopentane (b) and of the SRC (c) are summarized in Figure 1. In addition, the SRC with an IHX (d) is shown. ORC fluid properties are calculated using REFPROP (Lemmon *et al.*, 2007) and water chemical properties were calculated according to IAPWS IF-97.

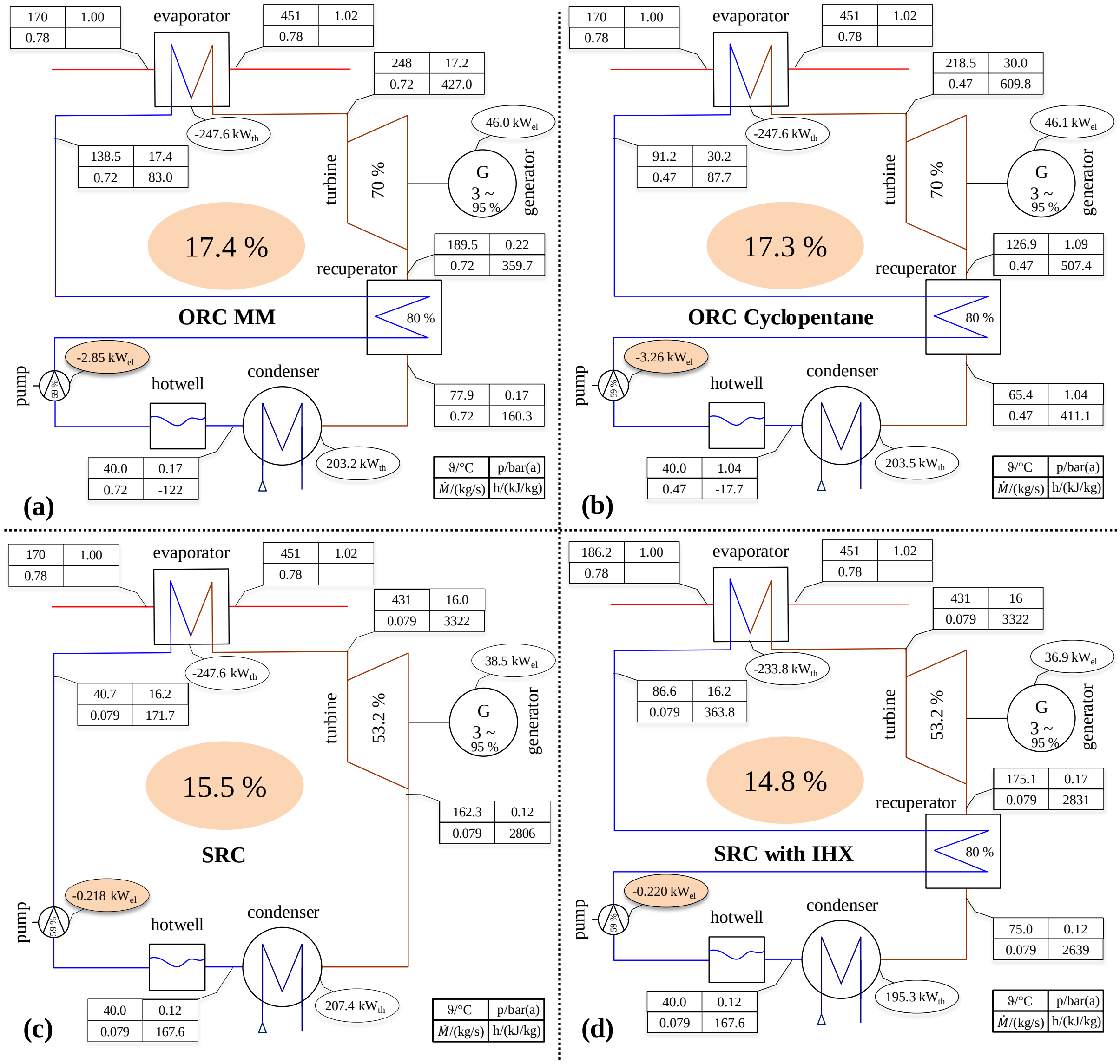

Figure 1: Process parameters of an ORC plant with MM (a) and cyclopentane (b) as working fluid, as well as the process parameters of a simple SRC (c) and a SRC with IHX (d)

As can be seen, the ORC with MM achieves an efficiency of 17.4 %, with cyclopentane 17.3 %, the simple SRC reaches 15.5 % under the design parameters and the use of an IHX in the SRC actually reduces the overall efficiency by 0.7 % because the pinch point constraint does not allow the waste heat source to be fully utilized.

Figure 2 shows the cycle efficiency at an isentropic turbine efficiency of 53.2 % with and without IHX and for steam turbine efficiencies of 40, 60 and 70 % over the live steam temperature. The gray dashed curves show possible live steam temperatures if higher waste heat temperatures were applied at the same total thermal power. The black dash dot line shows the reference ORC with MM as described in Figure 1. Higher live steam temperatures are often not possible in ORCs, therefore they are kept constant in this analysis. It can be seen that the use of an IHX only allows an increase in the overall efficiency at higher live steam temperatures without restrictions due to the pinch point. With the steam turbine efficiency of 53.2 %, approx. 540 °C live steam temperature would be necessary to compete directly with ORC. For the application considered here, from an isentropic turbine efficiency of 60 % and approx. 430 °C, SRC would achieve an overall efficiency comparable to the ORC with MM.

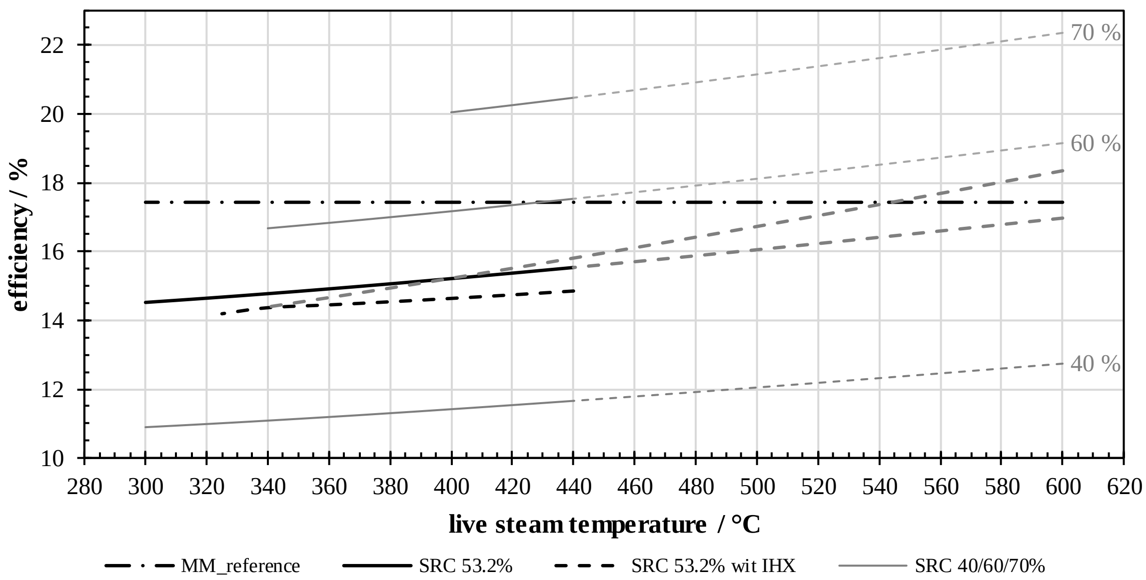

Figure 2: Cycle efficiency of the SRC with different isentropic steam turbine efficiencies, with and without IHX as function of live steam temperature and MM reference ORC

The influence of the live steam pressure on the overall efficiency is shown in Figure 3. Again, different turbine efficiencies and at 53.2 % the SRC with IHX and the reference ORC are shown. The gray dashed lines, in extension of the gray lines, represent the cycle without the influence of the selected pinch point of 30 K, i.e. at significantly higher waste heat temperatures. When this pinch point is taken into account, the live steam pressure of 16 bar selected in the SRC of the MicroRankine pilot plant can be seen. If the pressure is increased beyond 16 bar, e.g. at the turbine efficiency of 53.2 %, the overall efficiency does not increase, since the heat source cannot be utilized perfectly. At the same time, the apparatus costs increase due to higher pressures. The IHX would only have a small positive influence on the overall efficiency at pressures below 10 bar and would reduce it above. Thus, increasing the pressure would only achieve an efficiency comparable to ORC at significantly higher waste heat temperatures. The greatest influence here would also be the increase in turbine efficiency, at 60 % SRC would be comparable to the MM ORC from approx. 16 bar.

A condensing temperature of 50 °C is not always available with air cooling due to seasonal outdoor temperatures, furthermore some Rankine Cycle plants are operated seasonally heat controlled, where the district heat extraction serves as heat sink. The turbine exhaust pressure is then raised, resulting in lower turbine outputs and cycle efficiencies. Therefore, Figure 4 shows the overall efficiency of the SRC with the different turbine efficiencies and the SRC with IHX at 53.2 % over the condensation temperature. The efficiencies of the reference ORC with MM are also shown. The use of an IHX does again not appear to be useful at all condensing temperatures. It can be seen that the difference in efficiency of the SRC compared to the ORC decreases as the condensation temperature increases. While, for example, the SRC with a turbine efficiency of 60 % at 50 °C condensation temperature is nearly equal to the ORC MM, it is already more efficient from approx. 60 °C condensation temperature.

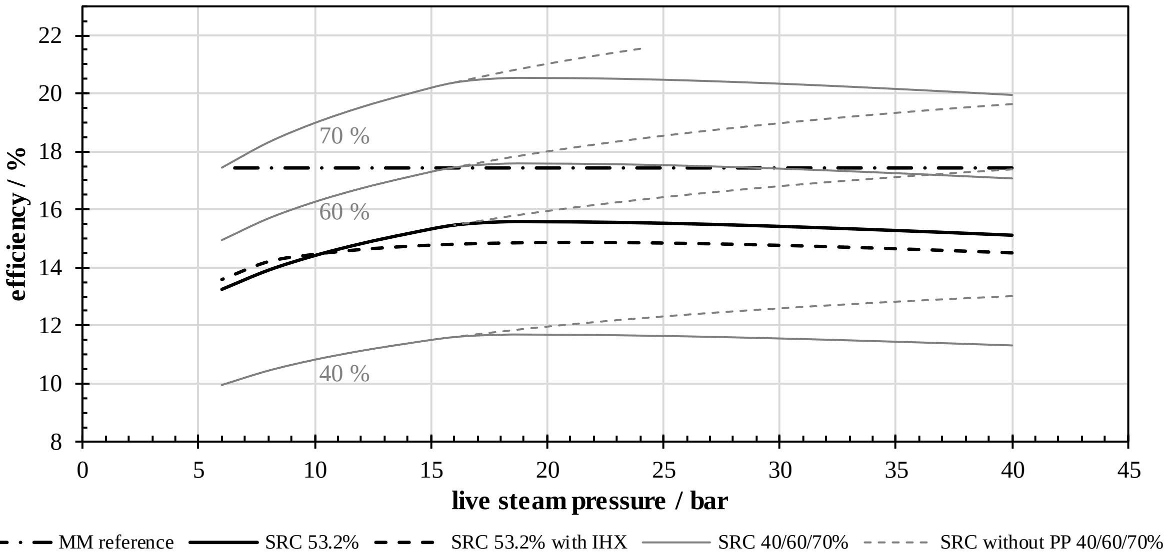

Figure 3: Cycle efficiency of the SRC with different isentropic steam turbine efficiencies with and without IHX and pinch point consideration as function of live steam pressure and MM reference ORC

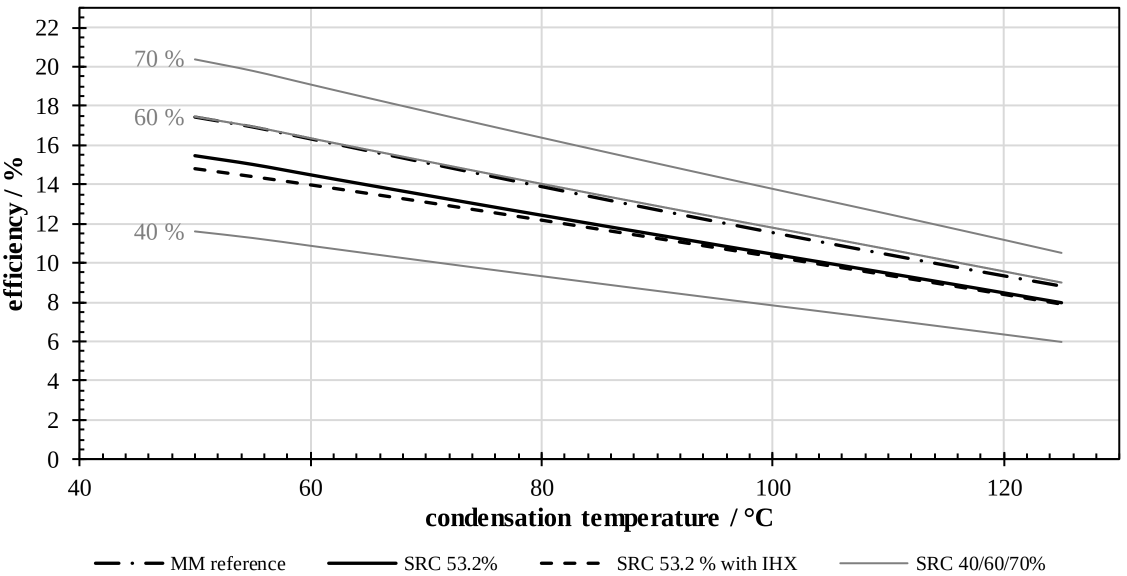

Figure 4: Cycle efficiency of the SRC with different isentropic turbine efficiencies with and without IHX, as well as the MM reference ORC as functions of condensation temperature

Fluids that can create explosive mixtures under the influence of oxygen from the ambient air are often not expanded below ambient pressure, which significantly limits the efficiency. Siloxanes, for example, and water are often expanded below ambient pressure at low condensing temperatures. In the case of toxic or carcinogenic substances, in addition to explosion protection when evacuating the plant during commissioning or during operation, sufficient discharge must also be ensured because vapor of the working fluid is also extracted with the air. However, different ORC fluids are more or less suitable for different condensation temperatures. If the condensation temperature varies, a compromise must be made (Menne and Struzyna, 2015).

3 COST, PLANT ENGINEERING, OPERATIONAL AND SAFETY ASPECTS

Especially at higher temperatures, organic fluids tend to decompose. According to Macchi and Astolfi (2017), fluids suitable for high temperature applications typically have critical decomposition temperatures of approx. 300 to 400 °C. Due to safety margins, the design parameters are always significantly below this temperature. The decomposition temperatures of MM and cyclopentane considered in this comparison are 300 °C and 275 °C, respectively (Preissinger and Brueggemann, 2016, Pasetti *et al.*, 2011). Since in applications with high waste heat temperatures the maximum permissible temperature can be exceeded in some areas of the steam generator, intermediate circuits are often used in which a carrier medium, e.g. thermal oil, flows. This additional heat exchanger and the piping lead to increased costs, which do not occur in the SRC. Nevertheless, even at lower temperatures, organic fluids are not infinitely stable in continuous operation. Decomposition products, however they are formed, can cause fouling in the steam generator and condenser, erosion in the turbine and the pump and a reduced overall efficiency due to the changed physical properties (Macchi and Astolfi, 2017).

Water as a working fluid is chemically stable in applications of WHR. If it nevertheless becomes necessary to replace it, e.g. due to maintenance work or corrosion, it can simply be released into the drain. Filling the system afterwards again with deionized water hardly causes any costs. Organic fluids account for up to 10 % of the investment price of an ORC plant, especially if they are non-flammable and non-toxic. Flammable fluids are less expensive, but an increased safety class must be maintained, which again leads to higher investments (Macchi and Astolfi, 2017). If the organic working fluid has to be changed, e.g. due to corrosion or decomposition products, it has to be disposed of at a cost and purchased again.

The high level of superheating in the steam generator of the SRC with the maximum pressure drop in the exhaust gas path to be maintained increases the construction volume and the acquisition costs compared to ORCs. Against this, water has a lower viscosity, therefore lower friction losses and higher heat transfer coefficients (Quoilin *et al.*, 2013). But since the determining heat transfer coefficient lies on the exhaust gas side, it does not have the dominant influence. In contrast to organic fluids, the high evaporation enthalpy of water leads to low pinch points in the steam generator. However, due to the rising inlet temperature in the ORC evaporator as a result of the IHX, the minimum pinch point is also often exceeded.

In mobile applications, pure water has the possibility of freezing while stillstand (Ringler *et al.*, 2009). The freezing point for organic fluids are usually significantly lower than for water.

For steam turbines in the lower power range, high peripheral speeds and a higher number of stages are required due to the high volumetric flow ratio between inlet and outlet (Macchi and Astolfi, 2017). As can be derived in Figure 1, the enthalpy difference in the SRC turbine is about 7.5 times higher than in the ORC. The size parameter of SRC turbines, according to Shu *et al.* (2014), are up to twice larger than with ORC turbines. This supersonic velocity of the steam, which occurs during expansion, also leads to a danger potential in the event of leaks in the steam system. If the superheating is not high enough, there is a risk of liquid contents being formed during expansion. Steam turbine lubrication bearing of the shaft is not easily possible, so that the water in the system is not contaminated. All this leads to a more complex and expensive turbine design.

Large SRC plants may not be entirely made of alloyed steel for economic reasons, so the water quality must be checked regularly to prevent corrosion and entails higher operating costs.

Safety regulations in the Occupational Health and Safety Act also enhance barriers for the decision to build and operate ORC plants. Although the approval process of steam boilers also involves a lot of bureaucracy and inspections, fewer or no regulations apply to explosion protection, maternity protection and ventilation, since water is neither highly flammable, toxic, carcinogenic nor teratogenic or is dangerous for the climate. In the case of flammable fluids, the explosion protection environment, in addition to extra sensors, leads to the control cabinets not being installed directly in the plant environment. For applications in urban areas, there are additional increased authorization processes and concerns from residents that impede the decision for ORC plants.

Steam makes the integration of a storage for the WHR of volatile waste heat possible, while with ORC fluids it are usually attempted to have as less of the fluid in the circuit as possible.

4 CONCLUSION AND OUTLOOK

Summarizing the thermodynamic comparison, it can be said that an IHX with the given constraints brings thermodynamic advantages in the SRC only at very high live steam temperatures, but in the other configurations leads to disadvantages due to the reduced utilization efficiency of the heat source. The economic benefit is furthermore not yet considered. With the turbine efficiency of the MicroRankine pilot plant, the SRC mostly achieves a lower overall efficiency than the ORCs under consideration. From approx. 60 % isentropic steam turbine efficiency, the SRC would become competitive with the ORCs from a purely thermodynamic point of view.
Considering the cost, plant engineering, operational and safety aspects, it becomes apparent that besides disadvantages of the SRC compared to the ORC, there are also obvious advantages. The thermo-physical properties of water requires more complex apparatus in the lower power range, which lead to higher investment costs. However, water offers advantages especially in the areas of safety and sustainability. Table 2 summarizes the qualitative advantages and disadvantages of water over organic fluids for high-temperature WHR.

Table 2: Summary of pros and cons of SRC vs. ORC

Pro SRC	**Con SRC**
Thermodynamic aspects:	
- Higher live steam temperatures possible - No performance reducing decomposition products - Easier to expand into vacuum - Lower viscosity – lower friction losses and higher exchange coefficients	- Less efficient at lower temperatures - Lower turbine isentropic efficiencies - Smaller evaporator pinch points - Danger of droplet erosion due to expansion into the wet steam area (negative saturation vapour curve)
Cost, plant engineering and operational aspects:	
- No intermediate circuit necessary - Electronics can be placed directly at the plant - Cheap working fluid, no disposal costs - No IHX necessary	- Lubrication bearing not easily possible - Water analysis required for unalloyed steel - Less compact and thus more expensive apparatuses
Safety aspects:	
- No flammable, explosive, toxic, carcinogenic or teratogenic fluids - No Global Warming Potential or Ozone Depletion Potential - No dangerous decomposition products - Simpler integration of a steam accumulator	- Possible corrosion with unalloyed steel - Higher vapour speed at leakages

Especially in applications where sustainability and occupational health and safety are important, a decision for SRC could be made even with minimally lower overall efficiency. Furthermore, if a steam network already exists, the integration of a SRC plant could make sense. Other studies show that a two-stage SRC-ORC plant can also be operated efficiently.
Finally, the application-specific advantages and disadvantages of SRC must be balanced for each WHR system in order to provide a well-founded decision. Stationary and mobile high temperature waste heat is available in various applications, besides fossil ICEs, hydrogen engines and solid oxide fuel cells will have high-temperature waste heat potential in future energy systems. In addition, higher efficiency is becoming increasingly important in industrial processes in the context of CO_2 pricing.
In future work, the economic factors discussed in this paper will be examined in detail, optimized and compared with a high-temperature ORC application in order to make a more general statement on when SRC could be preferred to ORC.
In a current research project of the TH Nürnberg with partners of industry and applied science, a efficient steam turbine, a compact steam generator and a scalable and economical system architecture for the WHR with SRC are being developed. With this techno-economically optimized apparatuses and plant design, various waste heat flows between 200 and 2,000 kW_{th} are to be converted into electricity and district heating as required with an adequate return on investment.

NOMENCLATURE

Symbols

$\dot{M}$	mass flow	(kg/s)
η	cycle efficiency	(%)
p	pressure (atmospheric)	(bar)

Subscript

el	electrical
gen	generator
G	waste gas
th	thermal

Abbreviations

ICE	Internal Combustion Engine
IHX	Internal Heat Exchanger
MM	Hexamethyldisiloxane
ORC	Organic Rankine Cycle
PP	Pinch Point
SRC	Steam Rankine Cycle
WHR	Waste Heat Recovery

REFERENCES

El Chammas, R., Clodic, D., 2005,"Combined Cycle for Hybrid Vehicles, *SAE 2005 World Congress & Exhibition*, 2005-01-1171.

Facão, J., Palmero-Marrero, A., Oliveira, A. C., 2008, Analysis of a solar assisted micro-cogeneration ORC system, *International Journal of Low-Carbon Technologies*, vol. 3, no.4, p. 365-264.

Gewald, D., Schuster, A., Spliethoff, H., König, N., 2010, Comparative Study of Water-Steam- and Organic-Rankine-Cycles as bottoming Cycles for Heavy-Duty Diesel Engines by means of Exergetic and Economic Analysis, *Proceedings of Ecos*, p. 63-71.

Gewald, D., Siokos, K., Karellas, S., Spliethoff, H., 2012, Waste heat recovery from a landfill gas-fired power plant, *Renewable and Sustainable Energy Reviews*, vol. 16, no. 4, p. 1779-1789.

Grob, 2013, *Arbeitsmittelauswahl, Messdatenanalyse und Modellüberprüfung eines Hochtemperatur-Organic-Rankine-Cycle*, Ruhr-Universität-Bochum, Department of Mechanical Engineering, Doctoral thesis. 166 p.

Huster, W. R., Schweidtmann, A. M., Mitsos, A., 2020, Working fluid selection for organic rankine cycles via deterministic global optimization of design and operation, *Optim Eng*, vol. 21, no. 2, p. 517-536.

Katsanos, C.O., Hountalas, D.T., Pariotis, E.G., 2012, Thermodynamic analysis of a Rankine cycle applied on a diesel truck engine using steam and organic medium, *Energy Conversion and Management*, vol. 60, p. 68-76.

Kraus M., Deichsel M., Opferkuch F., Hirsch P., Heckel C., 2016, Hermetic 40-kW-Class Steam Turbine System for the Bottoming Cycle of Internal Combustion Engines, *Proceedings of the ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition*, vol. 8.

Lai, N. A., Wendland, M., Fischer, J., 2011, Working fluids for high-temperature organic Rankine cycles, *Energy*, vol. 36, no. 1, p. 199-211.

Lemmon, E. W., Huber, M. L., McLinden, M. O., 2007, *NIST Reference Fluid Thermodynamic and Transport Properties REFPROP*. The National Institute of Standards and Technology (NIST).

Macchi, E., Astolfi, M., 2017, *Organic Rankine Cycle (ORC) Power Systems, Technologies and Applications*, Woodhead Publishing Series in Energy, 679 p.

Menne, A., Struzyna, R., 2015, Rankine-Fluid, Definition und Erprobung von Fluiden zum Einsatz in Waste-Energy-Anlagen (WER) von Mobilantrieben hinsichtlich ihrer Eignung und Stabilität für die Nutzung in einem Rankine-Prozess, Abschlussbericht, Forschungsvereinigung Verbrennungskraftmaschinen e.V., no. 1070-2015.

Ng, C., Tam, I. C. K., Wu, D., Thermo-Economic Performance of an Organic Rankine Cycle System Recovering Waste Heat Onboard an Offshore Service Vessel, *J. Mar. Sci. Eng.*, vol. 8, no. 5.

Pasetti, M., Invernizzi, C. M., Iora, P., 2014, Thermal stability of working fluids for organic Rankine cycles: An improved survey method and experimental results for cyclopentane, isopentane and n-butane, *Applied Thermal Engineering*, vol. 73, no. 1, p. 764-774.

Petrollese, M., Oyekale, J., Tola, V., Cocco, D., 2018, Optimal ORC configuration for the combined production of heat and power utilizing solar energy and biomass, *ECOS 2018 - Proceedings of the 31st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*.

Preißinger M, Brüggemann D., 2016, Thermal Stability of Hexamethyldisiloxane (MM) for High-Temperature Organic Rankine Cycle (ORC). *Energies*. vol. 9, no. 3, p.183.

Quoilin, S., Van Den Broek, M., Declaye, S., Dewallef, P., Lemort, V, 2013, Techno-economic survey of Organic Rankine Cycle (ORC) systems, *Renewable and Sustainable Energy Reviews*, vol. 22, p. 168-186.

Retting, A., 2011, Aus Abwaerme wird Strom, ZHAW homepage: https://www.zhaw.ch/storage/engineering/institute-zentren/iefe/PDFs/orc-fachartikel-et036-aus-abwaerme-wird-strom.pdf., last accessed 2021/03/04

Ringler, J., Seifert, M., Guyotot, V., Hübner, W., 2009, Rankine Cycle for Waste Heat Recovery of IC Engines, *SAE Int. J. Engines*, vol. 2, no. 1, p. 67-76.

Shu, G., Li, X., Tian, H., Liang, X., Wei, H., Wang, X., 2014, Alkanes as working fluids for high-temperature exhaust heat recovery of diesel engine using organic Rankine cycle, *Applied Energy*, vol. 119, p. 204-217.

Vaja, I., Gambarotta, A, 2010, Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs), *Energy*, vol. 35, no. 2, p. 1084-1093.

Vankeirsbilck, I., Vanslambrouck, B., Gusev, S., de Paepe, M., 2011, Organic Rankine cycle as efficient alternative to steam cycle for small scale power generation, *8th international conference on heat transfer, fluid mechanics and thermodynamics, proceedings*, p. 785–792.

Vélez, F., Segovia, J. J., Martín, M. C., Antolín, G., Chejne, F., Quijano, A., 2012, A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation, *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, p. 4175-4189.

Weith, T., Heberle, F., Preissinger, M., Brüggemann, D., 2013, Abwärmenutzung von Biogas-BHKWs mittels Nachverstromung in ORC-Anlagen, *Biogas in der Landwirtschaft - Stand und Perspektiven*, FNR/KTBL-Kongress 2013, p. 245-255.

Xiaojun, Z., Lijun, W., Xiaoliu, W., Guidong, J., Comparative study of waste heat steam SRC, ORC and S-ORC power generation systems in medium-low temperature, *Applied Thermal Engineering*, vol. 106, p. 1359-4311.

Yamamoto, T., Furuhata, T., Arai, N., Mori, K., 2001, Design and testing of the Organic Rankine Cycle, *Energy*, vol. 26, no. 3, p. 239-251.

Zhang, X., Wu, L., Wang, X., Ju, G., 2016. Comparative study of waste heat steam SRC, ORC and S-ORC power generation systems in medium-low temperature, *Applied Thermal Engineering*, p. 1427–1439.

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