Technical and economic feasibility of organic Rankine cycle-based waste heat recovery systems on feeder ships: Impact of nitrogen oxides emission abatement technologies

The International Maritime Organization recently revised the regulations concerning nitrogen and sulphur oxides emissions from commercial ships. In this context, it is important to investigate how emission abatement technologies capable of meeting the updated regulation on nitrogen oxides emissions affect the performance of waste heat recovery units to be installed on board new vessels. The objective of this paper is to assess the potential fuel savings of installing an organic Rankine cycle unit on board a hypothetical liquefied natural gas-fuelled feeder ship operating inside emission control areas. The vessel complies with the updated legislation on sulphur oxides emissions by using a dual fuel engine. Compliance with the nitrogen oxides emission regulation is reached by employing either a high or low-pressure selective catalytic reactor, or an exhaust gas recirculation unit. A multi-objective optimization was carried out where the objective functions were the organic Rankine cycle unit annual electricity production, the volume of the heat exchangers, and the net present value of the investment. The results indicate that the prospects for attaining a cost-effective installation of an organic Rankine unit are larger if the vessel is equipped with a low-pressure selective catalytic reactor or an exhaust gas recirculation unit. Moreover, the results suggest that the cost-effectiveness of the organic Rankine cycle units is highly affected by fuel price and the waste heat recovery boiler design constraints.
A review of the use of organic Rankine cycle power systems for maritime applications

Diesel engines are by far the most common means of propulsion aboard ships. It is estimated that around half of their fuel energy consumption is dissipated as low-grade heat. The organic Rankine cycle technology is a well-established solution for the energy conversion of thermal power from biomass combustion, geothermal reservoirs, and waste heat from industrial processes. However, its economic feasibility has not yet been demonstrated for marine applications. This paper

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ISI indexed (2011): ISI indexed yes
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Scopus rating (2010): SJR 1.35 SNIP 1.735
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Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.302 SNIP 1.798
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.471 SNIP 1.886
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.186 SNIP 1.807
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.294 SNIP 1.797
Web of Science (2006): Indexed yes
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Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.879 SNIP 1.382
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aims at evaluating the potential of using organic Rankine cycle systems for waste heat recovery aboard ships. The suitable vessels and engine heat sources are identified by estimating the total recoverable energy. Different cycle architectures, working fluids, components, and control strategies are analyzed. The economic feasibility and integration on board are also evaluated. A number of research and development areas are identified in order to tackle the challenges limiting a widespread use of this technology in currently operating vessels and new-buildings. The results indicate that organic Rankine cycle units recovering heat from the exhaust gases of engines using low-sulfur fuels could yield fuel savings between 10% and 15%.

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ISI indexed (2012): ISI indexed yes  
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Scopus rating (2011): CiteScore 7.39 SJR 2.717 SNIP 3.911  
Web of Science (2011): Impact factor 6.018  
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Design and optimization of a power hub for Brazilian off-shore oil production units

A worldwide trend to reduce greenhouse gases emissions has encouraged researchers to study more efficient solutions in diverse sectors, including Oil and Gas Industry. Most of offshore units are energized by redundant equipment operating at low loads, turning their energy consumption inefficient and increasing environmental impact. This work aims at identifying the optimal design of a gas and steam turbine combined cycle tailored for offshore oil production applications. The Brazilian pre-salt basin is taken as a case study to improve operational efficiency and reduce CO2 emissions of floating oil production units. The idea is to concentrate the power supply to a floating power plant, composed of combined cycle power blocks. A model is developed, integrating the design of the gas turbine, heat recovery steam generators (single pressure and double pressure), steam turbine and condenser. Genetic algorithms are applied in two optimization approaches, single-objective and multi-objective. Three parameters are evaluated: equipment purchase cost, thermal efficiency and total weight. The results of the multi-objective optimization indicate that dual-pressure arrangement steam cycles, featuring 3 gas turbines, 1 HRSG and 1 steam cycle, could be an attractive design solution for power hubs. This arrangement has a low cost and weight, while the thermal efficiency is maintained at a reasonable high level (around 53.2%). Moreover, the results indicate that by introducing a power hub, the CO2 emissions may be reduced by 18.7% to 27.2% compared with a conventional FPSO design.

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Optimization of organic Rankine cycle power systems considering multistage axial turbine design

Organic Rankine cycle power systems represent a viable and efficient solution for the exploitation of medium-to-low temperature heat sources. Despite the large number of commissioned units, there is limited literature on the design and optimization of organic Rankine cycle power systems considering multistage turbine design. This work presents a preliminary design methodology and working fluid selection for organic Rankine cycle units featuring multistage axial turbines. The method is then applied to the case of waste heat recovery from a large marine diesel engine. A multistage axial turbine model is presented and validated with the best available data from literature. The methodology allows the identification of the most suitable working fluid considering the trade-off between cycle and multistage turbine designs. The results of the optimization of cycle and turbine suggest that the fluid n-butane yields the best compromise in terms of cycle net power output, turbine cost and efficiency for the considered case study. When a conservative design approach is adopted, the turbine features a two-stage configuration with supersonic converging nozzles and post-expansion. Conversely, a single-stage turbine featuring a supersonic converging-diverging nozzle and Mach number up to 2 is the resulting ideal choice when a more advanced design approach is implemented.

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BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 6.4 SJR 2.835 SNIP 2.593
Web of Science (2015): Impact factor 5.746
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BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 6.93 SJR 3.158 SNIP 3.218
Web of Science (2014): Impact factor 5.613
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BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 6.59 SJR 3.06 SNIP 3.346
Web of Science (2013): Impact factor 5.261
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 5.69 SJR 2.778 SNIP 3.076
Web of Science (2012): Impact factor 4.781
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A Comparison of Organic and Steam Rankine Cycle Power Systems for Waste Heat Recovery on Large Ships

This paper presents a comparison of the conventional dual pressure steam Rankine cycle process and the organic Rankine cycle process for marine engine waste heat recovery. The comparison was based on a container vessel, and results are presented for a high-sulfur (3 wt %) and low-sulfur (0.5 wt %) fuel case. The processes were compared based on their off-design performance for diesel engine loads in the range between 25% and 100%. The fluids considered in the organic Rankine cycle process were MM(hexamethyldisiloxane), toluene, n-pentane, i-pentane and c-pentane. The results of the comparison indicate that the net power output of the steam Rankine cycle process is higher at high engine loads, while the performance of the organic Rankine cycle units is higher at lower loads. Preliminary turbine design considerations suggest that higher turbine efficiencies can be obtained for the ORC unit turbines compared to the steam turbines. When the efficiency of the c-pentane turbine was allowed to be 10% points larger than the steam turbine efficiency, the organic Rankine cycle unit reaches higher net power outputs than the steam Rankine cycle unit at all engine loads for the low-sulfur fuel case. The net power production from the waste heat recovery units is generally higher for the low-sulfur fuel case. The steam Rankine cycle unit produces 18% more power at design compared to the high-sulfur fuel case, while the organic Rankine cycle unit using MM produces 33% more power.

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A review of solar energy based heat and power generation systems

The utilization of solar energy based technologies has attracted increased interest in recent times in order to satisfy the various energy demands of our society. This paper presents a thorough review of the open literature on solar energy based heat and power plants. In order to limit the scope of the review, only fully renewable plants with at least the production of electricity and heat/hot water for end use are considered. These include solar photovoltaic and solar thermal based plants with both concentrating and non-concentrating collectors in both solar-only and solar-hybrid configurations. The paper also presents a selection of case studies for the evaluation of solar energy based combined heat and power generation possibility in Denmark. The considered technologies for the case studies are (1) solar photovoltaic modules, (2) solar flat plate collectors, (3) a ground source heat pump, (4) a biomass burner, and (5) an organic Rankine cycle. The various cases are compared on the basis of economic profitability and environmental performance. The results from the case studies indicate that it is economically and environmentally beneficial to invest in both small and large capacity solar-biomass hybrid plants for combined heat and power production in the Nordic climatic conditions. The results also suggest that the configuration with an organic Rankine cycle with solar thermal collectors and a biomass burner is particularly attractive for large capacity plants.
Expansion of organic Rankine cycle working fluid in a cylinder of a low-speed two-stroke ship engine

Electricity and power produced from waste heat is particularly relevant in shipping because fuel expenses constitute the majority of the cost of operating the ships; however, the cost-benefit aspect limits the widespread implementation of waste heat recovery power units on ships. This paper presents the thermodynamic analysis of a concept that aims at reducing the cost of an organic Rankine cycle unit by using one of the cylinders in a large diesel engine as expansion device. Numerical models were used to optimise the process parameters and thereby determine the power potential for this concept. The evaluation of 104 working fluids points to cyclopropane, R245fa and R1234ze(z) as the most promising. The results suggest that the power produced by the organic Rankine cycle cylinder is at least equivalent to that of the cylinders operating with the diesel process. This enables potential fuel savings and emissions reductions of about 8.3% in the studied scenario.
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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 5.17 SJR 1.974 SNIP 1.823
Web of Science (2016): Impact factor 4.52
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 5.03 SJR 2.22 SNIP 2.037
Web of Science (2015): Indexed yes
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Scopus rating (2014): CiteScore 5.7 SJR 2.575 SNIP 2.602
Web of Science (2014): Impact factor 4.844
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BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 5.02 SJR 2.458 SNIP 2.556
Web of Science (2013): Impact factor 4.159
ISI indexed (2013): ISI indexed yes
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BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 4.25 SJR 1.935 SNIP 2.214
Web of Science (2012): Impact factor 3.651
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
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Scopus rating (2011): CiteScore 4 SJR 1.566 SNIP 2.01
Web of Science (2011): Impact factor 3.487
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.712 SNIP 2.46
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BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.663 SNIP 2.357
Web of Science (2009): Indexed yes
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Scopus rating (2008): SJR 1.103 SNIP 1.438
Scopus rating (2007): SJR 0.902 SNIP 1.434
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.851 SNIP 1.315
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.942 SNIP 1.153
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Integrated working fluid-thermodynamic cycle design of organic Rankine cycle power systems for waste heat recovery

Today, some established working fluids are being phased out due to new international regulations on the use of environmentally harmful substances. With an ever-increasing cost to resources, industry wants to converge on improved sustainability through resource recovery, and in particular waste heat recovery. In this paper, an organic Rankine cycle process and its pure working fluid are designed simultaneously for waste heat recovery of the exhaust gas from a marine diesel engine. This approach can overcome design issues caused by the high sensitivity between the fluid and cycle design variables and otherwise high resource demands, which through conventional methods cannot be addressed. The global optimal design was a 1.2 MW cycle with 2,2,3,3,4,4,5,5-octafluorohexane as the new fluid. The fluid has no ozone depletion potential and a global warming potential under the regulatory limit. By using the simultaneous design approach, the optimum solution was found in 5.04 s, while a decomposed approach found the same solution in 5.77 h. However, the decomposed approach provided insights on the correlation between the fluid and cycle design variables by analyzing all possible solutions. It was shown that the high sensitivity between the fluid and cycle design variables was overcome by using the simultaneous approach. Correlation between net power output and the product of the overall heat transfer coefficient and the heat transfer area could further be addressed by employing a new solution strategy including maximum constraints for this product. The use of such constraints resulted in the design of a new fluid (5-chloro-4,5,5-trifluoro-2,3-dimethylpent-2-ene) with a 1.25 MW net power output. Finally, a comparison with conventional fluids was shown where 2,2,3,3,4,4,5,5-octafluorohexane offered an improvement on net power output and economic and environmental metrics.
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Scopus rating (2015): CiteScore 6.4 SJR 2.835 SNIP 2.593
Web of Science (2015): Impact factor 5.746
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 6.93 SJR 3.158 SNIP 3.218
Web of Science (2014): Impact factor 5.613
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 6.59 SJR 3.06 SNIP 3.346
Web of Science (2013): Impact factor 5.261
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 5.69 SJR 2.778 SNIP 3.076
Web of Science (2012): Impact factor 4.781
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 5.5 SJR 2.416 SNIP 2.827
Web of Science (2011): Impact factor 5.106
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.531 SNIP 2.259
Web of Science (2010): Impact factor 3.915
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.992 SNIP 1.85
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.95 SNIP 1.206
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.168 SNIP 1.704
Web of Science (2007): Indexed yes
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Scopus rating (2005): SJR 1.02 SNIP 0.988
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.67 SNIP 0.844
Web of Science (2004): Indexed yes
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Web of Science (2002): Indexed yes
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Organic Rankine cycle unit for waste heat recovery on ships (PilotORC)
The project PilotORC was aimed at evaluating the technical and economic feasibility of the use of organic Rankine cycle (ORC) units to recover low-temperature waste heat sources (i.e. exhaust gases, scavenge air, engine cooling system, and lubricant oil system) on container vessels. The project included numerical simulations and experimental tests on a 125 kW demonstration ORC unit that utilizes the waste heat of the main engine cooling system on board one of Maersk’s container vessels.

During the design of the demonstration ORC unit, different alternatives for the condenser were analyzed in order to minimize the size of the heat exchanger area. Later on the ORC unit was successfully installed on board, and it has been working uninterrupted since, demonstrating the maturity of the ORC technology for maritime applications. During the onboard testing, additional measuring devices were installed on the unit and experimental data at design and off-design conditions were collected.

Several simulation models were developed in order to evaluate alternative integrations of the ORC units with different sources and configurations. The developed models allowed for the study of different ORC configurations at design and off-design conditions, the simulation of radial-inflow turbines, and the prediction of thermophysical properties of alternative working fluids. The models for the ORC unit were validated with the collected experimental data. The validated models were used to evaluate the retrofit-fitting potential of using ORC units for maritime applications, and the relevance of this technology for new-building projects. Firstly, an evaluation of the waste heat resources available on board Maersk containers fleet, and an estimation of the potential energy recovery by means of the ORC technology was performed. The estimations showed that significant fuel savings can be achieved. It was found that integrating ORC units with the jacket cooling water within the service steam circuit could enable payback periods of approximately 5 years and high fuel savings. Conversely, if the heat from the exhaust gases was recovered, the total power production of the ORC unit could cover 10% of the main engine power. Larger energy savings, 10 - 15%, could be expected if advanced design methods are employed.

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Performance analysis of different organic Rankine cycle configurations on board liquefied natural gas-fuelled vessels
Gas-fuelled shipping is expected to increase significantly in the coming years. Similarly, much effort is devoted to the study of waste heat recovery systems to be implemented on board ships. In this context, the organic Rankine cycle (ORC) technology is considered one of the most promising solutions. The ORC favorably compares to the steam Rankine cycle because of its simple layout and high efficiency, achievable by selecting a working fluid with desirable properties. This paper aims at assessing the fuel savings attainable by implementing ORC units on board vessels powered by liquefied natural gas (LNG). The study compares the performance of six different ORC configurations both in design and off-design operation, and provides guidelines with respect to the most promising heat sources and sinks to be utilized by an ORC unit in order to maximize the annual fuel savings. In addition, this paper describes a novel ORC layout rejecting heat to two heat sinks. The results indicate equivalent fuel savings up to 8.9% when harvesting heat from the exhaust gases, and that the novel configuration ensures an increment of the ORC design power output up to 41% when utilizing the jacket cooling water as heat source.

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Prospects of the use of nanofluids as working fluids for organic Rankine cycle power systems

The search of novel working fluids for organic Rankine cycle power systems is driven by the recent regulations imposing additional phase-out schedules for substances with adverse environmental characteristics. Recently, nanofluids (i.e. colloidal suspensions of nanoparticles in fluids) have been suggested as potential working fluids for organic Rankine cycle power systems due to their enhanced thermal properties, potentially giving advantages with respect to the design of the components and the cycle performance. Nevertheless, a number of challenges concerning the use of nanofluids must be investigated prior to their practical use. Among other things, the trade-off between enhanced heat transfer and increased pressure drop in heat exchangers, and the impact of the nanoparticles on the working fluid thermophysical properties, must be carefully analyzed. This paper is aimed at evaluating the prospects of using nanofluids as working fluids for organic Rankine cycle power systems. As a preliminary study, nanofluids consisting of a homogenous and stable mixture of different nanoparticles types and a selected organic fluid are simulated on a case study organic Rankine cycle unit for waste heat recovery. The impact of the nanoparticle type and concentration on the heat exchangers size, with respect to the reference case, is analyzed. The results indicate that the heat exchanger area requirements in the boiler decrease around 4 % for a nanoparticle volume concentration of 1 %, without significant differences among nanoparticle types. The pressure drop in the boiler increases up to 18 % for the same nanoparticle concentration, but this is not found to impact negatively the pump power consumption.

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Scopus rating (2015): CiteScore 0.92 SJR 0.359 SNIP 0.562
BFI (2014): BFI-level 1
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Scopus rating (2012): CiteScore 1.08 SJR 0.411 SNIP 0.55
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Scopus rating (2010): SJR 0.416 SNIP 0.91
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An assessment of in-tube flow boiling correlations for ammonia-water mixtures and their influence on heat exchanger size

Heat transfer correlations for pool and flow boiling are indispensable for boiler design. The correlations for predicting in-tube flow boiling heat transfer of ammonia-water mixtures are not well established in the open literature and there is a lack of experimental measurements for the full range of composition, vapor qualities, fluid conditions, etc. This paper presents a comparison of several flow boiling heat transfer prediction methods (correlations) for ammonia-water mixtures. Firstly, these methods are reviewed and compared at various fluid conditions. The methods include: (1) the ammonia-water specific flow boiling correlations from the open literature, (2) the ammonia-water specific pool boiling correlations from the open literature extended to flow boiling by using the pure fluid correlation by Gungor and Winterton, and (3) the classical wide-boiling correlations. Secondly, their influence on the required heat exchanger size (surface area) is investigated during numerical design. For this purpose, two case studies related to the use of the Kalina cycle are considered: a flue gas based heat recovery boiler for a combined cycle power plant and a hot oil based boiler for a solar thermal power plant. The results indicate that the nucleate boiling contribution to flow boiling is small compared to the flow boiling contribution for the investigated conditions. Furthermore, the use of the different flow boiling correlation methods resulted in evaporator size differences within 6% for the heat recovery boiler and 28% for the oil based boiler.

Axial-flow turbines represent a well-established technology for a wide variety of power generation systems. Compactness, flexibility, reliability and high efficiency have been key factors for the extensive use of axial turbines in conventional power plants and, in the last decades, in organic Rankine cycle power systems. In this two-part paper, an overall cycle model and a model of an axial turbine were combined in order to provide a comprehensive preliminary design of the organic Rankine cycle unit, taking into account both cycle and turbine optimal designs. Part A presents the preliminary turbine design model, the details of the validation and a sensitivity analysis on the main parameters, in order to minimize the number of decision variables in the subsequent turbine design optimization. Part B analyzes the application of the combined turbine and cycle designs on a selected case study, which was performed in order to show the advantages of the adopted methodology. Part A presents a one-dimensional turbine model and the results of the validation using two experimental test cases from literature. The first case is a subsonic turbine operated with air and investigated at the University of Hannover. The second case is a small, supersonic turbine operated with an organic fluid and investigated by Verneau. In the first case, the results of the turbine model are also compared to those obtained using computational fluid dynamics simulations. The results of the validation suggest that the model can predict values of efficiency within ± 1.3%-points, which is in agreement with the reliability of classic turbine loss models such as the Craig and Cox correlations used in the present study. Values similar to computational fluid dynamics simulations at the midspan were obtained in the first case of validation. Discrepancy below 12% was obtained in the estimation of the flow velocities and turbine geometry. The
values are considered to be within a reasonable range for a preliminary design tool. The sensitivity analysis on the turbine model suggests that two of twelve decision variables of the model can be disregarded, thus further reducing the computational requirements of the optimization.

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Combined Turbine and Cycle Optimization for Organic Rankine Cycle Power Systems—Part B: Application on a Case Study

Organic Rankine cycle (ORC) power systems have recently emerged as promising solutions for waste heat recovery in low- and medium-size power plants. Their performance and economic feasibility strongly depend on the expander. The design process and efficiency estimation are particularly challenging due to the peculiar physical properties of the working fluid and the gas-dynamic phenomena occurring in the machine. Unlike steam Rankine and Brayton engines, organic Rankine cycle expanders combine small enthalpy drops with large expansion ratios. These features yield turbine designs with few highly-loaded stages in supersonic flow regimes. Part A of this two-part paper has presented the implementation and validation of the simulation tool TURAX, which provides the optimal preliminary design of single-stage axial-flow turbines. The authors have also presented a sensitivity analysis on the decision variables affecting the turbine design. Part B of this two-part paper presents the first application of a design method where the thermodynamic cycle optimization is combined with calculations of the maximum expander performance using the mean-line design tool described in part A. The high computational cost of the turbine optimization is tackled by building a model which gives the optimal preliminary design of an axial-flow turbine as a function of the cycle conditions. This allows for estimating the optimal expander performance for each operating condition of interest. The test case is the preliminary design of an organic Rankine cycle turbogenerator to increase the overall energy efficiency of an offshore platform. For an increase in expander pressure ratio from 10 to 35, the results indicate up to 10% point reduction in expander performance. This corresponds to a relative reduction in net power output of 8.3% compared to the case when the turbine efficiency is assumed to be 80%. This work also demonstrates that this approach can support the plant designer in the selection of the optimal size of the organic Rankine cycle unit when multiple exhaust gas streams are available.

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Forbedring af industrielle processers energieffektivitet
Et dansk forskningsprojekt, THERMCYC, arbejder på at udvikle løsninger, som kan gøre udnyttelsen af overskudsvarme til el- og varmeproduktion økonomisk og teknisk mulig og dermed øge industriens bæredygtighed.

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For zeotropic mixtures, the temperature varies during phase change, which is opposed to the isothermal phase change of pure fluids. The use of such mixtures as working fluids in organic Rankine cycle power plants enables a minimization of the mean temperature difference of the heat exchangers, which is beneficial for cycle performance. On the other hand, larger heat transfer surface areas are typically required for evaporation and condensation when zeotropic mixtures are used as working fluids. In order to assess the feasibility of using zeotropic mixtures, it is, therefore, important to consider the additional costs of the heat exchangers. In this study, we aim at evaluating the economic feasibility of zeotropic mixtures compared to pure fluids. We carry out a multi-objective optimization of the net power output and the component costs for organic Rankine cycle power plants using low-temperature heat at 90 °C to produce electrical power at around 500 kW. The primary outcomes of the study are Pareto fronts, illustrating the power/cost relations for R32, R134a and R32/R134a (0.65/0.35 mole). The results indicate that R32/R134a is the best of these fluids, with 3.4 % higher net power than R32 at the same total cost of 1200 k$. 

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Optimization of Cycle and Expander Design of an Organic Rankine Cycle Unit using Multi-Component Working Fluids

Organic Rankine cycle (ORC) power systems represent attractive solutions for power conversion from low temperature heat sources, and the use of these power systems is gaining increasing attention in the marine industry. This paper proposes the combined optimal design of cycle and expander for an organic Rankine cycle unit utilizing waste heat from low temperature heat sources. The study addresses a case where the minimum temperature of the heat source is constrained and a case where no constraint is imposed. The former case is the waste heat recovery from jacket cooling water of a marine diesel engine onboard a large ship, and the latter is representative of a low-temperature geothermal, solar or waste heat recovery application. Multi-component working fluids are investigated, as they allow improving the match between the temperature profiles in the heat exchangers and, consequently, reducing the irreversibility in the ORC system. This work considers mixtures of R245fa/pentane and propane/isobutane. The use of multi-component working fluids typically results in increased heat transfer areas and different expander designs compared to pure fluids. In order to properly account for turbine performance and design constraints in the cycle calculation, the thermodynamic cycle and the turbine are optimized simultaneously in the molar composition range of each mixture. Such novel optimization approach enables one to identify to which extent the cycle or the turbine behaviour influences the selection of the optimal solution. It also enables one to find the composition for which an optimal compromise between cycle and turbine performance is achieved. The optimal ORC unit employs pure R245fa and provides approximately 200 kW when the minimum hot fluid temperature is constrained. Conversely, the mixture R245fa/pentane (0.5/0.5) is selected and provides approximately 444 kW when the hot fluid temperature is not constrained to a lower value. In both cases, a compact and efficient turbine can be manufactured.
Thermoeconomic optimization of a Kalina cycle for a central receiver concentrating solar power plant

Concentrating solar power plants use a number of reflecting mirrors to focus and convert the incident solar energy to heat, and a power cycle to convert this heat into electricity. This paper evaluates the use of a high temperature Kalina cycle for a central receiver concentrating solar power plant with direct vapour generation and without storage. The use of the ammonia-water mixture as the power cycle working fluid with non-isothermal evaporation and condensation presents the potential to improve the overall performance of the plant. This however comes at a price of requiring larger heat exchangers because of lower thermal pinch and heat transfer degradation for mixtures as compared with using a pure fluid in a conventional steam Rankine cycle, and the necessity to use a complex cycle arrangement. Most of the previous studies on the Kalina cycle focused solely on the thermodynamic aspects of the cycle, thereby comparing cycles which require different investment costs. In this study, the economic aspect and the part-load performance are also considered for a thorough evaluation of the Kalina cycle. A thermoeconomic optimization was performed by minimizing the levelized cost of electricity. The different Kalina cycle simulations resulted in the levelized costs of electricity between 212.2 $ MWh$^{-1}$ and 218.9 $ MWh$^{-1}$. For a plant of same rated capacity, the state-of-the-art steam Rankine cycle has a levelized cost of electricity of 181.0 $ MWh$^{-1}. Therefore, when considering both the thermodynamic and the economic perspectives, the results suggest that it is not beneficial to use the Kalina cycle for high temperature concentrating solar power plants.
Working fluid selection for organic Rankine cycles - Impact of uncertainty of fluid properties

This study presents a generic methodology to select working fluids for ORC (Organic Rankine Cycles) taking into account property uncertainties of the working fluids. A Monte Carlo procedure is described as a tool to propagate the influence of the input uncertainty of the fluid parameters on the ORC model output, and provides the 95%-confidence interval of the net power output with respect to the fluid property uncertainties. The methodology has been applied to a molecular design problem for an ORC using a low-temperature heat source and consisted of the following four parts: 1) formulation of process models and constraints 2) selection of property models, i.e. Penge Robinson equation of state 3) screening of 1965 possible working fluid candidates including identification of optimal process parameters based on Monte Carlo sampling 4) propagating uncertainty of fluid parameters to the ORC net power output. The net power outputs of all the feasible working fluids were ranked including their uncertainties. The method could propagate and quantify the input property uncertainty of the fluid property parameters to the ORC model, giving an additional dimension to the fluid selection process. In the given analysis 15 fluids had an improved performance compared to the base case working fluid.

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Design and optimization of a novel organic Rankine cycle with improved boiling process

In this paper we present a novel organic Rankine cycle layout, named the organic split-cycle, designed for utilization of low grade heat. The cycle is developed by implementing a simplified version of the split evaporation concept from the Kalina split-cycle in the organic Rankine cycle in order to improve the boiling process. Optimizations are carried out for eight hydrocarbon mixtures for hot fluid inlet temperatures at 120 °C and 90 °C, using a genetic algorithm to determine the cycle conditions for which the net power output is maximized. The most promising mixture is an isobutane/pentane mixture which, for the 90 °C hot fluid inlet temperature case, achieves a 14.5% higher net power output than an optimized organic Rankine cycle using the same mixture. Two parameter studies suggest that optimum conditions for the organic split-cycle are when the temperature profile allows the minimum pinch point temperature difference to be reached at two locations in the boiler. Compared to the transcritical organic Rankine cycle, the organic split-cycle improves the boiling process without an entailing increase in the boiler pressure, thus enabling an efficient low grade heat to power conversion at low boiler pressures.
Design of organic Rankine cycle power systems accounting for expander performance

Organic Rankine cycle power systems have recently emerged as promising solutions for waste heat recovery in low- and medium-size power plants. Their performance and economic feasibility strongly depend on the expander. Its design process and efficiency estimation are particularly challenging due to the peculiar physical properties of the working fluid and the gasdynamic phenomena occurring in the machine. Unlike steam Rankine and Brayton engines, organic Rankine cycle expanders have to deal with small enthalpy drops and large expansion ratios. These features yield turbine designs with few highly-loaded stages in supersonic flow regimes. This paper proposes a design method where the conventional cycle analysis is combined with calculations of the maximum expander performance using a validated mean-line design tool. The high computational cost of the turbine optimization is tackled building a model which gives the optimal preliminary design of the turbine as a function of the cycle conditions. This allows to estimate the optimal expander performance for each operating condition of interest. The test case is the preliminary design of an organic Rankine cycle turbogenerator to increase the overall energy efficiency of an offshore platform. The analysis of the results obtained using a constant turbine efficiency and the method proposed in this paper indicates a maximum reduction of the expander performance of 10% points for pressure ratios between 10 and 35. This work also demonstrates that this approach can support the plant designer on deciding the optimal size of the organic Rankine cycle unit when multiple exhaust gas streams are available.

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Design of organic Rankine cycles using a non-conventional optimization approach

The organic Rankine cycle is a suitable technology for utilizing low grade heat for electricity production. Compared to the traditional steam Rankine cycle, the organic Rankine cycle is beneficial, since it enables the choice of a working fluid which performs better than steam at low heat input temperatures and at low power outputs. Selecting the process layout of the organic Rankine cycle and the working fluid are two key design decisions which are critical for the thermodynamic and economic performance of the cycle. The prevailing approach used in the design and optimization of organic Rankine cycles is to model the heat exchangers by assuming a fixed minimum temperature difference. The objective of this work is to assess the applicability of this conventional optimization approach and a non-conventional optimization approach. In the non-conventional optimization approach a total UA-value (the product of the overall heat transfer coefficient and the heat transfer area) is assigned to the cycle, while the distribution of this total UA-value to each of the heat exchangers is optimized. Optimizations are carried out for three different marine engine waste heat sources at temperatures ranging from 90 °C to 285 °C. The results suggest that the conventional optimization approach is not suitable for estimating the performance potential when the temperature profiles in the heat exchangers are closely matched. This is exemplified for the fluid MDM where the temperature profile of preheating aligns with the heat source fluid and for the zeotropic mixture R32/R134a where the temperature profile of condensation aligns with the cooling water. Furthermore, the conventional optimization approach shows weaknesses in evaluating the feasibility of using a recuperator, when the expander outlet temperature is high. In these cases the non-conventional optimization approach is the more suited methodology for designing organic Rankine cycles.

Economic optimization of a Kalina cycle for a parabolic trough solar thermal power plant

The Kalina cycle has recently seen increased interest as a replacement for the more traditional steam Rankine cycle for geothermal, solar, ocean thermal energy conversion and waste heat recovery applications. The Kalina cycle uses a mixture of ammonia and water as the working fluid. The ammonia-water mixture evaporates and condenses with a temperature glide, thus providing a better match with the heat source/sink temperature profile. This better match results in reduced thermal irreversibility, but at the cost of relatively larger heat exchanger areas. The parabolic trough collector is the most mature technology for the conversion of solar thermal energy into electricity. In this paper, a Kalina cycle and a steam Rankine cycle are compared in terms of the total capital investment cost for use in a parabolic trough solar thermal power plant without storage. In order to minimize the total capital investment cost of the Kalina cycle power plant (the solar field plus the power cycle), an optimization was performed by varying the turbine outlet pressure, the separator inlet temperature and the separator inlet ammonia mass fraction. All the heat exchangers were modelled as shell and tube type using suitable heat transfer correlations, and appropriate cost functions were used to estimate the costs for the various plant components. The optimal capital investment costs were determined for several values of the turbine inlet ammonia mass fraction and among the compared cases, the Kalina cycle has the minimum capital investment cost of 5851.2 United States Dollars (USD) per kW of net electrical power output. The steam Rankine cycle has much higher investment costs (7625.1 USD/kW) mainly due to the limitation imposed by the minimum turbine outlet vapour quality constraint.
Mapping of low temperature heat sources in Denmark

Low temperature heat sources are available in many applications, ranging from waste heat from industrial processes and buildings to geothermal and solar heat sources. Technical advancements, such as heat pumps with novel cycle design and multi-component working fluids, make the utilisation of many of those heat sources feasible. In this work a mapping of those heat sources is performed to gain an overview of the potential amount of waste heat and natural heat sources in Denmark. The energy potentials are mapped together with the temperature ranges at which the heat is available and the exergy content of the heat. The mapping is based on data and literature primarily published by Statistics Denmark and the Danish Energy Agency, as well as interviews with specialists and engineering estimates. The results indicate that up to 13 % of the energy input to the analysed sectors is available as waste heat. The total accessible waste heat potential is found to be approximately 266 PJ per year with 58 % of it below 100 °C. In the natural heat category, temperatures below 20 °C originate from ambient air, sea water and shallow geothermal energy, and temperatures up to 100 °C are found for solar and deep geothermal energy. The theoretical solar thermal potential alone would be above 500 PJ per year. For the development of advanced thermodynamic cycles for the integration of heat sources in the Danish energy system, several areas of interest are determined. In the maritime transport sector a high potential is found in exhaust gases, where also high temperatures are present. Also the industry sector has a large waste heat recovery potential from refrigeration and cooling processes, however at much lower temperatures.

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Multi-objective optimization of organic Rankine cycle power plants using pure and mixed working fluids

For zeotropic mixtures, the temperature varies during phase change, which is opposed to the isothermal phase change of pure fluids. The use of such mixtures as working fluids in organic Rankine cycle power plants enables a minimization of the mean temperature difference of the heat exchangers when the minimum pinch point temperature difference is kept fixed. A low mean temperature difference means low heat transfer irreversibilities, which is beneficial for cycle performance, but it also results in larger heat transfer surface areas. Moreover, the two-phase heat transfer coefficients for zeotropic mixtures are usually degraded compared to an ideal mixture heat transfer coefficient linearly interpolated between the pure fluid values. This entails a need for larger and more expensive heat exchangers. Previous studies primarily focus on the thermodynamic benefits of zeotropic mixtures by employing first and second law analyses. In order to assess the feasibility of using zeotropic mixtures, it is important to consider the additional costs of the heat exchangers. In this study, we aim at evaluating the economic feasibility of zeotropic mixtures compared to pure fluids. We carry out a multi-objective optimization of the net power output and the component costs for organic Rankine cycle power plants using low-temperature heat at 90°C to produce electrical power at around 500 kW. The primary outcomes of the study are Pareto fronts, illustrating the power/cost relations for R32, R134a and R32/R134a(0.65/0.35 mole). The results indicate that R32/134a is the best of these fluids, with 3.4% higher net power than R32 at the same total cost of 1200 k$.

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Part-load performance of a high temperature Kalina cycle

The Kalina cycle has recently seen increased interest as an alternative to the conventional steam Rankine cycle. The cycle has been studied for use with both low and high temperature applications such as geothermal power plants, ocean thermal energy conversion, waste heat recovery, gas turbine bottoming cycle, and solar power plants. The high temperature cycle layouts are inherently more complex than the low temperature layouts due to the presence of a distillation-condensation subsystem, three pressure levels, and several heat exchangers. This paper presents a detailed approach to solve the Kalina cycle in part-load operating conditions for high temperature (a turbine inlet temperature of 500 °C) and high pressure (100 bar) applications. A central receiver concentrating solar power plant with direct vapour generation is considered as a case study where the part-load conditions are simulated by changing the solar heat input to the receiver. Compared with the steam Rankine cycle, the Kalina cycle has an additional degree of freedom in terms of the ammonia mass fraction which can be varied in order to maximize the part-load efficiency of the cycle. The results include the part-load curves for various turbine inlet ammonia mass fractions and the fitted equations for these curves.

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Performance analysis of solar driven organic Rankine cycle using multi-component working fluids

Among the different renewable sources of energy, solar power could play a primary role in the development of a more sustainable electricity generation system. While large scale concentrated solar power plants based on the steam Rankine cycle have already been proved to be cost effective, research is still under progress for small scale low temperature solar-driven power plants. The steam Rankine cycle is suitable for high temperature applications, but its efficiency drastically decreases as the heat source temperature drops. In these cases a much more promising configuration is the organic Rankine cycle. The purpose of this paper is to optimize a low temperature organic Rankine cycle tailored for solar applications. The objective of the optimization is the maximization of the solar to electrical efficiency and the optimization parameters are the working fluid and the turbine inlet temperature and pressure. Both pure fluids and binary mixtures are considered as possible working fluids and thus one of the primary aims of the study is to evaluate whether the use of multi-component working fluids might lead to increased solar to electrical efficiencies. The considered configuration includes a solar field made of parabolic trough collectors and a recuperative organic Rankine cycle. Pressurized water is selected as heat transfer fluid and its maximum temperature is fixed to 150°C. The target power output for the plant is 100 kW. A part load analysis is carried out in order to define the most suitable control strategy and both the overall annual production and the average solar to electrical efficiency are estimated with an annual simulation. The results suggest that the introduction of binary working fluids enables to increase the solar system performance both in design and part-load operation.
Performance of ORC turbogenerators using zeotropic mixtures

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Selection and optimization of pure and mixed working fluids for low grade heat utilization using organic Rankine cycles

We present a generic methodology for organic Rankine cycle optimization, where the working fluid is included as an optimization parameter, in order to maximize the net power output of the cycle. The method is applied on two optimization cases with hot fluid inlet temperatures at 120°C and 90°C. Pure fluids and mixtures are compared to see how mixed working fluids affect performance and important design parameters. The results indicate that mixed working fluids can increase the net power output of the cycle, while reducing the pressure levels. The maximum net power output is obtained by fluids with a critical temperature close to half of the hot fluid inlet temperature. For some mixtures we find the maximum net power when the temperature glide of condensation matches the temperature increase of the cooling water, while for other mixtures there are large differences between these two parameters. Ethane is a fluid that obtains a large net power increase when used in mixtures. Compared to pure ethane, an optimized ethane/propane mixture attains a 12.9% net power increase when the hot fluid inlet temperature is 120°C and a 11.1% net power increase when the hot fluid inlet temperature is 90°C.

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Utilization of low temperature heat for environmentally friendly electricity production

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Utilization of low temperature heat for environmentally friendly electricity production
The focus on reduction of fossil fuelled electricity generation has increased the attention on exploitation of low grade heat as the energy source for electricity producing power plants. Low grade heat is heat, which is available at a low temperature, e.g. from waste heat from marine diesel engines and industrial processes or from geothermal and solar heat sources. Utilization of such heat sources makes it possible to produce electricity with no additional burning of fossil fuel, and does therefore represent an environmentally friendly alternative to fossil fuel based electricity production. Utilization of low grade heat is not feasible with conventional steam Rankine cycles (steam engines) due to undesirable properties of steam. Instead the organic Rankine cycle is typically used, since it enables the choice of a working fluid, e.g. hydrocarbons or refrigerants, with desirable properties. One of the key issues for improving the performance of organic Rankine cycles is to optimize the heat transfer processes for adding and removing heat from the cycle, which can be achieved by employing a working fluid consisting of a mixture of two or a number of pure fluids. This project is aimed at quantifying the benefits of using mixtures compared to pure fluids as working fluids in organic Rankine cycles. In order to do so, thermodynamic and economic analyses are carried out, first on an overall cycle level, and next on component level including detailed modelling of heat exchangers, pumps and expanders involving project collaborators with expertise in these areas. In addition to this, novel innovative cycle layouts are developed with the aim of increasing the economic feasibility of utilizing low temperature heat. As an example, this can be achieved by implementing separators in the power cycle to create optimal variations in mixture composition throughout the cycle (equivalent of combining a power cycle with a distillation process). In collaboration with DTU Chemical Engineering, a search for novel pure fluids and mixtures are initiated in order to develop working fluids that are tailored for maximizing the profitability of the power cycles; both the organic Rankine cycle and the novel power cycles.

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Projects:

PilotORC: Organic Rankine cycle unit for waste heat recovery on ships
PilotORC is aimed at evaluating the technical and economic feasibility of using an organic Rankine cycle (ORC) unit for recovering low-temperature waste heat on container vessels. The project includes numerical analyses and a demonstration of a 110 kW ORC unit utilizing the waste heat of the main engine cooling system on-board one of Maersk's
container vessels. The retro-fitting potential and the matureness of using ORC units for maritime applications will be evaluated. The project is funded by the Danish Maritime Fund and A.P. Moeller - Maersk.

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01/09/2015 → 28/02/2017
Collaborators: Maersk Group
Documents:
Final_Report_PilotORC
Project: Research

Improvement of heat transfer processes in power cycles utilizing low grade heat
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Elmegaard, B., Supervisor, Department of Mechanical Engineering
Kærn, M. R., Supervisor, Department of Mechanical Engineering

Samfinansieret - Andet
01/09/2014 → 01/03/2019
Award relations: Improvement of heat transfer processes in power cycles utilizing low grade heat
Project: PhD

THERMCYC: Advanced thermodynamic cycles utilising low-temperature heat sources

Energy sources at a low temperature level are available from a variety of sources ranging from waste heat from ships, industry and refrigeration plants, to renewable energy in the form of biomass, geothermal and solar. There is significant potential for improving the use of these sources in developing new cycles based on new multi-component fluid mixtures. These improvements will not only increase the efficiency of today's technology, but they will also make it possible to use low-temperature sources which, due to lack of technical feasibility or economy is not used today. This ambitious, interdisciplinary project will lead the way to innovative thermal systems for electricity generation, heat pumping and cooling by utilization of low value sources, at efficiencies that surpass today's level significantly. The project will develop advances in the design of both processes and media so that energy savings of 15% can be achieved. The analysis will include numerical simulation and advanced thermodynamic methods based on energy and exergy analysis and experimental verification of component performance. The development of a systematic approach to the optimization of cycle and the working medium in the given application. The results will provide a scientific basis for choosing the future use of low-temperature resources in Denmark. This may contribute significantly to the development of the future society using no fossil resources, but large amounts of fluctuating renewable energy.

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Collaborators: Maersk Group, Technical University of Munich, Danfoss AS, Arla Foods, Alfa Laval AB, MAN Diesel and Turbo, Viegand Maagée A/S, Delft University of Technology, Alfa Laval Copenhagen A/S, Aalborg University, Danish Technological Institute
Project: Research