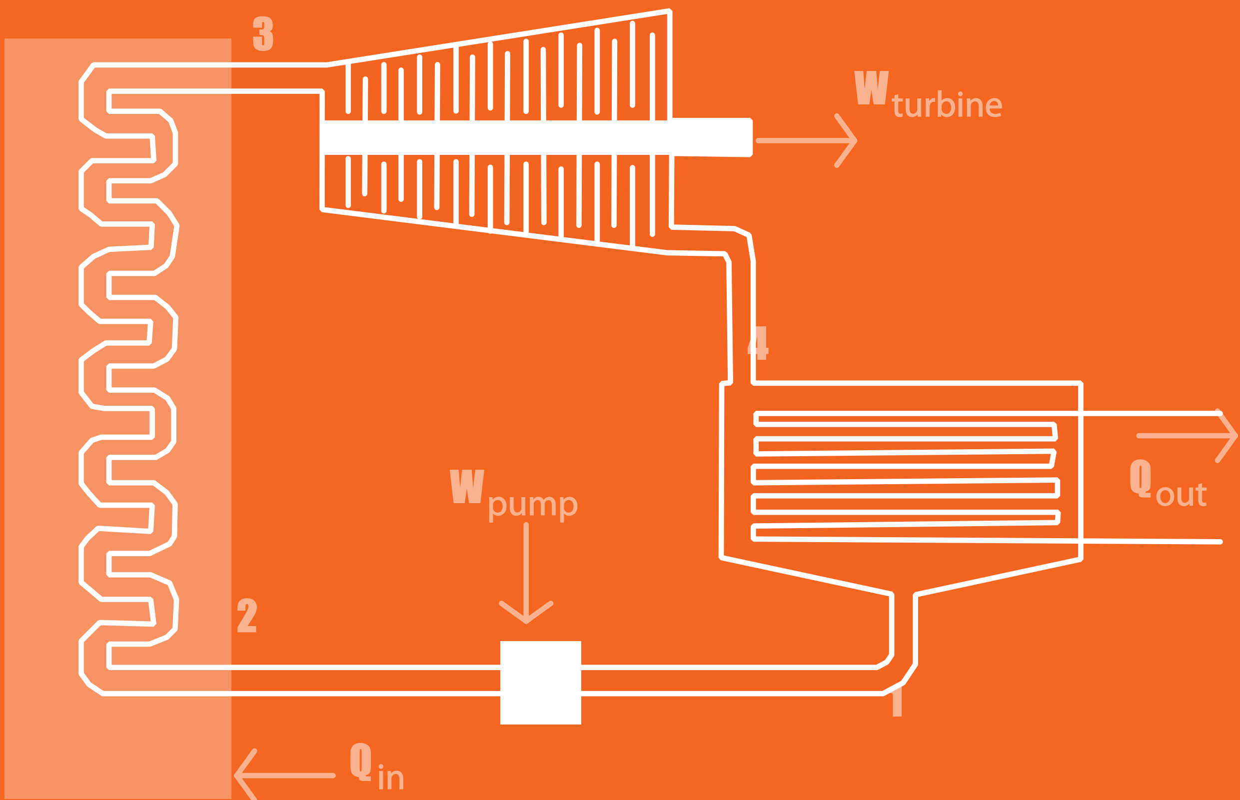
2011

ORC

1st International Seminar on ORC Power Systems

In memory of Prof. Gianfranco Angelino



program & abstracts

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PREFACE

The idea of organizing an international conference on ORC technology has been in the air for quite some time, and I am very glad things came finally together. I am very grateful to all the people who decided to join in and contributed in various ways: You have made it a success even before ORC 2011 starts!

The number of participants is much higher than anticipated, and they are coming literally from all over the world. Academia and industry are equally represented, and the abstracts collected in this booklet testify to the liveliness of research and development in this field, and how quickly and steadily ORC technology is growing. ORC is arguably the best technology for the conversion of renewable energy sources like solar radiation, biomass combustion/gasification, geothermal reservoirs, and heat recovery. Many other applications are possible, in a power range which spans from a few kilowatts up to a few megawatts for a single unit. The ORC principle is also at the basis of Ocean Thermal Energy Conversion (OTEC), a promising concept for baseload renewable electricity generation.

In this booklet you can find quite a number of examples. The work documented is very diverse and covers system design and optimization, simulation and optimization tools, operational experience, prototypes, experiments, measurement techniques, working fluids, heat exchangers, applications and cycle thermodynamics. Some of these abstracts will evolve into a full paper, which will be published in a special issue of the ASME Journal of Engineering for Gas Turbines and Power, because it has been recognized that much research work on ORC energy systems deserves a proper archival format.

The future for the International Symposium on ORC Power Systems looks very bright, because the technology is needed in order to face the many global energy challenges. A widespread diffusion of ORC power systems has been the hope of the late Prof. Gianfranco Angelino, to whom many in the ORC community are grateful for his major contributions to this field, starting from the early 70's. He inspired many, with his calm, kind and convincing manner, and his ideas paved the way to numerous successful realizations. This conference is wholeheartedly dedicated to him, a great scientist, engineer, and artist.

Prof. Gianfranco Angelino
1938 - 2010

SCIENTIFIC COMMITTEE

Chair
Prof. dr. ir. Piero Colonna
Renewable Energy Systems
Process and Energy Department
Delft University of Technology

Prof. Jaakko Larjola
Fluid Dynamics
Energy Department
Lappeenranta University of Technology

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Turboden Pratt&Whitney

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Manager Aero/Thermo
Danfoss Turbocor

Prof. ir. Jos van Buijtenen
Gas Turbines
Process and Energy Department
Delft University of Technology
&
Director and CTO, Tri-o-gen

GENERAL INFORMATION

Conference Secretariat

The registration desk will be open from 8 AM both days during conference hours. Your hostesses will be Gemma van der Windt (phone: +31 6 27227520) and Marion van den Boer

Meals and Refreshments

Coffee, tea breaks, and light meals at lunch will be served in the Foyer of the Aula Conference Center.

Wireless Internet access

The Wi-fi network can be joined by setting:
Network: TuDelft Congress
Web key: 8rplh

Audio Visual Equipment

All lecture rooms will be equipped with the following:

- 1 slide projector
- 1 Computer (upload your presentation in the break before your session). On Friday you can upload your presentation starting from 8.00 AM. (Please note that it is not possible to use your own laptop)
- 1 Podium microphone or 1 Wireless microphone (lapel mic)
- 1 laser pointer

Public Transport

For public transport you need a so-called “OV chip card” which you can buy at the train station of Delft, the Post offices and in tobacco stores & gift shops. The best website to plan your trip with public transport in the Netherlands is: http://journeyplanner.9292.nl/

Weather & Climate

In September it is fall in The Netherlands (15-18 degrees Celsius is average for this time of year). However, the maritime climate entails variable weather conditions, so be prepared for the some rain.

Currency

The local currency is Euro (divided into 100 cents). International credit cards are accepted all over the Netherlands in department stores, museums and most shops. All major credit cards are accepted in most stores, hotels and restaurants.

Health regulations

No vaccinations are required when entering the Netherlands from any other country.

(Health) Insurance
The organizers cannot be held responsible for injury to conference attendees or for damage to or loss of their personal belongings, regardless of the cause. Attendees are advised to make their own insurance arrangements.

Lost and Found
Lost and found articles may be taken to the conference Registration Desk.

Conference Dinner
The conference dinner will be held on Thursday, September 22nd. A luxurious touring bus will bring you to Rotterdam, where you will enjoy the view of the world's largest harbor in all its glory, while dinner is served on board of a special ship.

The busses will leave from the Aula Conference Centre at 18.00 hrs. and return to Delft at around 23.00 hrs.

More information about the tour of the harbor can be found at:
http://www.spido.nl/#pagina=920

ORC2011
Day 1: Thursday September 22, 2011

08.00	Arrival, Registration, Coffee/Tea				
Plenary Session (Auditorium)					
09.00	**Welcome speech by the Conference Chair Prof. Piero Colonna**				
09.10	**Keynote of Prof. M. Gaia:** *Thirty years of organic Rankine cycle development*				
09.40	**Break in the Foyer**				
Parallel Sessions					
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Simulation and Design Tools		**System Design, Optimization and Applications I**		**Operational Experience I**	
Chair: Stefano Rebay		*Chair*: Vincent Lemort		*Chair:* Piero Colonna	
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10.40 Page 3	**GLOBAL ANALYSIS OF ORGANIC RANKINE CYCLES INTEGRATING LOCAL CFD SIMULATIONS AND UNCERTAINTY** *Pietro Marco Congedo, Christophe Corre, Jean-Paul Thibault, Gianluca Iaccarino*	10.40 Page 10	**SUPERCRITICAL ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY AT HIGH TEMPERATURES** *Markus Preißinger, Theresa Weith, Dieter Brüggemann*	10.40 Page 16	**BENEFITS OF USING HIGH TEMPERATURE ORC-MODULES FOR ELECTRICITY-ONLY APPLICATIONS** *Hartmut Kiehne*

11.00	**Mini Break**				
Parallel Sessions					
Auditorium		**Senaatszaal**		**Frans van Hasseltzaal**	
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Chair: Francesco Casella		*Chair*: Vincent Lemort		*Chair:* Piero Colonna	
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11.30 Page 6	**DYNAMIC MODELLING AND OPTIMIZED MODEL PREDICTIVE CONTROL STRATEGIES FOR THE ORGANIC RANKINE CYCLE** *Vincent Lemort, Sylvain Quoilin, Sébastien Declaye, Assaad Zoughaib*	11.30 Page 12	**EVALUATION OF THE TECHNICAL FEASABILITY, ENERGY PERFORMANCE AND ECONOMICAL PROFITABILITY OF AN ORC-BASED MICRO-CHP SYSTEM INVOLVING A HERMETIC SCROLL EXPANDER** *Jean-François Oudkerk, Sylvain Quoilin, Vincent Lemort*	11.30 Page 18	**BACKGROUND AND SUMMARY OF COMMERCIAL ORC** *Antti Uusitalo, Jaakko Larjola, Teemu Turunen-Saaresti*
11.50 Page 7	**SHAPE OPTIMIZATION OF AN ORC RADIAL TURBINE NOZZLE** *David Pasquale, Antonio Ghidoni, Stefano Rebay*	11.50 Page 13	**OPTIMUM CONDITIONS OF A CARBON DIOXIDE TRANSCRITICAL POWER CYCLE FROM LOW TEMPERATURE HEAT SOURCE FOR POWER GENERATION** *Fredy Velez, José J. Segovia, M. Carmen Martín, Gregorio Antolin, Cecilia Sanz, Farid Chejne*	11.50 Page 19	**ORGANIC RANKINE CYCLES FOR GEOTHERMAL APPLICATIONS** *Asaf Mendelovitz*
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18.00	**Departure to from the Aula to Conference dinner**				

ORC2011
Day 2: Friday September 23, 2011

08.00	Arrival, Registration, Coffee/Tea
	Plenary Session (Auditorium)
08.30	**Keynote of Dr. J. Brasz**; *Low temperature / small capacity ORC system development*

Parallel Sessions

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10.40 Page 62	**EXPERIMENT OF PUMPLESS ORGANIC RANKINE-TYPE CYCLE FOR LOW-TEMPERATURE WASTE HEAT RECOVERY** *Noboru Yamada, Masataka Watanabe, Akira Hoshi*	10.40 Page 71	**SIMULTANEOUS OPTIMIZATION OF CYCLE AND HEAT EXCHANGER PARAMETERS FOR WASTE HEAT TO POWER CONVERSION AT ALUMINIUM PLANTS** *Trond Andresen, Yves Ladam, Petter Nekså*

11.00	**Break in the Foyer**		
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Operational Experience II		**Systems Design, Optimization and Applications III**	
Chair: Ennio Macchi		*Chair*: Steven Wright	
11.20 Page 72	**RANKINE CYCLE PLANT DESIGNS FOR WASTE HEAT RECOVERY** *Jean Gropper*	11.20 Page 77	**DESIGN SIMULATION AND CONSTRUCTION OF A TEST RIG FOR ORGANIC VAPOURS** *Andrea Spinelli, Matteo Pini, Vincenzo Dossena, Paolo Gaetani, Francesco Casella*
11.40 Page 74	**ORGANIC RANKINE CYCLE FOR SOLAR APPLICATIONS** *Asaf Mendelovitz* **THE**	11.40 0 Page 79	**EXERGOECONOMIC ANALYSIS OF A GEOTHERMAL ORGANIC RANKINE CYCLE WITH ZEOTROPIC FLUID MIXTURES** *Florian Heberle, Dieter Brüggemann*
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14.20 Page 85	**PRELIMINARY DESIGN OF ORC TURBOGENERATORS FOR WASTE-HEAT RECOVERY IN AUTOMOTIVE APPLICATIONS** *Wolfgang Lang, Piero Colonna, Raimund Almbauer*	14.20 Page 90	**HIGH-POTENTIAL WORKING FLUIDS FOR NEXT-GENERATION BINARY ORC** *Anna Lis Laursen, Pierre Huck*
14.40 Page 86	**PRELIMINARY DESIGN OF A LJUNGSTROM-LIKE CENTRIFUGAL TURBINE FOR ORC APPLICATIONS** *Emiliano Casati, Matteo Pini, Giacomo Persico, Andrea Spinelli, Vincenzo Dossena*	14.40 Page 91	**A FAST TWO-STEP EVALUATION OF FLUIDS FOR MICRO ORC-CHP SYSTEMS WITH VARYING RETURN FLOW TEMPERATURES** *Andreas Grill, Richard Aumann, Andreas Schuster, Jens-Patrick Springer*
15.00 Page 88	**MICRO-COGENERATION BASED ORGANIC RANKINE CYCLE (ORC) SYSTEM IN A DISTRICT HEATING NETWORK: A CASE STUDY OF THE LAUSANNE CITY SWIMMING POOL** *Malick Kane*	15.00 Page 92	**HEAT TRANSFER FLUIDS - EXTENDED FLUID LIFE AND IMPROVED PLANT SAFETY THROUGH HTF SYSTEM DESIGN AND MONITORING** *Matthias Schopf, Guillermo Botti*
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Heat Exchangers		**Cycle Efficiency**	
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16.40 Page 97	**EFFICIENCY IMPROVEMENT IN PRE-COMBUSTION CO2 REMOVAL UNITS WITH A WASTE-HEAT RECOVERY ORC POWER PLANT** *Carsten Trapp, Piero Colonna*	16.40 Page 103	**TO RECUPERATE OR NOT TO RECUPERATE - ORC CYCLES COMPARED TO IDEAL CYCLES** *Pall Valdimarsson*
Plenary Sessions (Auditorium)			
17.00	**Panel Discussion**		
17.30	**Conference Closure**		

MULTI-OBJECTIVE OPTIMIZATION OF AN ORC-BASED BIOMASS COGENERATOR FOR RESIDENTIAL APPLICATIONS

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ABSTRACT

The aim of this work is to present a design method for a CHP (Combined Heat and Power) system based on Organic Rankine Cycle. The procedure is based on the Energy Integration of the thermal streams [1] and leads to a multi-objective optimization of the system. The chosen case study is a micro cogenerator coupled with a biomass boiler sized to satisfy the heat demand of a residential building. A real woody biomass composition has been chosen and analyzed, in order to define reliable flue gases composition and cooling profile [2-4]. The simulated heat load scenarios (for an average-sized house) included stand-alone hot water production, floor heating system water demand and concurrent functioning of both the services. The aim of the procedure is to integrate an ORC in this system, in order to satisfy also a certain part of the electricity demand of the house. The Energy Integration method permits to couple all the streams of the system in order to achieve the Minimum Energy Requirement (MER) from the hot source for the given values of the output streams. The main variables of the cycle (i.e. the maximum and the minimum temperatures and the rated mechanical power) was the optimization variables: the two chosen objectives was the maximization of the exergetic performances of the system and the concurrent minimization of the evaporation pressure, always keeping the first law efficiency at its best value. The Pareto curves for different working fluids in each considered scenario have been compared, in order to find the best ones suitable for the studied application. Finally, the best system configurations in each scenario have been compared and a trade-off between them has been found: in particular, the multi-objective optimization presented in this work allowed to take decisions on the working fluid and on the Organic Rankine Cycle size and parameters.

REFERENCES

[1] I. C. Kemp, Pinch Analysis and Process Integration, 2^{nd} Edition, Butterworth-Heinemann, 2007.

[2] M. Gassner and F. Maréchal, "Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass", Biomass Bioenergy, Vol. 33, pp. 1587-1604, (2009).

[3] D. R. Morris, J. Szargut, "Standard chemical exergy of some elements and compounds on the planet Earth", Energy, Vol. 11 (8), pp. 733-755, (1986).

[4] K. J. Ptasinski, M. J. Prins, A. Pierik, "Exergetic evaluation of biomass gasification", Energy, Vol. 32 (4), pp. 568-574, (2007).

THREE-DIMENSIONAL RANS SIMULATION OF A HIGH-SPEED ORGANIC RANKINE CYCLE TURBINE

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ABSTRACT

There is a growing interest in organic Rankine cycle (ORC) turbogenerators because of their ability to efficiently utilize external heat sources at low to medium temperature in the small to medium power range. ORC turbines typically feature very high pressure ratios and expand the organic working fluid in the dense-gas thermodynamic region. Performance assessment and design by means of fluid dynamic analysis thus requires CFD solvers coupled with accurate thermodynamic models of the working fluid [1].

As a result of these additional technical challenges and the fact that commercial interest in ORCs has gained only in recent decades, the fluid dynamic design of ORC turbines using CFD has not yet reached the same level of maturity and sophistication as that of steam and gas turbines.

We present a steady-state three-dimensional CFD study of the Tri-O-Gen ORC radial turbine stage operating with toluene. The radial turbine stage consists of the high-expansion radial nozzle, the turbine rotor and the diffuser. They are coupled in the CFD model by adopting a mixing plane interface. The simulation is performed with a commercial Reynolds-averaged Navier-Stokes solver. In order to account for real gas behavior of the expanding working fluid, thermodynamic properties are calculated with the FluidProp library [2], implementing an accurate multiparameter equation of state [3]. A look-up table approach allows the CFD solver to obtain values for thermodynamic and transport properties in a computationally efficient way. Results are analyzed with the aim of providing guidelines for further improving he turbine performance and future work is also briefly discussed.

REFERENCES

[1] J. Harinck, T. Turunen-Saaresti, P. Colonna, S. Rebay, J.P. van Buijtenen, Computational Study of a High-Expansion Ratio Radial ORC Turbine Stator, ASME Journal of Engineering for Gas Turbines and Power, Vol. 132 / 054501, May, 2010.

[2] P. Colonna and T. Van der Stelt. "FluidProp: A program for the estimation of thermophysical properties of fluids", Energy Technology section, Delft University of Technology, The Netherlands (www.fluidprop.com).

[3] Lemmon, E., and Span, R., 2006, "Short Fundamental Equations of State for 20 Industrial Fluids, J. Chem. Eng. Data, 51(3), pp. 785–850.

GLOBAL ANALYSIS OF ORGANIC RANKINE CYCLES INTEGRATING LOCAL CFD SIMULATIONS AND UNCERTAINTY

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ABSTRACT

Organic Rankine Cycles (ORCs) are of key-importance when exploiting energy systems, such as power plants, with a high efficiency. Flexibility with respect to the characteristics of the heat source requires a design fitted to maximize the overall performance. The variability of renewable heat sources makes more complex the global performance prediction of a cycle. The thermodynamic properties of the complex fluids used in the process are another source of uncertainty. The need for a predictive and robust simulation tool of ORCs remains strong.

A finite-volume solver has been recently developed for efficiently computing a turbine stage in ORC applications [1]; it includes advanced equations of state in order to properly take into account the complex fluids classically used in ORCs. The performance of the turbine stage is evaluated by using three criteria computed from the numerical steady solution : the turbine isentropic efficiency, the enthalpy jump and the relative temperature variation. Based on this experience, it is now planned to insert the local approach devoted to the sole turbine stage into a more global analysis of the whole cycle.

This integration of the finely computed turbine stage into a more global cycle analysis will lead us to derive performance indices such as efficiencies based on the first and second laws as well as the net specific work of the cycle. The elements included in this analysis combine fluid properties with cycle working conditions, namely : high and low temperatures and pressures. In this cycle analysis the turbine is the only simulated component but its computed performances depend on the whole cycle conditions (super-heating or not, multistage expansion, etc).

Because of the strong existing sources of uncertainty in ORC cycles, a second objective of this work is to take into account uncertainty quantification (UQ) to increase the reliability of the coupled local/global approach and the robustness of the proposed designs. Several UQ strategies, already used for robust optimization of dense gas airfoils [2] and shock-tube [3], will be taken into account. For the turbine stage design, a parametrization and optimization loop similar to those proposed in [2] will be used. The flexibility of the analysis and its potential to contribute to innovative designs will be assessed on several cycles and working fluids among a selection of those used in the literature.

REFERENCES

[1] P. M. Congedo, P. Cinnella and C. Corre. Numerical investigation of dense-gas effects in turbomachinery. Submitted to Computers & Fluids.

[2] P. M. Congedo, C. Corre and J.-M. Martinez. Shape optimization of an airfoil in a BZT flow with multiple-source uncertainties. Computer Methods in Applied Mechanics and Engineering, Vol. 200, 216{232, 2011.

[3] P. M. Congedo, P. Colonna, C. Corre, J. Witteveen and G. Iaccarino. Robust simulation of nonclassical gas-dynamics phenomena. Proceedings of the Summer Program 2010, Center for Turbulence Research, Stanford, 2010.

DYNAMICS AND CONTROL OF ORC POWER SYSTEMS

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ABSTRACT

Several applications of ORC power systems demand for stringent control requirements. Examples are solar conversion by means of a direct vapour generator [1], heat recovery from automotive engines [2] and operation in island mode, connected to a local grid and local loads, as it would be the case for instance for installations in remote areas of developing countries. In all these cases normal operation is intrinsically dynamic and a suitable control strategy must be implemented. Dynamic models are an indispensable tool to study and optimize the design the control system [3][4]. A dynamic model suitable for ORC power systems and flexible in terms of plant configuration and working fluids is presented. As an example, the model of the Tri-o-gen power unit is obtained by assembling components and modules of the Modelica ThermoPower library linked to the FluidProp package for the calculation of fluid thermophysical properties. Simulation results are validated by comparison with field data obtained from ad hoc experimental runs. A discussion about possible control strategies is briefly outlined.

REFERENCES

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DYNAMIC MODELLING AND OPTIMIZED MODEL PREDICTIVE CONTROL STRATEGIES FOR THE ORGANIC RANKINE CYCLE

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ABSTRACT

The behaviour of the ORC has been extensively studied theoretically and experimentally in the past few years. Most of the proposed ORC models are steady-state models, accounting for stabilized working conditions.

However, some ORC applications are used with inherently variable heat source inputs. The case of heat recovery on internal combustion engines is a good example of varying heat source flow rate and temperature in very short periods of time. ORC cycles coupled to solar applications can also be highly dynamic in the absence of storage since direct radiation can fluctuate quickly depending on the climatic conditions.

Steady-state models are not able to predict the transient behaviour of the cycle with such heat sources, nor can they simulate a proper cycle control strategy during part-load operation or start & stop procedures.

This paper proposes a dynamic model of an ORC by focusing specifically on the dynamic behaviour of the heat exchangers, the dynamics of the other components being of minor importance. The model is developed under the Modelica environment using the TILMedia library for the computation of the working fluid thermodynamic properties. This model is specifically designed to ensure the robustness and the speed of the simulation algorithms:

- Initialization strategies are developed by simplifying the problem at time zero in order to avoid too complex non-linear initial systems of equations.
- Simplified heat transfer laws are proposed based on heat transfer correlations available in the scientific literature.
- Numerical issues such as division by zero are avoided by linearising or limiting to a finite value some thermophysical equations or properties.

The studied system is a small-scale waste heat recovery system using a scroll machine as expansion device. The heat exchangers are plate heat exchangers and the pump is a diaphragm pump. In order to control the system under transient conditions, the set point of the evaporating temperature is optimized using a steady state model and implemented into the control unit, where it is continuously re-adjusted to the optimal value. The two control variables are the superheating at the expander inlet and the evaporating temperature.

Two types of controllers are implemented and compared in terms of performance (seasonal performance of the system), safety (achievement of set points), and robustness: a feedback control strategy based on two PID controllers and a model predictive control strategy (MPC).

The potential of the later controller over classical PID is discussed

SHAPE OPTIMIZATION OF AN ORC RADIAL TURBINE NOZZLE

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ABSTRACT

During the last decade, organic Rankine cycle (ORC) turbogenerators have become very attractive for the conversion of low-temperature heat sources in the small to medium power range. ORCs usually operate in thermodynamic regions characterized by high pressure ratios and strong real-gas effects in the flow expansion, therefore requiring a non-standard turbomachinery design. In this context, due the lack of experience, a promising approach for the design can be based on the intensive use of computational fluid dynamics (CFD) and optimization procedures to investigate a wide range of possible configurations.

In this work an optimization strategy which aims to increase the performance of ORC turbines is presented. The capability of this strategy is demonstrated by analyzing an existing turbine, which is an impulse one-stage radial turbine where a strong shock appears in the stator channel due to the high expansion ratio.

The goal of the optimization is to minimize the total pressure losses produced by the shock and to obtain a uniform anular flow at the stator discharge section, in terms of magnitude and direction of the flow velocity. To achieve this purpose, a global optimization method and a computational fluid dynamic solver are adopted. In particular, the optimization strategy is based on the coupling of a Genetic Algorithm with a surrogate-model (Kriging). The numerical solutions of the two-dimensional Euler equations are computed with the in-house built code zFlow [1]. The working fluid is toluene, whose thermodynamics properties are evaluated by an accurate equation of state, available in FluidProp [2]. The computational grids created during the optimization process have been generated through a fully automated 2D unstructured mesh algorithm based on the advancing-Delaunnay strategy [3].

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MODULAR SUPERCRITICAL ORC TURBOGENERATOR SYSTEM FOR CONCENTRATED SOLAR POWER

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ABSTRACT

Thermodynamic conversion of solar radiation is one of the high-potential solutions to the global energy problem [1]. One of the key issues is the high capital cost and relatively low conversion efficiency of current technology [2]. We are exploring the concept of a small capacity modular (30-50 kWe) system powered by linear solar collectors. Economy of scale can be achieved by large series production. The small footprint makes it suitable for easier delivery and installation and the system is applicable even if only limited surface is available for the solar field. The adoption of the supercritical cycle configuration, which does not pose acute problems in terms of operating pressure and temperature with the adoption of complex molecule working fluids, arguably entails benefits from the efficiency and cost point of view, as well with respect to thermal storage and controllability. Challenges are identified with respect to, among others, the high compression ratio pump and the turbo-expander. A siloxane has been selected as the working fluid. A model of the solar absorber is presented, together with its coupling to the model of the power unit, which is capable of off-design simulations. A preliminary design of the equipment has been performed in order to investigate feasibility. Results of system simulations encompassing a solar year are presented. They lead to the preliminary thermodynamic optimization of the system, which is analyzed and discussed. Future work is briefly outlined.

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COMPARISON OF SCROLL AND PISTON EXPANDERS FOR SMALL SCALE ORC APPLICATIONS

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ABSTRACT

The lack of suitable expanders hinders the use of ORCs (organic Rankine cycle engines) for solar power or waste heat recovery at small (kilowatt) scales. Purpose-built turbomachinery is cost prohibitive at these scales. Positive displacement machines derived from HVAC scroll compressors are generally inexpensive alternatives and are available in various displacements. A drawback of HVAC scrolls as expanders, however, is their inbuilt volume ratio, usually ~3, which is only useful with typical ORC fluids at thermal resource temperatures of ~100°C, i.e. much lower than the potential of concentrating solar and some waste heat sources.

Kane addressed this problem by using modified HVAC scrolls and operating two ORCs in series, driven by solar thermal and diesel exhaust gas at 150°C [1]. This solution has the drawback of requiring the duplication of equipment needed to match the fluid and machine volume ratios. We report here on three alternative approaches using a single ORC operated from a 150°C thermal source and various configurations of positive displacement expanders: a pair of HVAC scrolls in series, an HVAC machine incorporating a purpose-built high volume ratio scroll, and a piston expander.

The compounding of HVAC scroll expanders is greatly facilitated by removing the limitation of asynchronous generation at grid frequencies. Without this constraint, testing at MIT on a 3kWe ORC test bench confirms that HVAC scrolls of suitable displacements can be paired and loaded separately for effective two-stage expansion of the working fluid R245fa to a volume ratio of 9, albeit with the added complexity of recombination of electrical outputs. Starting from the geometric framework of HVAC scrolls [2], we created a new scroll design derived from an examination of the tradeoffs between volume ratio, scroll size, number of turns, and spiral equations for constant and varying wall thicknesses. We also examined the potential of applying the ubiquitous IC engine, reconfigured for two-stroke operation as an expander using redesigned cam profiles to alter the valve gear timing; this approach has the advantage of being low-cost with standard volume ratios of 8-10. For these several approaches machine characteristics were related to a thermodynamic model to derive machine speeds (RPM) at mass flow rates corresponding to a few kilowatts of power output. Sizing, specification, and performance models are developed in Matlab and EES, prototype expanders are designed, and performance characteristics are compared on the MIT 3kWe test system using R245fa at 150°C.

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SUPERCRITICAL ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY AT HIGH TEMPERATURES

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ABSTRACT

Organic Rankine Cycle (ORC) is a state of the art technology in low temperature geothermal applications. Besides, ORC systems are used in biomass fired heat and power plants as well as for waste heat recovery at high temperatures. A promising way to further increase the efficiency of ORC systems is the supercritical mode of operation.

In the present work subcritical and supercritical ORC for waste heat recovery at high temperatures are analyzed. Nine potential working fluids out of three chemical classes (alkanes, alkylbenzenes, siloxanes) are investigated with waste heat temperatures in the range of 633.15 K to 823.15 K and ORC working pressures up to $1.3 \cdot p_{crit}$. Simulations are carried out using Peng-Robinson Equation of State (EOS). In addition, the influence on thermodynamic and plant-specific properties using other EOS are discussed within this work.

Simulations for supercritical octamethyltrisiloxane (OMTS) show an increase in electric net power of more than 5.5 % compared to subcritical process. The gain in electric power of the generator is even higher (8.5 %). However, it is pointed out that the enhancement of electric power is quite sensitive to waste heat temperature. This is also valid for the optimal working pressure in subcritical process in which net power is maximized at a working pressure of 0.58 MPa (0.80 MPa, 1.38 MPa) for heat source temperatures of 633.15 K (663.15 K, 693.15 K).

In addition to thermodynamic analysis further aspects like overall size of the turbine and heat transfer characteristics of the heat exchange equipment have to be considered. Therefore, volume flow rates at turbine inlet and outlet as well as heat transfer coefficients are calculated to allow for a holistic evaluation of supercritical ORC.

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PERFORMANCE ANALYSYS OF HYBRID SOLAR OCEAN PLANTS WITH CLOSED ORC CYCLE

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ABSTRACT

Among the renewable energy sources, Ocean Energy is encountering an increasing interest at present days. Several technologies can be applied in order to convert the ocean energy in electric power: in some areas power is produced by means of ad hoc developed turbines while in the equatorial and tropical belt the temperature difference between surface warm water and deep cold water allows the adoption of an OTEC system. Although the idea is very old (was first proposed in the late eighteen century) no commercial plant has been built. Nevertheless lot of studies are being conducted at present time and several prototypes are under construction. Some of the studies concern hybrid solar-ocean energy plants: in this case the ocean thermal gradient, which is usually comprised in the range 20-25 °C in the favourable belt, can be increased during day time.
The present study performs firstly a review of the state of the art for OTEC plants, and is then focused on a hybrid plant with closed ORC cycle, by investigating the obtainable performance with different suitable working fluids both during day and night operations.

EVALUATION OF THE TECHNICAL FEASABILITY, ENERGY PERFORMANCE AND ECONOMICAL PROFITABILITY OF AN ORC-BASED MICRO-CHP SYSTEM INVOLVING A HERMETIC SCROLL EXPANDER

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ABSTRACT

The Organic Ranking Cycle (ORC) is often considered as a suitable technology for micro Combined Heat and Power (CHP): the ORC unit can indeed be associated with a boiler to produce heat (at the condenser of the cycle) and electricity (at the expander). The advantages of this technology are a high reliability and simple maintenance and a large fuel flexibility because of the external combustion.

For micro-CHP units (i.e a few kWe), scroll machines are often preferred to turbomachines as expansion device because of their low cost, simplicity, low rotating speed and their capacity to handle high pressure ratios. Moreover, scroll compressors do not require much adaption to work in expander mode.

This paper aims to evaluate the performance and profitability of an ORC-based micro-CHP system. It focuses more particularly on the use of a hermetic scroll compressor used as expander in the ORC.

The first part of the paper describes the design and the performance of a prototype of hermetic scroll expander (compressor adapted to work in expander mode), tested into a gas cycle test rig with R245fa as working fluid. A semi empirical model using a limited number of physical meaning parameters is then built and validated with the experimental results.

In the second part of the paper, this model is inserted into an ORC model and coupled with a boiler model. With this global model, three systems configuration are evaluated in term of electrical and thermal efficiencies and the best one is selected.

Once the best configuration is determined, the operation of the system is simulated on a full year in order to evaluate the seasonal performance of the ORC-based micro CHP system.

Using economical criteria such as net present value and levelized electricity cost, the profitability of the system is evaluated. Parametric studies are performed on the profitability varying several parameters like discount rate, price of fuel, subsidies…

Finally, adaptations of the hermetic scroll compressor are proposed to improve the efficiency of the system.

OPTIMUM CONDITIONS OF A CARBON DIOXIDE TRANSCRITICAL POWER CYCLE FROM LOW TEMPERATURE HEAT SOURCE FOR POWER GENERATION

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ABSTRACT

Since that conventional steam power cycles cannot give a better performance to recover low-grade waste heat, and due to with this same purpose, other possible processes such as the Organic Rankine Cycles show the known pinching problem, the use of carbon dioxide in supercritical conditions solves both problems. The present paper aims to report the results obtained after analyzing energetic and exergetically the effect of the inlet turbine pressure on transcritical Rankine cycles using refrigerant carbon dioxide (CO2) as the working fluid, which achieves a variable temperature when heat is added to the working fluid, giving therefore a better fit with the heat source. The procedure for analyzing the behaviour of the proposed cycle has consisted in modifying the turbine input pressure, from 66 bar until the point in which the net work reaches approximately zero, while the inlet turbine temperature is maintained in a constant value of 150 ºC. As a result, the maximum value of the energy efficiency is 8.1% whereas the exergy efficiency has no maximum. On the other hand, while the operation pressure of the process rises, the exergy efficiency also increases.

Keywords:

Carbon dioxide, energy efficiency, exergy efficiency, power generation, waste heat.

HIGH EFFICIENCY (25%) ORC FOR 'POWER ONLY' GENERATION MODE IN THE RANGE 1-3 MWel: AN ALREADY PROVEN TECHNOLOGY ALSO AVAILABLE FOR PARTIALLY COGENERATIVE APPLICATIONS

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ABSTRACT

A new development of ORC technology recently introduced to the market is presented.
This class of high efficiency organic Rankine cycle has been introduced to produce electric energy from medium temperature biomass or heat recovery application in the 1 MW el power range. To obtain an electrical efficiency of about 25 % (net of ORC auxiliaries) the cooling of the condenser is kept as low as reasonably possible using air coolers to cool down water circulating in a closed loop.
Hence these units have been conceived for 'power only' production, i.e. where cogeneration is not required.
A further development of the system has been patented by Turboden to allow for a partial utilization in 'cogeneration mode'. With this implementation it is possible to obtain a fraction of the overall discharged thermal power at a temperature suitable for cogeneration applications (80-90 C), extracting the heat from the ORC unit regenerator.
The paper will describe also this solution and the advantages achievable.

DESIGN, DEVELOPMENT AND OPERATION OF THE TRI-O-GEN ORC POWER UNIT

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ABSTRACT

Starting from 2002, a novel ORC power unit has been developed by Tri-O-Gen B.V. of The Netherlands, based on technology originally defined in Finland (Lappeenranta University of Technology). The development in The Netherlands was strongly supported by the Dutch government (AgentschapNL), involving among others Delft University of Technology and the Dutch National Aerospace Laboratory NLR.

The ORC system is based on a thermally stable hydro-carbon as a working fluid, hence suitable for direct use of intermediate temperature heat sources from 350 C and above.

The core of the unit consists of a combined turbine – generator – pump: the High Speed Turbo-Generator (HTG). Thanks to the use of a high speed generator (26 – 27 krpm), the turbine and pump could be laid out at their optimum specific speed, leading to high internal efficiencies. Moreover, this concept allowed for a seal-less design: no shaft seals are necessary, and the only interaction between the internals and the outside world are flanged connections for the working fluid to enter and exit the HTG and the well-sealed electric cables. Lubrication of bearings and cooling of the generator is taken care of by the working fluid itself, so there is no need for lub-oil and related system. The unit can therefore be considered completely hermetic.

After successful testing of the prototype, the first commercial package was designed (called the WB1), consisting of four modules for turn-key delivery:

- The standard process module, made up of HTG, recuperator, condenser, hot well, pre feed pump, main valve and bypass valve, including connecting piping and instrumentation
- The heat supply module: an evaporator tuned at the conditions of the available heat, to be connected directly to the heat source
- The heat rejection module: the cooling system for the cooling water which cools the condenser, tuned to the need for extra low temperature heat usage or to the local ambient conditions.
- The standard power preparation module, which connects the high speed generator directly to the grid to supply the power at 400 V, 3 phase, 50 or 60 Hz.

Fourteen units are now in commercial operation in different applications, while there are more than 10 units on order. Heat sources vary from exhaust gasses of gas- and diesel engines to landfill gas combustion and wood firing as well as industrial waste heat. This presentation will describe the unique features of the design, such as the hermetically closed turbo generator, the cycle design and the balance of plant. Units are being built as a standard packages for 60 to 165 kWe, being adapted to the heat source by sizing the evaporator. Moreover, current operating experience (more than 50.000 accumulated hours) will be reported on.

BENEFITS OF USING HIGH TEMPERATURE ORC-MODULES FOR ELECTRICITY-ONLY APPLICATIONS

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ABSTRACT

Small capacity combined heat and power (CHP) plants are suitable for efficient energy conversion. CHP is arguably the only way to use fuel or thermal energy optimally, and the only way to optimally use fuel or thermal energy and the only way to operate ORC plants efficiently.

ORC plants for cogeneration are less electrically efficient than plants designed for electricity generation only, as the higher condensation temperature penalizes the thermodynamic cycle. As a result, investors for electricity-only projects demand ORC plants with higher electrical efficiencies, and manufacturers attempt to fulfill this demand with so-called low-condensing temperature ORC plants.

Selecting a suitable ORC fluid can help reducing the condensation temperature and thus increasing the electrical efficiency. However, this rules out cogeneration due to the low condensation temperature. Notably, the assumed improved economy deriving from higher electricity production is often offset by the increased electrical power demand for the condenser cooling.

In low-temperature ORC plants for generating electricity only, the condenser is generally cooled by means of air-water coolers. The lower the temperature difference between the condenser cooling water and the ambient temperature, the more electricity is required for cooling, i.e. the assumed advantage of increased electrical efficiency is compensated by the higher system electricity demand.

The use of so-called low-condensation temperature ORC plants is not advantageous in projects with no heat requirements, as the system electricity requirement can be reduced significantly via higher condensation temperatures, thus achieving higher net electrical efficiency. As ORC plants are often implemented in areas with higher ambient temperatures, a larger temperature difference between the condenser cooling water and the ambient temperature is beneficial.

CLEAN CYCLETM – WASTE-HEAT-RECOVERY TECHNOLOGY

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ABSTRACT

Clean Cycle™, from GE Energy, adapts Organic Rankine Cycle (ORC) technology for the vast majority of smaller-scale heat-wasting processes. Clean Cycle takes waste heat from sources as low as 250°F (121°C) and transforms it into 125 kW of electricity for the renewable and distributed energy segments.

An integrated Power Module (IPM) is the heart of the Clean Cycle system and houses the high speed turbine and generator. Magnetic bearings that support the turbine and rotor facilitate the shaft spinning in a magnetic field rather than riding on a mechanical bearing. The bearings require no lubrication systems, and the entire generator and turbine are hermetically sealed so external seals are not required, either. Clean Cycle's Power Electronics convert the raw power generated at the IPM to usable electricity at the exact same frequency and voltage as the grid to which the IPM is attached -- without gearboxes or other mechanical means. The power generated has a constant power factor of 1, so costly capacitors are not needed.

Clean Cycle can operate in small spaces, be moved from site to site, and accommodate a broad range of facilities, including factories, foundries and cement plants.

To utilize Clean Cycle, waste heat must be exclusively available, with no diversion to other purposes such as heating water. The number of engines determines the type of installation. Customers have the option of installing a collection of smaller engines to combine their accumulated waste heat.

BACKGROUND AND SUMMARY OF COMMERCIAL ORC

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ABSTRACT

The first Organic Rankine Cycle (ORC) power plants were built at the beginning of the 1960s and the principle of ORC process has been known for decades. The majority of the early ORC plants were built between 60's and 80's. Excluding chloro-fluoro-carbons, the most popular working fluids at that time were chlorobenzenes, fluorinol 85 and toluene. Nowadays the most ORC applications are related to produce electricity and heat from biomass, industrial waste heat, geothermal heat and solar power. In the early stages of the commercialization there were only few manufactures and during the 90's and the beginning of millennium only very few ORC plants were realized. However, the interest towards the ORC has been raised recently, and there have been many new manufacturers coming on markets during the last decade. The number of delivered ORC units and installed power worldwide has increased rapidly and several hundred ORC plants have been built during the last decade. Also a wide range of more suitable and environmental friendly working fluids have been adapted for the commercial ORC plants compared to the earliest ORC plants.

The tightening of the greenhouse gas emission regulations have set the goals and the limits for the use of energy efficient processes and better fuel economy in both large and small scale energy production systems. Nowadays, it is very important to decrease CO2 and CH4 emissions having an effect on the global warming. CH4-rich gases, (biogas, landfill gas) produced by the decay of organic material and biomass, can be exploited in distributed electricity and heat production.

Utilizing the waste heat streams from the industrial processes in electricity and heat production is a suitable way to achieve improvements to the energy efficiency of the processes and reducing CO2 emissions. In these kinds of applications the ORC technology is a feasible choice due to its flexible power range and therefore, it is expected that the number of installed ORC plants will increase rapidly in the near future.

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ORGANIC RANKINE CYCLES FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

Many innovative power cycles have been proposed in the past 20 years to widen the range of resources suitable for power generation beyond dry steam and flashed steam plants. During recent history, some (such as Kalina, Bi-Phase, etc.) have been experimented with, but only four are in commercial operation – single and double flash steam cycles, and two configurations of the Organic Rankine Cycle (ORC): the binary power cycle and geothermal combined cycle.

The ORC has become the preferred means of exploiting low- to moderate-enthalpy geothermal and waste heat resources. The system has been widely used to efficiently and reliably utilize the brine in existing single flash geothermal plants, as well as with many other applications in the form of water only or water and low pressure steam.

Over the years, the basic ORC has been improved and modified to adapt the cycle more efficiently to various heat source conditions.

No single thermodynamic cycle provides a "cookie cutter" solution to all low- and medium-enthalpy cases. Adapting and combining the power cycles in the correct manner enables the optimal solution selection for specific resource conditions. An optimum power conversion cycle provides for the maximum output from an available heat source, while maintaining power plant simplicity combined with a high level of reliability.

The optimization of the whole geothermal power plant system is accomplished by matching the working cycle and fluid properties to the characteristics of the resource, in considering not only the resulting efficiency and cost, but also the impact on the environment, the long-term pressure support requirements for make-up wells and the O&M costs.

Operational experience has confirmed the advantages of the ORC plants, not only for the low enthalpy water dominated resources, but also at high enthalpy for aggressive brine or brine with high non condensable gas content. The somewhat higher installed cost of these systems is often justified by environmental and long-term resource management consideration.

This presentation will describe advanced versions of the ORC and demonstrate their ability to provide an efficient conversion cycle adaptable to specific thermal and chemical properties in a wide variety of heat sources.

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SELECTION OF THE OPTIMUM WORKING FLUIDS IN ORC USING FUZZY LOGIC APPROACH

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ABSTRACT

Recent development in ORC has heightened the need for choosing the optimum working fluids which are the heart of the performance of Organic Rankine cycle (ORC). Currently, the working fluid is defined as optimum if it is able fulfils some requirements namely thermodynamic, economic, safety and environment. However, research has consistently shown that no working fluids that able to achieve all those requirements. Therefore, studies continue searching the best strategies for selecting the working fluids. So far, selection methods based on traditional way which are firstly select several working fluids candidate, secondly, set the objective of the studies (net power output, thermal efficiency, irreversibility), lastly, select the working fluid based on maximum or minimum of the objective. This paper seeks to remedy of this trial and error method by fuzzy logic approach which able to filter the near optimum working fluids among the working fluids candidates at very first level. This approach firstly begins with setting a number of working fluids commonly tested by previous study. Secondly, setting up some optimum working fluids rules such as low molecular weight, high latent heat, cheap price, high critical temperature, high flow rate, low volume flow rate, high availability, low boiling point, low global warming potential, low ozone depletion potential, low toxicity, low flammability and low corrosiveness. Next, the working fluids values related to the defined rules are simulated using fuzzy Matlab toolbox. Finally, the result of this simulation is sorted from highest to lowest and the highest value is chosen as the highly recommended working fluid. The highly recommended working fluid is expected to achieve maximum net power output, high thermal efficiency, low cost, low irreversibility, high safety and low environmental effect.

Keywords : Organic Rankine cycle, working fluids, fuzzy logic

FLOW MEASUREMENTS IN TRANSONIC FLOWS OF ORGANIC FLUIDS WITH A LUDWIEG TUBE TYPE SETUP

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ABSTRACT

The Flexible Asymmetric Shock Tube setup has been designed and built at the Process and Energy Laboratory of the Delft University of Technology in order to study non-classical gasdynamic phenomena in flows of dense organic fluid vapors [1]. It operates according to the Ludwieg tube principle. One of the main objectives is the detection of rarefaction shock waves, which are theoretically predicted to occur at operating conditions close to the vapour-liquid critical point in the superheated vapor thermodynamic region of so called BZT fluids [2]. Fluids of the siloxanes family qualify as BZT fluids therefore they are employed in the FAST setup [3]. Siloxanes are also working fluids for organic Rankine cycle power plants [4]. Gasdynamic measurements performed with the FAST setup are therefore also relevant especially for the aerodynamic design of ORC expanders. The FAST can be operated at temperatures up to 400 °C and pressures up to 30 bar. The current status with respect to the commissioning of the setup is illustrated. In addition the FAST laboratory has been recently equipped with Laser-based diagnostics for flow visualization and measurements. The experience gained in handling siloxanes and the FAST setup triggered interest into the design of a new test rig for flow measurements in transonic flows around blade shapes, with the objective of accurately validating an in-house CFD code for flows of dense organic vapors in conditions typical of ORC turbo-expanders. Preliminary results of the initial design process are described and discussed.

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EXPERIENCES FROM OPERATION OF DIFFERENT EXPANSION DEVICES IN DOMESTIC MICRO ORC

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ABSTRACT

Combined production of heat and power to cover the demand of the individual household or a small enterprise can be accomplished using the Organic Rankine Cycle with the low boiling-point fluid as the working fluid. In this light we can see significant perspectives for development of micro power plants, which should be capable of producing heat and electricity in so called dispersed scale. Bearing in mind a vast number of individual heat sources we can expect to be in line with the EU directive 2004/8/EU for decentralized production of heat and electricity.

Design and manufacture of a small size turbine (expansion machine) featuring the effective power of the order of few kilowatts, high internal efficiency and ensuring the full air-tightness in the presence of the low boiling-point fluid as a working fluid is a formidable engineering challenge. The smaller the turbine capacity the higher is the nominal speed of the turbine. Ensuring of a requested power implies the rotational velocities reaching 100 thousands rev/min. For such range of velocities of significant importance are issues of manufacturing, dynamical balancing of rotating elements as well as coupling of turbine with the electricity generator. One of the possible routes which can be followed in order to develop an expansions device suitable for an ORC system suitable for domestic cogeneration is to adapt and modify existing devices. The authors have experimented with the modification of three such devices, namely a scroll compressor, a pneumatic expander of a drill, and that of a wrench.

The presentation covers the experience derived from operating these devices using a test rig especially designed for this purpose. Experiments have shown that the two pneumatic devices feature a higher performance if compared to the scroll expander, indicating an isentropic efficiency in the range 61-82%. The volume occupied by expanders derived from pneumatic devices is much smaller than that of the reversed scroll compressor, which is also a positive characteristic for a component destined to micro-CHP applications. The low rotational speed of expanders derived from pneumatic devices will also simplify the connection to the grid of the electrical generator converting the mechanical power produced by the expander into electricity. The “pneumatic devices” under scrutiny here could be an alternative to the typical vapour turbine in the ORC cycle, which is in the process of development at the IFFM in the frame of the national research project.

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PRELIMINARY EVALUATION OF AN INNOVATIVE 190ºC SOLAR ORC PILOT PLANT AT THE PLATAFORMA SOLAR DE ALMERIA

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ABSTRACT

The coupling of an organic Rankine cycle with a solar thermal collector field as a thermal energy source offers an alternative to PV systems or Stirling dishes in remote areas without access to power supply. A wide variety of solar ORC systems has been proposed on the literature but very few experimental solar ORC setups have been reported. Most of them are either large plants with large power production working with solar field sizes of thousands of m2 and maximum cycle temperatures (Tmax) between 200-300 ºC, or kW sized installations working at maximum cycle temperatures lower than 150ºC. The efficiency of these small systems is limited by their lower Tmax. However, there is still another ORC concept not yet implemented, where the Tmax of a kW sized installation reaches 190ºC, and therefore higher efficiencies can be obtained. This work presents a description of a test facility installed at the Plataforma Solar de Almería (PSA), to evaluate an ORC prototype of such kind powered by solar energy. The test bed consists of an ORC pilot unit coupled to an existing parabolic through solar field which provides heat at 200ºC. The ORC unit is a prototype developed by the company Eneftech which presents two main innovations: the use of a new refrigerant as working fluid (Solkatherm ES36), and a new scroll-type expander specifically designed for ORC applications. This means that the efficiency of the ORC is expected to reach 17%. The main objective of the experimental facility is to assess the stationary and dynamic behaviour of the ORC pilot unit and its performance when coupled to a solar thermal field. An evaluation based on experimental results will be shown.

REVIEW OF THE POLISH RESEARCH WORKS ON APPLICABILITY OF THE ORC POWER PLANTS

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ABSTRACT

During recent years the research activity in the area of the ORC power plants has been growing also in the Polish scientific institutions. This is motivated especially by the need to utilize low and moderate temperature heat sources of renewable origin like geothermal water, biomass or the sun collectors. The research work is being carried out at the Polish Academy of Science, Institute of Turbomachinery in Gdansk, at the Technical Universities in Wroclaw, Gdansk and Lodz, and at the West Pomeranian University of Technology in Szczecin.

Covered research problems refer in particular to the question of the energy and exergy effectiveness of the single cycle ORC power plant, as well as to the question of their effectiveness improvement by means of application of the evaporators with an internal working fluid circulation. Experimental work is carried out at the West Pomeranian University of Technology on the first in Poland fully operational small ORC power plant built by the Turboservice Company of Lodz.

The research on the area of the ORC power plant applications is further extended to cover utilization of the waste heat encountered in various industrial branches like chemical, cement or ceramic plants.

The works published by the Polish scientific institutions refer also to some other types of the power plant solutions. They include double and triple cycle power plant schemes with sequential supply of the economizers and evaporators, as well as power plants for which the conventional saturated or superheated steam cycle functions as the upper temperature cycle.

On the basis of the works published by the institutions quoted above the most interesting, valuable and novel research results will be presented.

COMBINED POWER AND REFRIGERATION CYCLE FOR GEOTHERMAL HEAT SOURCES

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ABSTRACT

In this paper a power and cooling cycle which combines the organic Rankine cycle (ORC) and the ejector refrigeration cycle supplied by geothermal heat energy sources is analyzed. The thermodynamic and physical properties of thirteen working fluids, including wet, dry and isentropic fluids are investigated in the proposed combined cycle, and their performances are compared. With a fixed power/refrigeration ratio, the effects of the various operating conditions on the cycle performance are examined.

The proposed model is validated with the results of the combined power and ejector refrigeration cycle using R245fa as the working fluid presented by Zheng et al. [1] and Hasan et al. [2]. Also it is validated with the results of Dai et al. [3] in which R123 was selected as the working fluid.

The main conclusions from this study are as follows:

1- The results confirm the thermodynamic superiority of dry and isentropic ORC fluids over the wet fluids.

2- Exergy efficiency decreases with increasing evaporator temperature but increases with decreasing turbine inlet temperature and increasing heat source temperature.

3- Thermal efficiency increases with the increase in the turbine inlet temperature and expansion ratio of the turbine.

4- Entrainment ratio of the ejector decreases as the evaporator temperature rises.

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OPTIMUM DESIGN OF THE AXIAL ORC TURBINES WITH SUPPORT OF THE ANSYS CFX FLOW SIMULATIONS

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ABSTRACT

The ORC power plants require essentially their turbines to be individually designed for each power plant case. This is due to the varying parameters (temperature, capacity) of the heat sources to be utilized by a prospective ORC power plant. Moreover, selected cycle working fluid and its critical parameters, as well as certain design constraints (like in the case of the hermetic turbogenerators), are all affecting the final design of the turbine that should yield the maximum power output. Occurrence of the transonic and supersonic flows in the turbine channels is another difficulty to reach the optimum turbine design.

Several basic turbine designs will be discussed in this contribution. Their final form was achieved with support of the numerical 3D viscous flow simulations by using the ANSYS CFX code. The thermodynamic parameters of the organic fluids were taken from the REFPROP library. The discussed turbine solutions will refer mainly to application of HFC 227ea as the organic cycle fluid.

POWER CYCLES USING ORC TECHNOLOGY: A CRITICAL COMPARATIVE ANALYSIS WITH RESPECT TO CONVENTIONAL WATER RANKINE CYCLES

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ABSTRACT

In this paper, an in-depth comparative analysis between the Organic Rankine Cycle (ORC) and the classical Water Rankine Cycle (WRC) technologies is carried out. For this purpose, the behavior of a cogenerative power plant fed by the output gases of a micro-gas turbine at a temperature of 300°C was considered where the net electrical power level requested was 30kW.

Through this comparative analysis we have picked out the advantages of ORC technology in terms of thermal efficiency (i.e. more electric power can be produced from a given heat source) and feasibility of the turbine. In order to deepen the characterization of the ORC we have simulated the plant performance for three different organic fluids: N-pentane, Cyclohexane and Toluene. Thanks to this approach we have parameterized the main subjects of the power plant as a function of the thermophysical properties of the organic fluid.

The work is divided into two parts.

In the first part we have investigated, after an appropriate choice of evaporation and condensation temperatures, the cycle thermal efficiency. Great attention has been given towards the heat exchange behavior and the volume flow rates of the plant. From this first analysis we have demonstrated that the ORC technology makes it possible to obtain higher thermal efficiencies when low enthalpy heat sources are available. In this way, we have shown the dependence of efficiency from the properties of fluid and then important guidelines to choose the suitable fluid are given.

In the second part, a preliminary design of the turbine is carried out. From the temperature-enthalpy diagrams for organic fluids you can see, contrarily to water, a positive slope of satur-vapour curve. This fundamental characteristic allows organic fluids an expansion in a superheated vapor region. Otherwise, if you spare a superheating process, water expands in a two phase region whit a great disturbance of the flow field and the consequent decrease of the turbine expansion efficiency. With the purpose to realize a preliminary study of the main geometrical and functional parameters of the turbine we have developed a dedicated computational code. In this case we have parameterized, as a function of the fluid, the dimension of the rotor inlet blade and other main turbine parameters. Great attention has been given towards the behavior of the flow field at the exit of the turbine nozzle.

In the last part of this paper we have matched, for each fluid, thermodynamic efficiency and feasibility of the turbine. In this way some considerations arose about the selection of suitable organic fluid in accordance with plant power level and heat source temperature. As a consequence you can understand the reason why some companies are looking for new organic fluids or mixtures of them.

The importance of this work is related to the general approach utilized and the results obtained represent an important preliminary guideline to design ORC systems.

DESIGN OF A SCROLL EXPANDER FOR AN ORC APPLICABLE TO A PASSENGER CAR FOR FUEL CONSUMPTION IMPROVEMENT

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ABSTRACT

Application of an organic Rankine cycle to a passenger car has been considered to improve fuel consumption by recovering engine coolant heat, which usually amounts to about one third of the fuel energy. The high-side and low-side temperatures of the ORC were limited by the engine coolant and radiator temperatures, respectively. The evaporator and condenser temperatures of the ORC were set at TH=93oC and TL=60oC, respectively, for the vehicle speed of 120km/hr. At this temperature condition, theoretical efficiency of the Rankine cycle with R1234yf as the working fluid was 7.23%. A scroll expander was designed for energy conversion from thermal energy of the working fluid in the ORC to useful shaft power. For axial compliance, a back pressure chamber was provided on the rear side of the orbiting scroll.

Lubrication oil was to be delivered by a positive displacement type oil pump driven by the expander shaft. Performance analysis on the designed scroll expander showed that the expander efficiency was 68.6%. It extracts the shaft power of 1.7 kW out of engine coolant waste heat (plus some portion of the exhaust gas heat) of 32.1 kW. This amount of the expander output is equivalent to the fuel consumption improvement of about 8% for the passenger car under consideration at the vehicle speed of 120km/hr. With decreasing the vehicle speed, the scroll expander efficiency was calculated to decrease accordingly: it turned out to be 38.4% at 60km/hr, resulting in about 4.5% improvement in the fuel consumption.

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COMPARISON OF TRILATERAL CYCLES AND ORGANIC RANKINE CYCLES

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ABSTRACT

For conversion of medium or low temperature heat to power one may think of using besides organic Rankine cycles (ORC) also trilateral cycles (TLC). In the TLC the liquid working fluid is pressurized and heated to its boiling point. Then it undergoes a flash expansion into the wet vapour region whereby it delivers work. Finally, the fluid is condensed. The advantage of the TLC is a very good match between the heating up curve of the working fluid and the cooling down curve of the heat carrier. The advantage of the ORC is that its cycle is closer to the Carnot cycle. Hence one would expect that the exergy efficiencies of both cycle types are similar. Recent papers, however, claimed that the efficiency of the TLC is 1.5 to 3 times higher than that of the ORC and hence we decided to reinvestigate that question.
We consider optimized TLC- and ORC-systems which include the heat transfer from the heat carrier to the working fluid, the cycle process, and the heat transfer from the working fluid to the cooling agent. Optimization criterion is the exergy efficiency of the system for power production xp being the ratio of the net power output to the incoming exergy flow of the heat carrier. Model calculations were made for five cases I to V specified by the inlet temperature of the heat carrier and the inlet temperature of the cooling agent. The inlet temperature pairs are for I (350°C, 62°C), II (280°C, 62°C), III (280°C, 15°C), IV (220°C, 15°C), V (150°C, 15°C). For TLC we use water throughout as working fluid and hence the only parameter for optimization is the boiling temperature. For the ORC we use different working fluids depending on the temperature interval. Their thermodynamic properties are obtained from the molecular based BACKONE and PC-SAFT equations of state.
First, we searched for optimal ORC working fluids for the cases I and II considering alkanes, aromates and linear siloxanes in subcritical cycles (p/pc = 0.9) with and without superheating and supercritical cycles (p/pc = 1.2), all with internal heat exchange. Rankings based on the exergy efficiency xp, the cycle thermal efficiency hth and on the volume and the heat flow rates show cyclopentane to be the best working fluid for all studies of cases I and II which is caused by its only slightly overhanging dew line in the T,s-diagram. Moreover its autoigintion temperature is more than 100 K higher than the maximum cycle temperature considered.
Hence, we used in the comparison between TLC and ORC as ORC working fluid for cases I to III cyclopentane, for case IV n-butane and for case V propane. It is found that the exergy efficiency xp is larger for the TLC than for the ORC between 14% and 20% for cases I to IV and by 29% for case V. On the other hand, the outgoing volume flows from the expander are larger for the TLC than for the ORC by a factor ranging from 2.8 for case I to 70 for case V which is caused by the low vapour pressure of water for the low temperatures.

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ON THE OPTIMIZATION OF ORC SYSTEMS

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ABSTRACT

Subcritical and transcritical Rankine cycles operating between a low temperature heat source (Ts,in = 100, 165 and 230 °C) of fixed volume flowrate (1.2 106 m3/h, idealized as atmospheric air at Ps = 101 kPa) and a fixed temperature heat sink (water at Tp,in = 10 °C) have been analyzed using the principles of classical and finite-size thermodynamics. The model of the system and its validation have been presented elsewhere [1].

Optimum operating conditions (pressure of the working fluid during heat addition, Pev, and temperature difference DT between the working fluid and the two external fluids) and the corresponding values of several system characteristics have been determined for different net power outputs using the variable metric method for each of the following objectives: maximum thermal efficiency, minimum total exergy destruction, minimum total thermal conductance of the two heat exchangers UAt and minimum turbine size SP.

Typical results with R134a as the working fluid are presented. For this fluid the cycle is subcritical for Ts,in = 100 °C and transcritical for the other two values of the heat source temperature. At the turbine outlet the fluid is always superheated vapor.
The lowest exergy losses as well as the smallest total conductance and turbine are obtained with Ts,in = 100 °C while the highest thermal efficiencies are obtained with Ts,in = 230 °C.
The combinations of Pev and DT which maximize the thermal efficiency and minimize the exergy destruction are essentially identical. For these conditions the net power output has no effect on the thermal efficiency. On the other hand the exergy losses as well as the size of the turbine and heat exchangers increase with the net power output, albeit at different rates (the variation of the exergy losses, UAt and SP with the net power output is not linear). In all these cases the pinch in the high temperature heat exchanger occurs at the heat source inlet.
The combinations of Pev and DT which minimize UAt and SP are different from each other and from those which maximize the thermal efficiency. The conditions which minimize UAt give turbine sizes not much bigger than the corresponding minimum size; on the other hand, the conditions which minimize SP give a thermal conductance significantly bigger than the corresponding minimum values.

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SYNERGY EFFECT IN THE HYBRID ORC POWER PLANT DRIVEN BY TWO LOW ENTHALPY HEAT SOURCES

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ABSTRACT

Organic Rankine Cycles (ORC) are used in an increasing number of applications in the field of the distributed electricity generation. There is also a tendency to convert heat of lower and lower temperature, i.e. such as 100 OC and below that value. However, the thermodynamic efficiency of the energy conversion is very low at this temperature level. To overcome that situation several hybrid systems were considered within which the low temperature heat would be in various ways coupled with additional high temperature heat.

Irrespectively from the energy conversion efficiency in those systems (the high temperature heat source requires application of the conversion technology that is different from ORC) this kind of approach calls for a high temperature heat source to be provided at the location of the existing low temperature heat source, which in most cases might be not feasible.

Now, a requested positive effect in the efficiency of the energy conversion results when two low temperature heat sources (of different temperature values) are engaged in one hybrid ORC system, and the cycle generates saturated vapour to drive the turbine. An example discussed in the presentation refers to the case of low enthalpy geothermal water (with the temperature of, say, 70 OC) and heat delivered by a biomass fired water boiler (water output at 100 – 120 OC). It appears that, with properly adjusted heat streams of those two heat sources, the power output of such hybrid ORC system is up to 40 % greater than the sum of the power outputs of the two ORC units utilizing the respective individual heat sources at the equivalent heat stream capacities. The synergy effect comes from a thermodynamically better utilization of the upper heat source.

MODELLING FLUID FLOW & HEAT TRANSFER IN THE ORC POWER PLANT CO-FUELLED BY HEAT SOURCES OF DIFFERENT TEMPERATURE

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ABSTRACT

A schematic diagram and description of the ORC installation incorporating a single turbine will be presented for the case where the saturated dry vapour is produced in evaporators with an internal circulation of the individual energy carrying fluids.

In the case of the heat sources of different temperature the internal circulation coefficients of the evaporators can be selected for each energy carrying fluid in such a way that the saturated dry vapour at the outlet of evaporators will have equal values of pressure and temperature.

An algorithm of calculations will be also presented to enable the determination of the output power and efficiency of the power plant that works according to the subcritical Clausius-Rankine cycle. Calculation results will be shown for the cases of one, two and three energy carrying fluids of different temperature. On that basis, final conclusions will be given in respect to the possibility of application of the heat sources of different temperature to co-fuel the ORC power plant.

OPTIMIZATION OF A COMBINED POWER AND EJECTOR REFRIGERATION CYCLE USING LOW TEMPERATURE WASTE HEAT

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ABSTRACT

Recently, there is a strong interest toward exploiting renewable energies and waste heat instead of fossil fuel sources. The main reason is that the renewable energy sources are environment friendly, cheap and abundant. On the other hand the use of waste heat improves energy efficiency. Several studies have investigated the performance of cycles using low temperature heat sources [1, 2].

The present paper presents a thermodynamic study and optimization of a combined organic Rankine cycle (ORC) and ejector refrigeration cycle driven by low-temperature waste heat. The performance of different working fluids (R123, R141b, R245fa, R600a, R601a) was investigated. The analysis has been performed for a case for which the power/refrigeration ratio is 2, the pinch point temperature difference is fixed, the waste heat source temperature varies between 393 and 443 K, and the evaporator temperature varies between 258 and 278 K. Results show that the inlet pressure of the pump and inlet pressure of the turbine can be optimized to get a minimum total thermal conductance. The main results from this study at the defined ranges are as follows:

1- Inlet pressure of the pump and inlet pressure of the turbine can be optimized to get a minimum total thermal conductance.
2- Working fluid R601a is the suitable working fluid if the cycle is optimized according to the turbine inlet pressure, because it has the highest thermal efficiency (18.67%) and the lowest total thermal conductance (1479 kW/K). On the other hand, if the cycle is optimized according to the pump inlet temperature, R141b is the best choice because it has the lowest exergy destruction rate (911.8 kW) and the highest thermal efficiency (19.02 %).
3- Total exergy destruction of the proposed cycle increases as the heat source temperature and evaporator temperature increase but decreases as the condenser temperature and turbine expansion ratio increase.
4- Thermal efficiencies of the working fluids increase as the heat source temperature and expansion ratio of the ejector goes up.

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EFFECTS OF TURBINE EFFICIENCY TO ORC PROCESS ELECTRICITY PRODUCTION AND PROFITABILITY

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ABSTRACT

The Organic Rankine Cycle (ORC) consists at least of a turbine, a pump, a condenser and an evaporator. The optimal operation of all process components is important to the efficient performance of the ORC. This is especially true in a case of a small electrical output and a low evaporation temperature processes where initial conditions are not supporting the high efficiency. The turbine efficiency can vary widely and it is affected by many factors e.g. the operation point, size, design and type of the turbine. Also when optimum operation of the turbine is sought, the maximum efficiency of the turbine is obtained using highly laborious and complex techniques. Therefore, it is important to study the necessity of achieving the top efficiency.

In this study, the sensitivity of the ORC process to the turbine efficiency is evaluated. The ORC process is designed to produce about 10 kW of electric power and the heat source temperature is about 400 degree of centigrade. The working fluid of the cycle is siloxane, MDM. The effects of the turbine efficiency on the ORC process electric efficiency and on the measure of the ORC process quality are presented in this paper. The electric efficiency of the ORC process is rather insensitive for the turbine efficiency. The change in the electrical efficiency of the process is about 0.2 percent while the isentropic efficiency of the turbine changes one percent. Therefore, benefits improving the turbine efficiency using laborious methods and resulting complex geometry are not economically essential in units where the electric power is small. The financial benefit increasing the turbine isentropic efficiency by 5 percent is 174€ - 347€ per year with the electric price varying from 60€/MWh to 120 €/MWh and 5000 operation hours per year in the unit studied in this article. The financial benefits of the higher turbine efficiency are larger when the unit size is larger but in units with the small electric power the financial benefits are very low. Therefore, the main focus should be paid to the manufacturing costs of the turbine/unit rather than to optimize the turbine efficiency.

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EVALUATION OF SUITABLE WORKING FLUIDS FOR SINGLE ORC IN GEOTHERMAL POWER PLANTS BY THE CONCEPT OF POWER MAXIMIZATION

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ABSTRACT

The use of geothermal energy for power generation at brine temperatures of less than 200°C is usually achieved by the Organic-Rankine-Cycle (ORC). Thereby, the choice of a suitable fluid results in another level of complexity in the design of such a process.

The study analyses criteria for the evaluation of an ORC related to a given brine flow. Due to the given temperature and the given heat capacity rate, the aim for ORC design is to maximize the power output. Since the heat flow and the heat capacity rate from the geothermal source are limited, a simple efficiency consideration for the ORC based only on the Carnot efficiency will not lead to the maximum power output. The heat transfer between the brine and the working fluid must also be included into efficiency considerations. Using the concept of power maximization [1] to characterise the process temperatures, the choice of the fluid is used as a design parameter to optimise the heat transfer into the ORC.

Based on a preliminary developed theoretical concept, the study analyses eight different working fluids, which have been chosen by their thermodynamic properties in relation to the maximum temperature of the brine. Within under-critical conditions the simple power cycle is then calculated over an interval of process power. As a reference, the conditions for a prospected geothermal power station in the German Upper Rhine Valley are taken.

It is shown how the choice of the fluid influences the power output and the ability of the ORC to transfer the brine's heat into work. Furthermore, considerations for a consistent efficiency definition are presented.

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THERMODYNAMIC INVESTIGATION ON DIFFERENT ORC CONFIGURATIONS

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ABSTRACT

The organic Rankine cycle (ORC) is an emerging technology for power generation by recovering heat from different thermal sources. The most common applications are biomass power plants, recovery of wasted heat from industrial process and engine flue gases; applications under investigation are also geothermal, solar desalinization, biogas applications and heat recovery from waste-to-energy power plants.

The ORC adopts a simple thermodynamic concept and is based on the use of particular organic fluids as working medium and their characteristics have a strong influence on the cycle performance.

The general aim of the study started on the ORC at the University of Bologna is to perform different thermodynamic investigations on the potentiality of this kind of energy system, considering specific applications.

The starting point for the analysis described with this paper/poster is the study of subcritical cycles, by considering fourteen fluids as working medium, including aromatics, linear siloxanes, refrigerants and hydrocarbons.

This paper/poster represents a preliminary numerical study to assess the relevance of the main cycle parameters and to calculate the performance in term of heat recovery efficiency.

To improve the recovery efficiency and the net power output of the ORC different cycle modifications are evaluated, such as superheated cycle, supercritical conditions and other cycle modifications.

A parametric analysis of these cycles has been carried out at different evaporation pressure values, to identify the best operating condition. Preliminary results of the investigation will be provided.

SIMULATION MODEL OF AN EXPERIMENTAL SMALL SCALE ORC COGENERATOR

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ABSTRACT

The paper presents the simulation model of a small-scale Organic Rankine Cycle (ORC), conveniently usable to recover electrical power from low-temperature heat sources, such as the exhaust gases of internal combustion engines, solar panels or biomass boilers. Aim of the paper is to achieve an overall knowledge of the expected performance of the experimental test bench currently under development at the Energy Systems Laboratory (EneSysLab) of the Department of Mechanical Engineering and Naval Architecture of the University of Trieste.
The global model has been implemented with Aspen® simulation software, taking into account the real behavior of the system components in design and off-design conditions. All the heat exchangers have been modeled referring to the geometrical data provided by the manufacturer, and have been validated by comparing the simulated performances with the declared ones. Detailed one-dimensional models have been developed to predict the behavior of the expander, since it represents the most critical component of the cycle in terms of efficiency: MatLab® codes have been implemented for both a scroll expander [1-3] and an alternative (piston-type) machine [4, 5]. Several working curves (at various operating conditions and with reference to R245fa and isopentane as working fluids) have been obtained and used in the global model. In such a way, main dissipative phenomena in all components - like heat transfers toward ambient, pressure drops, expander leakages, etc. - can properly be taken into account in different applications and operating conditions, and the relative weight of each dissipative phenomenon and of each heat transfer irreversibility, affecting the cogenerator behavior, can be separately evaluated, highlighting possible design improvements for some components and for the whole system.

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PRELIMINARY EXPERIMENTS OF AN ORC PLATFORM

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ABSTRACT

An ORC platform has been built to investigate its performance. In this platform, heated oil and circulating cooling water are used as heat source and sink respectively, organic fluid R123 is selected as the working medium, and a fabricated micro turbo-expander of high speed is employed as the heat engine. A DC motor-generator is attached to the turbo-expander via a gearbox, electricity is produced and then consumed by a series DC bulbs.

Preliminary experiments were executed to examine the performance of the platform as well as the turbo-expander. In these tests, heat source temperature was regulated by a heat oil controller, and the turbo-expander inlet pressure was adjusted and controlled by the pump. The output power of the generator was regulated by adjusting the number of the bulbs manually.

The experimental results show that the system works well. While the heat source and sink temperature were fixed at 108 ℃ and 31 ℃ respectively, the peak rotational speed of the turbo-expander reached to 24000 r/min, and the corresponding isentropic efficiency was 0.65.

RECOVERY OF WASTE HEAT FROM THE COAL-FIRED POWER UNIT USING ORGANIC RANKINE CYCLE

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ABSTRACT

The domestic coal resources are the guarantee of Polish power engineering security from the perspective of next decades or even centuries. The Polish power plants however will be subjected to the necessary modernization works, which will help them to satisfy the ecological standards and to be comparative in the overall efficiency with other similar installations in the world. In this situation the recovery of low-temperature waste energy becomes one of the possibilities to supplement that task [1].

In the paper the application of ORC in the installation of heat recovery from the power unit is described. Presented works form a part of the national strategic project. The analysis of possible configurations of waste recovery is done in several stages. In the first stage it is assumed that the ORC evaporator is supplied with hot water of temperature equal to 80^{o}C. Such temperature of working medium is resulting from the energy conversion of all identified and possible to use waste energy sources in the power plant. Next, attention is focused on the possibility of increasing the upper temperature of the cycle. That could be done, for example by incorporation of absorption heat pumps or solar collectors in the cycle. By far the best results are obtained by using of the bleed steam from the LP stage.

In the course of accomplished works several possible working fluids have been scrutinized as most applicable to such installation. Finally, five fluids were selected and calculations are presented for them. Calculations were accomplished for two temperatures of the upper source, namely 80^{o}C and 120^{o}C. As mentioned earlier exploitation of such resources as waste heat in power plants has a significant potential in future.

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APPLICATION OF AN ORGANIC RANKINE CYCLE FOR RECOVERY OF LOWGRADE WASTE HEAT IN A (WET) BIOMASS SUPERCRITICAL WATER GASIFICATION SYSTEM

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ABSTRACT

Green platform chemicals and biofuels(s) can be produced from wet biomass pretreatment integrated with supercritical water gasification. This is a novel biorefinery concept. However, the utilization of low grade heat to improve economics has been a challenge.

This article describes a process model and simulations in which an Organic Rankine Cycle (ORC) was combined with Supercritical water gasification (SCWG) system. The working fluid used in this study is CO_2. It has many advantages, low cost, low toxicity, is non-flammable and has no environmental impact. In this modeling, water temperature in the range of 170 – 200 ºC and a flow of 7200 kg/hr was used as the low-grade heat source. CO_2 is biomass derived in the same process which can be produced about 1300 kg/hr. Aspen Plus$_{TM}$ process modeling software is used to model this system. The efficiency of the process is evaluated.

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DESIGN OF A 150W OTEC PROTOTYPE BASED ON THE KALINA CYCLE AND COMPARISON BETWEEN ORC BASED OTEC

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ABSTRACT

The increasing need for clean, renewable energy is causing a renewed interest in Ocean Thermal Energy Conversion (OTEC). This concept developed at the beginning of the 20th century aims at generating electricity through a thermodynamic cycle, using the temperature difference between the hot surface water and the cold deep water in the ocean. The main advantage of OTEC, compared to other renewables like wind and solar energy, is the fact that it is a so-called baseload source of energy, available day and night. Furthermore, in addition to electricity production, OTEC also offers the possibility of co-generating other products like clean drinking water and enhancing agriculture and aquaculture productivity. However the available temperature difference found in tropical oceans of little more than20°C highlights the true difficulty but exciting opportunity in harnessing ocean energy. Few successful demonstration power-plants have already been built worldwide, nevertheless research and investors are still lacking in this field. Thus to fill this gap and demonstrate the validity of the OTEC principle we are currently designing and building a small-scale (150W) working power-extraction cycle, an 'OTEC Demo'.

A thorough study of current practice and an evaluation of the available cycles have led to the choice of the Kalina cycle as extraction-cycle. The latter has been selected based on its (claimed) high efficiency for low-grade, large capacity thermal resources, like the ocean.Using Cycle Tempo [1], a software for thermodynamic analysis and optimization, the cycle has been modeled and the different components have been sized. A detailed comparison of the modeled Kalina cycle based OTEC prototype and an ORC based OTEC prototype is made with a view point of efficiency and economics is performed and greater efficiency for the Kalina based OTEC is expected.

If the prototype proves to be successful it would be the first OTEC power plant based on this cycle in the world.

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EXPERIMENTAL STUDIES OF LOW POWER ORC`s WITH VANE EXPANDERS

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ABSTRACT

Works in the field of the ORC`s with mechanical power of 1-2 kW were carried out at the Institute of Power Engineering and Fluid Mechanics of Wrocław University of Technology since the early 1990s. Then the test stand of the ORC using as expander vane rotary machine was designed and built. Working medium was R-11. At the test stand, series of experiments were carried out, and the results have been collected by Mr Stanislaw Biernacki in his PhD thesis. The need for the withdrawal of R-11 from use was associated with the exploration of new working mediums and analysis of their property and properties of thermodynamic systems using different rotary vane expanders. New organization of a low potential heat conversion process to mechanical work has been proposed. Also the methodology of working medium selection has been designed. That methodology was then developed by Dr. ing. Piotr Kolasiński. CHP ORC systems that can be used in households and small workshops were designed, analyzed and tested. Works in ORC area are still carried out.

ELECTRICITY FROM WASTE HEAT BY USING AN ORGANIC RANKINE CYCLE

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ABSTRACT

Within renewable energy installations such as biogas-, landfill gas- and bio oil engines, and even at all kinds of industrial plants lots of waste heat is dissipated into the atmosphere. On the other hand, there is a proven, commercially available technology to convert it (partially) into electricity. This is the Organic Rankine Cycle (ORC), which has been used for several decades within f.i. geothermal plants. Applications of the same technology for waste heat recovery are rather premature.

To transfer this technology to such applications, practical research, in collaboration with industry was performed with the following output : technology review (used working fluids to replace water/steam, expander types...), a market overview, view on technical and economical feasibility, simulation models, comparison between the steam cycle and ORC and selection criteria, industrial case studies (landfill- and biogas engines, within steel, glass, paper, automotive, chemical and clay industry, water treatment).

As a conclusion, ORC-projects were found to be very attractive on renewable energy applications with the help of green certificates. On non-renewable industrial cases, economic feasibility strongly depends on integration costs and electricity prices. To demonstrate the ORC-technology, a lab scale test facility has been built. As a result of industrial collaboration, a unique 11 kWe ORC unit has been composed and integrated as a scale model of the 50 and 250 kWe units that are commercially available already.

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TWO ALGORITHMS FOR THE RELIABLE ESTIMATION OF ORGANIC RANKINE CYCLE PERFORMANCE

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ABSTRACT

As the demand grows for low-temperature waste heat recovery systems, ORCs (Organic Rankine Cycles) and other alternatives to traditional steam Rankine cycles are becoming more common in industry. Although analytical tools exist that can predict the performance of a steam cycle in a given waste-heat application, the development of a similar tool for ORCs has been hampered by the large choice of possible working fluids. In this paper, two methods are presented with the aim of providing an estimate of the best performance possible for any ORC in a given industrial application. The first is a purely analytical approach assuming an idealized fluid, and the second compares real fluids through cycle simulations to select the most appropriate parameters for the application. The analytical approach provides a rough baseline for performance, while the simulation method refines the estimate to give predictions that are more consistent with the documented performance of ORC plants currently in operation. Together, the two approaches represent a robust means of quickly estimating the capability of an ORC plant, to allow quick comparisons with other technologies.

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CANDIDATE RADIAL-INFLOW TURBINES AND HIGH-DENSITY WORKING FLUIDS IN ORC CYCLES FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

Optimisation of Organic Rankine Cycles (ORCs) for binary-cycle geothermal applications could play a major role in the competitiveness of low to moderate temperature geothermal resources. Part of this optimisation process is matching cycles to a given resource such that power output can be maximised. Two major and largely interrelated components of the cycle are the working fluid and the turbine. Both components need careful consideration.

Due to the temperature differences in geothermal resources a one-size-fits-all approach to surface power infrastructure is not appropriate. Furthermore, the traditional use of steam as a working fluid does not seem practical due to the low temperatures of many resources. A variety of organic fluids with low boiling points may be utilised as ORC working fluids in binary power cycle loops. Due to differences in thermodynamic properties, certain fluids are able to extract more heat from a given resource than others over certain temperature and pressure ranges. This enables the tailoring of power cycle infrastructure to best match the geothermal resource through careful selection of the working fluid and turbine design optimisation to yield the optimum overall cycle performance.

This paper presents the rationale for the use of radial-inflow turbines for ORC applications and the preliminary design of several radial-inflow turbines based on a selection of promising ORC cycles using five different high-density working fluids: R134a, R143a, R236fa, R245fa and n-Pentane at sub- or trans-critical conditions. Numerous studies published compare a variety of working fluids for various ORC configurations. However, there is little information specifically pertaining to the design and implementation of ORCs using realistic radial turbine designs in terms of pressure ratios, inlet pressure, rotor size and rotational speed.

Preliminary 1D analysis leads to the generation of turbine designs for the various cycles with similar efficiencies (77%) but large differences in dimensions (139~289 mm rotor diameter). The highest performing cycle (R134a) was found to produce 33% more net power from a 150°C resource flowing at 10 kg/s than the lowest performing cycle (n-Pentane).

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ECONOMIC COMPARATIVE STUDY OF KALINA CYCLE, SUB- AND TRANS-CRITICAL ORGANIC RANKINE CYCLE (ORC) FOR LOW-TEMPERATURE GEOTHERMAL

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ABSTRACT

Kalina cycle, sub- and trans-critical ORC are three promising cycles to use low-temperature (i.e. 80-100°C) geothermal sources. However, little studies were published on the economic performance comparison of the three systems under their optimized operation parameters.

The objective of this study is to provide favorable cycle and fluids as well as the corresponding optimum operation conditions for low-temperature (i.e. 80-100°C) geothermal ORC power system. And the minimum cost of geothermal power plant should be the determining factor of both choices. The LECplant value of the geothermal power plant can be divided into LECsystem and LECfield. The exploration, transmission, drilling, piping, control system, land use costs, etc, which almost const for a specific geothermal source, are indicated by LECfield. And the costs of refrigerant pump, turbine and heat exchangers are revealed by LECsystem and almost the same by our previous study [1] for both cycles when the optimum working fluids and parameters were used. So the fluids with maximum power output will be favored in this study. The power output of the system is used the objective function.

The simulation is performed by using a program written in Matlab referred to our previous study [1]. The inlet temperature of the heat source and sink is 90oC and 20oC, respectively. The pinch temperature difference is 5oC and flow rate of the heat source is 1kg/s. And saturated vapor was assumed at the turbine inlet in subcritical ORC system. Aside from the 16 different working fluids considered in our previous study [1], the mixtures of ammonia/water with four solutions (Ammonia/Water mole fraction: 0.78/0.22, 0.82/0.18, 0.92/0.08, 0.98/0.02) are included.

The results indicate that the R227ea exhibits the highest power output in subcritical ORC and the R218 is the excellent fluid by the highest power output of 12.3kW in transcritical ORC. The power output of Kalina cycle increases with the increasing of ammonia concentration in the mixture. The power output of the R218 is 30.2% larger than that of R227ea and 5% larger than that of ammonia/water (mole fraction: 0.98/0.02) mixture in Kalina cycle. In conclusion, the transcritical power cycle with R218 as the working fluid is a cost effective approach for the low-temperature geothermal ORC system.

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FLUIDIZED BED BIOMASS COMBUSTION COMBINED WITH ORGANIC RANKINE CYCLE FOR SMALL-SCALE CHP

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ABSTRACT

Combined heat and power (CHP) is an interesting application in which low-grade waste heat from combustion can be used to drive a turbine to produce electrical power. This article describes a simple model in which combustion of biomass (i.e. demolition wood) in a bubbling fluidized bed (BFB) is combined with an Organic Rankine Cycle (ORC) of 800 kWthermal operating on toluene. The advantage of using an organic fluid is that the turbine can efficiently operate at lower temperatures than with steam. Toluene as a working fluid, furthermore, has an extremely low global warming potential.

The thermal input of the fluidized bed combustor is 1.1 MW (HHV based) and complete combustion is assumed with an excess air ratio of 20% at 1 bar and 850 °C. Furthermore, the system is designed in such a way that the temperature of the freeboard zone does not exceed 350 °C in view of the stability of the thermal oil.

For optimal efficiency of the 800kW ORC system and under particular assumptions of fuel utilization and heat exchanger efficiency, a fuel flow rate of 230 kg/h (with a moisture content of 9.1% for demolition wood) and an air flow rate of 1600 kg/h lead to a flue gas flow rate of 1800 kg/h. A model is set up to calculate the heat capacity and flow rates of the flue gas, and it is found that the inlet air must be preheated to an optimum of 133 °C. Part of the stack heat lost could be used to preheat the air to the optimum temperature, therefore increasing the system efficiency. Heat losses through the reactor walls are neglected.

Heat released during combustion is transferred to the ORC via heat exchangers on the bed and the freeboard section. The two separate flows are combined to a single flow to transfer the heat to the ORC generator. The heat exchanger system is assumed to have an overall efficiency of 85% and a heat transfer coefficient of 400 W/m²K for the bed heat exchanger, and 50 W/m²K for the freeboard heat exchanger. A heat exchanging area of 3.3 m² for the bed heat exchanger, and 53.4 m² for the freeboard heat exchanger is sufficient to transport the heat, due to the temperature difference between the freeboard entrance and the thermal oil. This leads to a total flow rate of 3300 kg/h for the thermal oil. The model estimates a boiler thermal efficiency of 80.7% and electricity is produced with a system efficiency of 10.2%, which is in accordance with other studies [2]. If the heat from the flue gas is used to preheat the incoming air, the thermal efficiency could be raised up to 84%. A MATLAB model is implemented in which the efficiency and other parameters can be easily changed to obtain more precise temperature requirements and fluid flows. Key performance factors of the BFB and the ORC are identified and discussed.

A considerable degree of uncertainty is found on the heat exchanger system efficiency. A change in the heat exchanger efficiency of +/- 5% can yield a difference in preheat temperature of 60-100 °C. Also, a cost benefit analysis of the cost of heat exchangers vs. efficiency of the complete system should be performed. A more sophisticated model can be designed to produce more a more accurate result.

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STUDY OF AN ISOLATED-GRID BIOMASS ORGANIC RANKINE CYCLE USING THE TIL MODELICA LIBRARY

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ABSTRACT

The Organic Rankine Cycle technology allows combined heat and power (CHP) or purely electrical generation from biomass sources. For medium output powers (typically lower than 1 or 2 MWe), it turns out to be more cost-effective than the traditional steam Rankine cycle. However, the investment costs increase when the plant size decreases due to scale effects. This higher investment cost can be justified if the electricity price is high, which is the case in most remote area, not or poorly connected to the grid. These areas generally make use of diesel gensets, with high fuel and generation costs (often higher than 250-300€/MWh). For these markets, production of thermal energy is not a priority whereas a standalone and easyoperation is a major constraint.

The present paper focuses on the use of a medium temperature ORC cycle running in isolated grid conditions, as a replacement of the traditional diesel generators. The ORC cycle shows the advantage of allowing the use of biomass, which is generally available on-site and at low cost. However, the use of such a system on a small grid involves the necessity of matching properly the power generation with the load from the grid and requires advanced control strategies for the ORC unit.

The studied biomass ORC is a 1000 kWe system using Solkatherm as working fluid. The turbine is an axial type with a flow rate control system at inlet. The pump is a centrifugal type and the exchangers are shell and tube heat exchangers. The electrical generator is a synchronous machine. The turbine is coupled to a flywheel and a bank of variable resistors is installed.

In order to simulate the cycle in transient conditions, a dynamic model is built by interconnecting the models of each subcomponent: the heat exchanger model is discretized and uses heat transfer and pressure drop correlations; the turbine is modelled by its characteristic curves. All the models are developed under the Modelica Environment, using the TIL library for most components of the cycle. The ability of the ORC unit to follow the typical load curve of an isolated grid is then evaluated in different cases. The comparative advantage of controlling the flow rate at turbine inlet and/or the use of storage/dissipative equipment (flywheel, variable resistors) is evaluated with regard to the quality of the power delivered to the grid (variation range of frequency and voltage). In all cases, the pump speed is controlled to adjust the working fluid mass flow rate and thus the level of liquid in the evaporator.

PROCESS MODELLING OF ORGANIC RANKINE CYCLES

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ABSTRACT

Organic Rankine Cycles (ORCs) are often integrated in more complex systems such as geothermal plants, biomass combustion and gasification plants, solar power plants or industrial processes. To optimize the performance of the resulting system, accurate models of the thermodynamic system are of great value. This paper describes the process modeling system IPSEpro and its application to ORCs.

With IPSEpro, process models are created from individual components. The user can set up the process scheme graphically by arranging components appropriately and entering the required data in the flowsheet. IPSEpro is a open framework: Components and physical property calculations are not coded into the system. All application specific information is contained in model libraries. A model library for modeling ORC processes is available. The user can combine the ORC library with other existing libraries, like libraries for power processes, for solar power or for biomass gasification. Additionally the user can modify libraries and create new ones using a Model Development Kit (MDK). The paper illustrates the capabilities of the ORC library and presents results obtained.

Once a process model exists, its usage is not limited to normal performance calculations. With additional modules, the model can be used for parameter optimization as well as for the validation of measured data. The paper show examples for this usage.

INTEGRATION OF ORGANIC RANKINE CYCLES FOR THE SIMULTANEOUS RECOVERY OF WASTE HEAT AT TWO TEMPERATURE LEVELS IN A CEMENT INDUSTRY

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ABSTRACT

Cement manufacturing is an energy intensive process, in which a large part of the consumed energy is emitted as waste heat. The BREF reference document [1] reports waste heat recovery for electricity generation as one of the Best Available Techniques for the cement industry. In this paper, integration of two Organic Rankine Cycles (ORC) using two different working fluids is proposed and analyzed.

Electricity generation potential of the cycle is very closely related to the availability of the heat source. In the cement manufacturing process two waste heat sources mainly exist: the preheater exhaust and clinker cooler exhaust gases, which have different temperature levels. Energy recovery from both heat sources has been analyzed, considering typical values of exhaust gases flow and temperature.

Efficiency of ORC depends mainly on the thermodynamic properties of the working fluid and its operating conditions. Therefore, selection of the working fluid plays a key role in ORC systems, and is determined by the waste heat level. For this particular application, where waste heat at two different temperature levels is available, the use of two Organic Rankine Cycles is analyzed, by using suitable fluids for each heat source. The analysis and comparison of several integrated configurations is presented. Integration of both cycles is optimized in order to maximize heat recovery. The proposed configuration is also compared with a more conventional ORC making use of both waste heat sources but with a single fluid.

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A NOVEL MICROJET HEAT EXCHANGER FOR DOMESTIC ORC UNIT

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ABSTRACT

The authors are at the moment involved in a large scale national project with the objective of developing a commercially available ORC CHP unit for domestic applications. This technology is also likely to be fully mature much earlier than other promising technologies such as Stirling engines and fuel cells based ones. Apart from the completely new design of the expansion machine, which presents by far the most significant challenge, the installation should be equipped with highly efficient and small heat exchangers such as evaporator and condenser. An example of a novel concept of such device is studied in the present paper.

The authors acquired knowledge and gained experience in the topic of ORC prototyping by constructing and investigating the prototype micro power plant [1]. They have also developed their own prototype microjet heat exchanger constructed using the quite attractive minichannel technology [2]. Its main part consists of 28 steel membranes with cut microchannels. Their length is 2.5 mm, width - 200 µm and depth - 100 µm, respectively. The membranes were sandwiched between the plates made of aluminum alloy. The total heat transfer surface was equal to 0.0072 m^2. The membranes and plates have had holes, through which the working media could flow and exchange the thermal energy. In each of the circuits there were 1120 microchannels.

In the paper the idea of such heat exchanger is shown together with the flow and thermal experimental results of the prototype. Two flow cases are studied, namely water-water and air-air. In case of measurements of such complex geometries recording of wall temperatures is impossible and hence determination of heat transfer coefficient difficult. Therefore the Wilson technique was used for determination of the heat transfer coefficient. The results of accomplished measurements are satisfactory with the view of developing effective heat exchangers.

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DEVELOPMENT AND CONSTRUCTION OF BINARY GEOTHERMAL POWER PLANT IN RUSSIA

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ABSTRACT

Modern technologies for the exploitation of geothermal energy in power plants or heating systems have been developed in Russia since the late 60's [1]. In 1967, the first binary cycle geothermal power plant in the world was built in Russia, at Paratunsky . This plant used hot water at 90$_o$ C for electricity generation. In 1999 the 12 MW Verkhne-Mutnovsky geothermal power plant (V-M GeoPP) in Kamchatka was put into operation. The Mutnovsky GeoPP (50 MW) was commissioned in October 2002 and has been in successful operation despite of severe climate conditions.

Currently a new generation of geothermal binary power plants is being developed in Russia. This new technology is aimed at the production in series of smaller systems for the conversion of low-enthalpy heat sources into electricity and/or heating. JSC "RusHydro Engineering Center of Renewable Energy" with the scientific and technical assistance of SC "Geotherm-EM" have designed and are building a pilot plant at the Pauzhetsky site [2, 3]. Research and development activities include system design, fluid selection, experimental investigation of several aspects, components selection and development of the control system..

The Pauzhetsky installation will include: the turbo-unit and its auxiliaries, condenser, heat exchangers (heater, evaporator and super-heater share a common housing), feed pumps, auxiliaries of the power unit (including storage tank for waste working fluid), corrosionprotection and salt-sedimentation-protection devices, and cooling water pumps. The project is at the stage of pre-commissioning. Various aspects of the design, construction and commissioning are discussed.

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COMPUTER-AIDED DESIGN AND SELECTION OF OPTIMUM WORKING FLUIDS AND ORC SYSTEMS FOR POWER GENERATION FROM LOW-ENTHALPY HEAT SOURCES

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ABSTRACT

Power generation from low enthalpy heat sources requires the use Organic Rankine Cycle systems (ORC), where organic fluids such as hydrocarbons or refrigerants are utilized to facilitate efficient heat extraction. The economic, operating and environmental performance of the ORC depends on the properties of the selected working fluids, the design and operating characteristics of the ORC process and the characteristics of the heat source (e.g. hot fluid temperature, flowrate etc.). This raises the challenge of selecting working fluids and ORC process features that will result in an integrated system of optimum performance for a particular heat source. Available works address the selection of ORC fluids based on fluid- and process-related properties by testing various available fluids in ORC simulation models, sometimes combined with optimization of process operating parameters. A common characteristic shared among all these approaches is the use of a data set containing several available working fluid options. Although useful, this approach limits the search for efficient working fluids that exhibit favourable properties to an often empirically compiled dataset containing ‘‘the usual suspects”. Such a small set is extremely limiting in view of the vast number of molecules that could be considered as candidate ORC working fluids.

Instead, this work proposes a systematic approach combining computer-aided molecular design (CAMD) methods with process optimization to enable the design of working fluid options and ORC processes of optimum performance. CAMD tools utilize a database containing a few chemical groups that are used to generate and search a vast number of conventional or novel molecular structures to identify those working fluids that offer the best performance with respect to the properties of interest. The evaluation of the investigated working fluids is based on multi-objective optimization technology to identify a broad set of options with optimum physical, chemical, environmental and safety characteristics. The generated working fluids are subsequently introduced to ORC optimization in order to identify process and molecular features resulting in optimum economic performance [1]. Several ORC design stages are considered incorporating increasing modelling and design detail to enable fast and efficient screening of working fluid candidates in view of varying heat source conditions. The proposed developments are illustrated with applications in power or heat and power cogeneration from low enthalpy geothermal fields. Important working fluid properties are considered such as toxicity, flammability, ozone depletion and global warming potential, in conjunction to economic ORC performance.

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DEVELOPMENT OF A WASTE HEAT RECOVERY ORC PROTOTYPE USING AN OIL-FREE SCROLL EXPANDER

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ABSTRACT

The world is facing a historical increase in energy demand and energy consumption. As consequence the conventional fossil fuels are depleting faster with an inherent pollution causing sever damages to our environment. Renewable energy sources are considered as a solution to both environmental issue and energy demand. At the same time a lot of waste heat is witnessed in processes in industries. Our objective is to contribute to the development of ORC systems, that appear to us as a good solution to recover this wasted heat.

In such waste heat applications, depending on the heat source flow rate and temperature, electrical power output can be as low as a few kilowatts. In this power range, there is no cost effective expansion machine available on the market. On existing prototypes, expansion devices are usually retrofitted volumetric compressors originally designed for refrigeration or air compression applications. Air compressors have the advantage to handle higher inlet temperature but tightness is often an issue in ORC application since the fluids used have a non negligible environmental impact.

This paper presents the development of a small-scale WHR ORC unit at the Thermodynamic Laboratory of the University of Liège: the prototype uses a scroll expander, plate heat exchangers, a diaphragm piston pump and a liquid receiver. This system was tested with different working fluids (R123, R245fa and HFE7000) and a thermal efficiency close to 8% was obtained for a net output power of about 2 kWe.

The specificity of the proposed prototype is the absence of lubrication: in order to avoid oil circulation in the ORC loop, an oil-free scroll expander is developed. This expander is originally an air scroll compressor that was modified using a magnetic coupling to ensure tightness. The experimental results highlight the good efficiency of the device, despite a relatively high internal leakage due to absence of lubrication. The necessity of using magnetic coupling is also justified by comparing the experimental results with previous ones obtained using mechanical sealing.

INFLUENCE OF MOLECULAR COMPLEXITY ON NOZZLE DESIGN FOR AN ORGANIC VAPOR WIND TUNNEL

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ABSTRACT

A novel test rig for investigating the real-gas behavior of organic fluids operating at subsonic-supersonic speed in the proximity of the liquid-vapor critical point and the saturation curve has been constructed at the Politecnico di Milano, Italy. This is a blow-down facility in which an organic vapor is expanded from a high-pressure reservoir kept at controlled super-heated or super-critical conditions into a low-pressure reservoir, where the vapor is condensed and pumped back into the high-pressure reservoir. Expansion to supersonic speeds occurs through a converging-diverging Laval nozzle. A standard design technique based on the Method Of Characteristics (MOC) is used to design of the supersonic portion of the nozzle [1]. The transonic potential equation is solved by means of the approximate solution procedure of Sauer [2], which is applicable to real-gas flow without significant modifications, to compute the transonic flow at the nozzle throat. The transonic flow solution provides the initial data curve for the MOC. The expansion through the divergent section to the desired exit pressure is achieved via an initial circular profile followed by the so-called turning region, in which the nozzle upper wall geometry is determined by imposing the conservation of the mass flow at each section. The resulting flow at the nozzle exit is with uniform Mach number and parallel to the x axis. Further details on the design procedure, including comparisons with available ideal gas solutions, are given in [3].

Differently from the well-known ideal-gas results, the shape of the supersonic expander - the divergent section of the nozzle - depends on the reservoir or total flow conditions and therefore diverse designs are obtained for a given exit Mach number depending on the relative location of the initial state in the volume-pressure thermodynamic plane with respect to the liquid-vapor saturation curve. For flow states close to the liquid-vapor saturation curve and critical point, the nozzle length and height are larger than the corresponding ideal gas designs. Four different operating conditions for siloxane fluid MDM (Octamethyl-trisiloxane) and refrigerant R245fa are considered and the resulting nozzle designs are thoroughly discussed.

The effect of the molecular complexity of the fluid on the final design is throughly investigated for the cyclic siloxanes D4 (Octamethyl-cyclotetrasiloxane), D5 (Decamethyl-cyclopentasiloxane) and D6 (Dodecamethyl-cyclohexasiloxane) and for the linear ones MM (Hexamethyl-disiloxane), MDM, MD2M (Decamethyl-tetrasiloxane), MD3M (Dodecamethyl-pentasiloxane).

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ORC MICRO-POWER PLANT FOR COMBINED HEAT AND ELECTRIC POWER GENERATION

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ABSTRACT

The micro steam turbines have found their applications in the micro-power plants, including the poly-generation power systems and the combined gas-steam installations. Apart from the traditional medium, i.e. water vapour, also low-boiling media, as a rule, organic ones, are applied. On the market the co-generation systems working with organic media are already available, however only a few examples can be found of ORC installations of output power smaller than 100kW. The problems faced by designers of such turbines are associated with very small volume flow rate of working medium which leads to small values of blades' height and high values of rotor speed, up to hundred thousand rpm or more. The co-generative micro-power plant with the HFE7100 as a working medium was designed and built for experimental investigations. The values of the main cycle parameters were as follows:

- heat output: 20 kW,
- electric output: 3kW
- medium mass flow rate: 0.017kg/s,
- the pressure at turbine inlet: 1200kPa,
- the temperature at turbine inlet: 162 $^{\circ}$C,
- the pressure behind the turbine: 119kPa (the saturation temperature equal to about 65 $^{\circ}$C).

In PART A a description of the experimental power plant is presented. Special attention is paid to the advanced design of the main elements of the power plant: a boiler, heat exchangers, a pomp and a turbine generator. The results of the preliminary experimental research are given and analysed. In PART B a design of a multi-stage micro-turbine with partial admission of all the stages is described in detail and the results of the particular experimental investigations and numerical calculations are shown, followed by an appropriate discussion and conclusions. It is worth emphasising that the turbine efficiency is higher than 80%.

ORC POWER PLANTS WITH HERMETIC TURBOGENERATORS: FIRST PRACTICAL EXPERIENCES

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ABSTRACT

The power plants based on the Organic Rankine Cycle find recently numerous applications in utilization of the low temperature heat sources. The first in Poland experimental plant of that type was built and put into operation at the West Pomeranian University of Technology in Szczecin in 2008. In that plant, a high speed ORC turbine was driving a small centrifugal air compressor. Problems were encountered with sealing system of the turbine shaft and, in consequence, with the leakage of the organic fluid. Therefore, for the next solutions of the ORC power plants that should generate electricity, several concepts of the hermetic turbogenerators were invented. In those concepts the ORC turbine and the electric generator are enclosed in a common hermetic casing, and the electric generator is cooled with the turbine outlet vapour.

First small ORC power plant incorporating the invented hermetic turbogenerator and a commercially available hermetic organic liquid pump was then put into operation in 2010. This was preceded by long lasting endurance tests for the insulation materials of the electric generator, during which those materials were immersed in the vapour of the organic fluid selected to work in the ORC power plant. The successful operation of the entirely hermetic ORC power plant will be reported and presented. Additionally, several aspects of the design and applications of the hermetic turbogenerators will be discussed.

A SMALL SCALE TURBINE FOR THE ORGANIC RANKINE CYCLE

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ABSTRACT

It was pointed out [1] that small-scale CHP systems need to be simplified in order to be competitive with medium or large-scale systems. The KompaktDampfTubine (KDT, meaning compact steam turbine), originally invented at the Hochschule Darmstadt2 addresses this demand. The KDT consists of a rotating cylinder (200mm in diameter and 300mm in height) and a static axis, therefore reversing the traditional arrangement in a turbine. The cylinder is divided by a plate into evaporation- and condensation-chamber. The plate is fixed to the cylinder therefore co-rotating with it. Between the rim of the dividing plate and the cylinder exists a small gap, allowing the working fluid to pass through it. Laval-nozzles are fixed to the dividing plate. The working cycle is similar to that of a traditional turbine. The thrust from Laval-nozzles of the vaporized and accelerated working fluid is used as the first stage in the power transfer. Further power is generated by a suitable arrangement of blades similar to a traditional turbine, only the roles of blade and guide wheel are interchanged.

The condensed working fluid is caught by the rotating cylinder wall and fed back through the gap between the plate and cylinder into the evaporation chamber. By choosing the right amount of working fluid in combination with the right rotational speed the gap will always be covered. The working fluid serves as a seal between evaporation and condensation chamber. If the KDT is enclosed in a sealed static housing then the vapors of the working fluid are well insulated from the environment. Such a setup also reduces the friction of the rotating cylinder. The goal is to achieve an overall electrical efficiency of 10%. For a typical residential home heating this would yield 1.5-2 kW of electrical output. In order to achieve the necessary thermal efficiency for the temperatures and pressures under consideration one has to use some kind of ORC fluid3. So far experiments have been carried out with air and water, simulating the pressure difference between evaporation and condensation chamber and testing the sealing behavior of the working fluid. In the next step an organic fluid will be used together with an appropriate heat source. On the theoretical side we have done calculations relating to the fluid seals the heat transfer and the Ljungström like blade assembly for a 2-stage turbine with rotating nozzles.

The KDT is essentially a fully integrated power plant with numerous advantages: Very few parts, no valves, and no seals, allowing for a competitive realization and low maintenance costs. The goal is to build a robust integrated CHP heat-power transfer for € 1.000

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EXPERIMENT OF PUMPLESS ORGANIC RANKINE-TYPE CYCLE FOR LOW-TEMPERATURE WASTE HEAT RECOVERY

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ABSTRACT

Among the components of the conventional organic Rankine cycle (ORC) for low-temperature waste heat recovery, the working fluid pump tends to cause a critical decline in the net cycle efficiency. Pump efficiency drops sharply under off-design conditions, such as high or low pressures at the inlet/outlet and mass flow rates that are greater or lower than the designed value. This trend is pronounced in systems whose power output is less than 10 kW and whose heat source temperature level is less than 200 deg C (473 K). Furthermore, the working fluid pump limits the compactness of the system arrangement because the pump must be placed at a level lower than that of the condenser (i.e., a net positive suction head of the pump) in order to maintain sufficient inlet pressure to prevent the occurrence of cavitation, which results in considerable power consumption by the pump. These adverse effects of the working fluid pump appear in any ORC system with a small power output and a low-temperature heat source whose temperature level and heat amount vary during operation. It should be noted that heat obtained from renewable energy sources, such as solar thermal energy, geothermal energy, waste heat from factory processes, biomass thermal energy, and heat obtained from the automobile engine have similar characteristics.

To overcome the abovementioned problems, one of the authors have attempted to develop “pumpless” ORC system [1]. The pumpless ORC mainly consists of an expander, two heat exchangers, and switching valves for the expander and heat exchangers. Instead of using a working fluid pump, the switching valves method (SVM) is employed to control the cycle. The SVM makes each heat exchanger switch between functioning as an evaporator and functioning as a condenser. In this arrangement, the working fluid flows back and forth between the two heat exchangers without a working fluid pump. Therefore, this cycle does not involve problems caused by a pump. The first experimental result with a displacement-type expander was carried out to clarify the feasibility of pumpless ORC. The experimental results showed that the proposed cycle works and produces power. Time-varying characteristics of the proposed cycle will be also shown and discussed.

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A NEW CONFIGURATION FOR ORGANIC RANKINE CYCLE POWER SYSTEMS

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In the large spectrum of organic fluids suitable for Rankine cycles, a fluid that is already well-known and available on industrial scale but currently excluded from this kind of application has been selected.
This choice is due to the remarkable characteristics of the fluid, such as its high molecular weight, good thermal stability, non-flammability, and atoxicity.

Compared to those fluids nowadays common in the ORC market, its thermodynamic properties and fluid dynamic behavior lead to a peculiar configuration of the cycle:

- Supercritical cycle, when heat input is at medium-high temperature;
- Massive regeneration, to obtain higher efficiency;
- Low specific work of the turbine;
- Relatively high volumetric expansion ratio and relatively low absolute inlet volumetric flow;

Accordingly, an innovative cycle design has been developed, including a once-through Hairpin primary heat exchanger and a multi-stage radial outflow expander.
This last innovative component has been designed to get the best performance with the chosen fluid:

- The high inlet/outlet volumetric flow ratio is well combined with the change in cross section across the radius;
- Compared to an axial turbine, the lower inlet volumetric flow is compensated by higher blades at the first stage. It is feasible thanks to the change in section available along the radius, so that there is no need for partial admission;
- The prismatic blade leads to constant velocity diagrams across the blade span;
- It minimizes tip leakages and disk friction losses, due to the single disk / multi-stage configuration;
- The intrinsical limit of a radial outflow expander to develop high enthalpy drop is not relevant for this cycle, presenting itself a very low enthalpy drop. Moreover the tip speed is limited by the low speed of sound and consequently this kind of expander suits well with this cycle arrangement.

The results of this study, conducted through thermodynamic simulations, CFD, stress analysis and economic optimization show an ORC system that reaches high efficiencies, comparable to those typical of existing systems.

INVESTIGATING THE DOUBLE-STAGE EXPANSION IN A SOLAR ORC

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ABSTRACT

A small-scale, low-temperature Organic Rankine Cycle (ORC) is developed at the moment, within the framework of the project 09SYN-32-982, partly financed by the greek government. The heat input will be provided from evacuated tube solar collectors (maximum heat input: 100 kW_{th} at around 130 °C), while the power produced will feed a Reverse Osmosis unit for desalinating seawater. Due to the seasonal, and mainly daily, solar radiation variation, critical issues should be addressed, in order to improve the performance of the system. Some important issues involve the control of the pump and the expander, and the fundamental design principles of the ORC (e.g. heat exchanger sizing, evaporation temperature etc.).

One design principle that has not been extensively investigated so far is the number of expansion stages of the organic fluid, where two major configurations are identified for small-scale ORCs (except for the single-expansion). The first configuration concerns the use of a cascade ORC (two circuits), where the condensation heat of the upper-stage (with higher temperature) is actually the evaporation heat of the lower-stage [1]. The second configuration consists of a single circuit, with two expanders connected in-series, where the first expander is by-passed at low heat input [2]. Both these configurations can improve the performance of the system at part load in comparison to a single-expansion ORC, if they are properly controlled.

The first goal of this study is to theoretically investigate the performance of these two alternative configurations under intermittent heat input (and feed temperature). For both configurations the same parameters have been used (e.g. organic fluid's subcooling/superheating, expanders' efficiency etc.) and the organic fluids have been carefully selected (HFC-245fa/HFC-134a for the upper/lower-stage respectively [3] and HFC-245fa for the two in-series expanders ORC). The thermal efficiency is calculated for each configuration and for the whole range of heat input (0-100%). An interesting observation is the increased efficiency of the ORC with two in-series expanders for the entire range of heat supply. Especially at low heat input, the efficiency gain is significant (4% instead of 2%), while it is limited at the maximum heat input (10.4% instead of 9.8%). Additionally, in the cascade ORC design the installation cost increases, due to the use of additional components and the higher complexity of the control unit of the system. The final design chosen is the one with two in-series expanders. Next steps will be the development of a smart control logic, the design of the system and at a later stage the construction of a prototype unit.

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ENHANCEMENT OF THE ELECTRICAL EFFICIENCY OF COMMERCIAL FUEL CELL UNITS BY MEANS OF AN ORGANIC RANKINE CYCLE: TWO CASE STUDIES

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ABSTRACT

Fuel cells (FC) are a promising technology for distributed electricity production, especially for power applications in the few hundred kW to 10 MW size range, but they have not yet achieved significant penetration into energy market, mainly due to their high specific costs compared to other conventional technologies. They can be applied to combined heat and power, recovering heat dissipated by stack exhaust gases, when the power plant can be installed in presence of a heat demand, and they can use natural gas as primary fuel as well as biogas (for instance from wastewater treatment) or fuel blends. A possible way to improve a FC power plant economics consists in enhancing the electrical efficiency of the overall system as much as possible, exploiting the waste heat to generate additional electricity by means of an Organic Rankine Cycle (ORC) used as a heat recovery bottom cycle [1]. In this paper, the potential benefits of the integration between a fuel cell (topping cycle) and an ORC (bottoming cycle) are assessed in relation to a specific case study, related to a fuel cell unit which is in an early commercialization stage: the molten carbonate fuel cell (MCFC) unit recently proposed by Fuel Cell Energy [2].

This kind of fuel cell has been selected due to its well established performances, its increasingly competitive cost of electricity and its availability on the market. On the other hand, the relatively low temperature of the exhaust heat generated by the fuel cells (the exhaust gases are released from the MCFC at about 370°C) is particularly suitable for recovery through a bottoming cycle based on the ORC technology. ORC are nowadays more and more applied in many fields, for example in the exploitation of low entalphy geothermal sources [3] or waste heat from biomass. In this study, to enhance the performances of the fuel cell+ORC combined cycle, both subcritical and supercritical technology for the ORC are considered and optimized for the chosen working fluid.

Thanks to the modular features of the fuel cell system, it is possible to analyze two different power sizes, with the ORC resulting at about 500 kWel and 1 MWel power output, evidencing scale effects on the integration. Simulation of the integrated plant of the bottoming cycle are performed in Aspen Plus® environment and optimized by means of a Matlab® code. Results show that recovering waste heat from a MCFC unit could increase the electrical power and efficiency of the plant by more than 10%, well exceeding a 50% overall electrical efficiency. A preliminary economic analysis investigates the feasibility of the proposed solution, showing a reduction of about 8% of the levelized cost of electricity (LCOE) of the MCFC plant. On the other hand, an environmental comparison shows the extremely low pollutant emissions which could be achieved by this power plant with respect to competitive conventional technologies.

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ENERGETICAL, TECHNICAL AND ECONOMICAL CONSIDERATIONS BY CHOOSING BETWEEN A STEAM AND AN ORGANIC RANKINE CYCLE FOR SMALL SCALE POWER GENERATION

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ABSTRACT

To generate electricity from biomass combustion heat, geothermal wells, recovered waste heat from internal combustion engines, gas turbines or industrial processes, both the steam cycle and the Organic Rankine Cycle (ORC) are widely in use. Both technologies are well established and can be found on comparable applications.

This paper presents a thermodynamic analysis and a comparative study of the cycle efficiency for a simplified steam cycle versus an ORC. The most commonly used organic fluids have been considered : R245fa, Toluene, (cyclo)-pentane, Solkatherm and 2 silicone-oils (MM and MDM). Working fluid selection and its application area is being discussed based on fluid characteristics.

The thermal efficiency is mainly determined by the temperature level of the heat source and the condenser conditions. The influence of several process parameters such as turbine inlet and condenser temperature, turbine isentropic efficiency, vapour quality and pressure, use of a regenerator (ORC), is derived from numerous computer simulations. The temperature profile of the heat source is the main restricting factor for the evaporation temperature and pressure.

Finally, some general and economic considerations related to the choice between a steam vs. ORC are discussed.

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THERMODYNAMIC ORC CYCLE DESIGN OPTIMIZATION FOR MEDIUM-LOW TEMPERATURE ENERGY SOURCES

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ABSTRACT

In the last ten years, the increasing attention to pollutants and greenhouse gases emission from the power generation sector and the concerns about fossil fuel supply and price have led to a massive growth of those technologies that can produce electric energy from renewable sources or from waste heat recovery.

In this context, the exploitation of heat from a wide variety of sources, like hot geothermal brines, sun and exhaust gases from engines and industrial processes using an Organic Rankine Cycle (ORC) is certainly one of the most promising solution.

The basic idea is to exploit low and medium enthalpy energy sources by a Rankine cycle using an organic fluids instead of water as working fluid. This choice is confirmed by several feasibility studies and industrial applications which clearly show that, in a range from 500kW to 5MW, ORC power plants can reach higher efficiencies than common Rankine steam cycles. Moreover, ORC power plants guarantee a compact design of turbines, primarily thanks to the properties of organic fluids, and permit to overcome the drawbacks related to the challenging design and the high specific cost of steam turbines in the considered power range.

Fluids normally used in ORC plants cover a large variety of different compounds like siloxanes and perflourated organic molecules, whose thermodynamic properties notably differ from each other in term of critical parameters, maximum allowable temperatures and chemical stability.

The wide option in the available working fluids and the various types of cycles that can be adopted entail a non univocal choice for the exploitation of a given heat source.

An Excel®-VBA code was created in order to define the most efficient combination of fluid and cycle thermodynamic parameters. Thermodynamic properties of fluids are taken from Refprop® database, which allows to carry out the study with huge number of fluids including most of the commercial refrigerants, hydrocarbons and siloxanes.

To achieve the purpose of this study, different heat sources at variable temperature are considered, in order to model the exploitation of different primary energy sources like medium-low enthalpy geothermal brine, solar energy and biomass or waste heat from industrial processes and endothermic engine exhaust gasses.

For all the above-mentioned cases, an extensive thermodynamic analysis is carried out by investigating the potential of a number of fluids with different cycle configurations, starting from the basic non-recuperative saturated cycle up to supercritical and two pressure level cycles that allows the achievement of the highest efficiencies. The effects of fluid choice and cycle parameters on the main component design, e.g. heat exchangers surface and turbine size, are also discussed to provide a further term of comparison between the different options.

All the plant assumptions for the calculation of the plant components, in particular related to heat exchangers and turbo-machinery, are set on the basis of data from literature, real power plants data sheets and preliminary design.

SIMULTANEOUS OPTIMIZATION OF CYCLE AND HEAT EXCHANGER PARAMETERS FOR WASTE HEAT TO POWER CONVERSION AT ALUMINIUM PLANTS

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ABSTRACT

Aluminium production generates vast amounts of heat. In Norway, smelting plants are installed in remote places were there is no market for the surplus heat as such. Conversion to electricity is an attractive alternative. However, power production from medium to low temperature heat sources is today impeded by high investment cost and poor efficiency. Cycle optimization is critical.

One interesting heat source in an aluminium smelter is the pot gas. This is a sensible heat source, in which temperature decrease as heat is recovered. In order to recover more heat, the area of the Heat Recovery Heat Exchanger (HRHE) has to be increased. As the conversion efficiency from heat to power decreases with the heat source temperature, increase of power production will come to the expense of a large increase of HRHE area and therefore will lead to a non linear increase of plant cost.

An in-house power cycle simulator based on physical heat exchanger geometry has been implemented. It allows for simultaneous optimization of power cycle parameters (heat uptake pressure and working fluid mass flow) and HRHE geometry, such that for a given maximum area of the HRHE, a maximum net power output is found. External constraints such as maximum cooling of the heat source can be taken into account in the optimization procedure.

The case of a typical aluminium smelter was investigated. Typical power production potential and heat exchanger size and optimal layout were obtained. The performance of subcritical R134a cycles and supercritical carbon dioxide cycles are compared.

RANKINE CYCLE PLANT DESIGNS FOR WASTE HEAT RECOVERY

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ABSTRACT

This paper summarizes experience in developing cycles, configurations and equipment for electricity generation from low grade waste heat.

Theoretical investigation and practical applications in the past are briefly presented and referenced. Applications of this technology (which matured mainly in geothermal applications), to the recovery of exhaust heat of simple cycle gas turbines driving compressors on gas pipelines, gas processing plants, cement and glass industries are presented.

Many pilot plants were constructed generally operating for a relatively short time, such as in Raft River Idaho and Heber Binary in California. In the last 20 years, four manufacturers brought the Organic Rankine Cycle (ORC) to maturity assuring a reasonable life span in the geothermal energy utilization, the companies include: Barber Nichols in the U.S., Ben Holt in the U.S., Turboden of Italy and ORMAT.

Ormat has manufactured about 100 MW in capacities ranging from 200 kW to 20 MW of Waste Heat recovery ORC plants and about 1200MW for geothermal applications in capacities from 200 kW to 130 MW.

Most of the compressor stations have a capacity below 50 MW and operate basically unattended. The complexity and the necessity of an operator prevents the use of bottoming steam systems (combined cycle) on this size of plant. Hydrocarbons condense at higher pressure than steam. This feature mitigates the need for vacuum maintenance. Most of these plants are air-cooled, thus enhancing sustainability in addition to reducing the environmental impact. In these applications, which are mainly retrofits, the ease of ORC operation make its use possible where steam turbines were unsuccessful. Supplied oil temperature to the OEC is between 160°C to 200°C and the return temperature is 90°C.

Power generation from waste Heat is also applicable to other industries such as glass and cement manufacturing. For example, at the Heidelberg's Cement Plant, Lengfurt, Germany, waste heat from the clinker cooler is recovered in a heat exchanger after the precipitator. Under these operating conditions 8.2 MW of heat is transferred from the clinker cooler waste air flow to the thermal oil circuit and fed into the ORC facility connected behind, where it is used as a heat source. Under the operating conditions, some 1.3 MW of 50 Hz electric power is generated.

Many commercial plant applications will be presented in the applications mentioned above, cycle parameters and operational results are also included.

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ORGANIC RANKINE CYCLE FOR SOLAR APPLICATIONS

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ABSTRACT

The presentation describes the characteristics of experimental solar-powered units ranging from 600W to 5 MW. A historical perspective is given of piston engines of the 1940s and sealed 600 W turbo generator-driven pumps in Africa. In the 1980s, three solar pond-powered Organic Rankine Cycle (ORC) power plants were built providing 150, 70 and 5000kW. One of the ORC systems operated for 15 years in Texas. Details of the 5 MW ORC with a solar pond will be presented. The turbo generator itself displayed conversion efficiency in terms of the input and output temperature to the turbine, over 60% of the Carnot limit. With the actual condensing temperature at 30°C of this installation, the thermo-dynamic conversion efficiency was 5.7%.

The Bureau of Reclamation Solar Pond Power Plant, consisting of a 70 kW Ormat Organic Rankine Power system, generated power from a 3000 sq m. solar pond. In 1986, it was installed in El Paso, Texas and operated for 14 years. The program addressed control of salinity, to generate power and produce fresh water in Western United States.
In 2005 a 1.5MW (gross) ORC was supplied to Arizona Public Service (APS), powered by a Parabolic Trough. This project demonstrated the ease of operation and, in addition, an early start of operation thanks to the low cut-off of the system.

The combination of the highly reliable and low maintenance ORC units coupled with a 160-400°C thermal fluid temperature solar collectors, is cost-effective for power plants up to 10 MWe. Another promising path for this technology is the combination of the solar ORC with a simple biomass backup boiler allowing an "all renewable solar-biomass" package. The system can be operated with or without heat storage.

Technical details and operating parameters will be presented for the aforementioned applications.

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THE VERDICORP ORC TURBINE

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ABSTRACT

Verdicorp, a company focusing on next generation green technologies (www.verdicorp.com), has completed the development of an oil-free ORC turbine as a derivative of the award-winning, high-volume Danfoss-Turbocor direct-drive centrifugal HFC134a refrigeration compressor and is in the final phase of product qualification of its first three models with turbine output powers of 50, 60 and 75 kWel. The turbine is designed for low temperature heat source ORC applications.

The fluid section of the turbine consists of a single-stage radial-inflow turbine using HFC245fa as its working medium. The remainder of the machine contains - just like the Danfoss Turbocor compressor - a set of active magnetic bearings, a high-speed (up to 45,000 rpm) direct-drive permanent magnet generator and a power module that converts the high-frequency power of the generator to the regional 50/60 Hz line frequency at 380/400/460/575V to satisfy local grid requirements. Turbine, generator, bearings, power conversion and control are all integrated in a single hermetically sealed unit, cooled internally by the working fluid, resulting in a very compact design. The variable-speed operation of the unit allows variation of the turbine speed to adjust for differences in available head/pressure ratio as a result of changes in ambient heat sink temperatures. The inverter section of the turbine allows grid-independent island operation of the ORC system.

Prototype testing at actual operating conditions has started April 2010 and was successfully completed late last year. A number of field trial units are currently running at beta sites. Field trial qualification will be completed later this year.

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SMALL ORGANIC RANKINE CYCLE POWER UNITS FOR REMOTE UNATTENDED APPLICATIONS

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ABSTRACT

Over the last 40 years, the development of backbone telecommunications systems and construction of strategic oil and gas pipelines has spanned tens of thousands of kilometers in harsh environments (arctic to tropical, unmanned or developing areas). As the vast majority of these areas are off grid, the need arose for a highly reliable and maintenance-free power supply to allow the continuous operations of these projects.

The objectives for high reliability in telecommunications, cathodic protection and SCADA systems in strategic projects have become very demanding and the problems faced by power systems designers in areas not serviced by commercial power are very stringent. This since power generators must operate continuously on a 24-hour-per-day, 365-days-per-year basis.

Modern solid state electronic equipment require relatively low power (from a few hundred watts to 4 kW) but stringent requirements for power supply: high reliability, long life (20 years+) and low maintenance. Conventional diesel generators were not adequate. Intensive research followed in the development and application of sophisticated energy converters with attention directed to practical units. Two technologies emerged: the Thermoelectric Generator (TEG) and the Organic Rankine Cycle-based Closed Cycle Vapour Turbine Generator (CCVT). Both are widely used TEG bellow 1 kW and CCVT from 600 W to 4 kW. PV systems were introduced lately but are hindered by vandalism and stealing (unattended sites). And, Fuel Cells have too short a life, at least for now.

To achieve long life and avoid mechanical and thermal stress, it was necessary to develop a heat engine that would operate at comparatively low temperatures (below 200°C). To accommodate these low temperatures and small sizes, it was decided to design a prime mover, based on a Rankine cycle, specifically for the applications in mind. A turbine rather than a reciprocating engine was chosen and steam was replaced by other working fluids selected and tested for stability.

In 1966, after work on process fluid lubricated bearings and hermetically sealed systems, the first hermetically sealed solar and fuel operated systems operated and have since been followed by some 3000 fuel-operated units. These CCVT have logged more than 40 million field operational hours, many units have been in operation for more than 35 years without overhaul demonstrating a MTBF of 300 000 hours for the turbogenerator itself.

Characteristic of this class of ORC will be presented as well as case histories and key criteria for selecting remote, unattended power solutions.

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DESIGN, SIMULATION AND CONSTRUCTION OF A TEST RIG FOR ORGANIC VAPOURS

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ABSTRACT

A blow-down wind tunnel for real-gas applications has been designed, validated by means of dynamic simulation and finally constructed. The facility is aimed at characterizing an organic vapour stream, representative of expansions taking place in Organic Rankine Cycles (ORC) turbines, by independent measurements of pressure, temperature and velocity. ORC turbine performances are expected to strongly benefit from characterization of such flows and validation of design tools using experimental data, which still lack in scientific literature.

The flow field investigation within industrial ORC turbine passages has been considered strongly limited by the unavailability of calibration tunnels for real-gas operating probes, by poor plant availabilities and by restricted accesses for instrumentation. As a consequence, the opportunity of building a test rig has been exploited and a dedicated facility has been implemented.

The paper thoroughly discusses the design and the dynamic simulation of the apparatus, presents its final layout and shows the facility “as built”.

A straight-axis planar convergent-divergent nozzle represents the test section for early tests, but the test rig can also accommodate linear blade cascades.

The facility implements a blow down operating scheme, due to high fluid densities and temperatures of operation, which result in an unaffordable thermal power to be provided in case of continuous operation. A wide variety of working fluids can be tested with adjustable operating conditions up to maximum temperature and pressure of 400 °C and 50 bar respectively. Despite the fact that the test rig’s operational mode is unsteady, the inlet nozzle pressure can be kept constant by a control valve.

In order to estimate the duration of both set-up and experiments and to describe the time evolution of the main cycle processes (namely the fluid heating/evaporation, the vapour expansion and the vapour condensation) the dynamic plant operation, including the control system, has been simulated.

Design and simulation have been performed with either a lumped parameter or a 1D approach using siloxane MDM and hydrofluorocarbon R245fa as the reference compounds and by adopting state-of-the-art thermodynamic models of the selected fluids.

The above calculations shown how experiments may last from 12 seconds to several minutes (depending on the fluid and test pressure) while their set-up requires a few hours. These durations have been considered consistent with those required to perform the desired experiments. Moreover, the economic constraints have been met by the technical solution adopted for the plant, allowing the construction of the facility.

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EXERGOECONOMIC ANALYSIS OF A GEOTHERMAL ORGANIC RANKINE CYCLE WITH ZEOTROPIC FLUID MIXTURES

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ABSTRACT

Optimal operating parameters for geothermal applications of the Organic Rankine Cycle (ORC) are identified under exergoeconomic criteria [1]. For typical geothermal conditions in Germany the use of the zeotropic mixture isobutane/isopentane as a working fluid is evaluated compared to the pure components. Therefore the minimum temperature difference in the evaporator and condenser is varied to figure out the minimal specific costs of electricity generation. In addition, exergetic variables, like second law efficiency and irreversibilities of each component, are calculated. The purchase equipment costs are determined as a function of heat surface area and power of the turbine or pump [2]. The costs of the fuel consist of costs associated with the exploration of the geothermal resource and operating and maintenance costs of the borehole pump.

The results of the exergetic analysis show that second law efficiency using the zeotropic mixture increases up to 15 % compared to the pure components. Due to a better glide matching the irreversibilities in the condenser decrease significantly for those mixture compositions, where temperature glide at phase change and temperature difference of the cooling water are equal. In general the condenser shows the highest required surface area in consequence of a low logarithmic mean temperature difference and a high amount of transferred heat. In case of fluid mixtures, a reduction of the heat transfer coefficients due to additional mass transfer effects lead to a higher surface area of the condenser and evaporator compared to pure fluids. Therefore the total purchase equipment costs increase in the range of 5 % and 30 %. In case of pure working fluids, isobutane leads to slightly lower specific costs of electricity than isopentane. In both considered geothermal case studies, the most suitable concept under exergoeconomic criteria is the choice of the fluid mixture as a working fluid.

The investigations show that the use of an isobutane/isopentane mixture is a promising optimization strategy for low-temperature geothermal applications. Related with high exploration costs, the efficiency increase overcompensates the additional heat transfer areas. The calculations point out that fluid selection would differ significantly, if a constant minimum temperature difference in the condenser and evaporator was assumed.

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INFLUENCE OF CONDENSER CONDITIONS ON ORC LOAD CHARACTERISTICS

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ABSTRACT

Introduction:
Within the EU-project POLYCITY over six years of supply and demand in a city quarter with app. 7000 people have been monitored. The cornerstone of the energy supply is a combined heat and power plant (CHP) with 5.3 MW_{th} and 1 MW_{el} nominal output based on an ORCycle. A district heating system is serves as sink for the power plant and a thermal cooling device (single effect absorption chiller) is connected to it. All applied systems such as biomass furnace, thermal oil system, district heating and heat rejection unit have been monitored long-term, to show the constraints of the heat guided operational mode for the grid feed-in. The measured states have been analysed to elaborate the influence of components in the process.

Relevance:
Many ORC systems fuelled by biomass are heat-guided. In order to increase the annual or seasonal overall performance, the interaction of heat losses, electric efficiencies and performance of thermal cooling systems have to be taken into account. Questions regarding solar thermal support of district heating in summer can only be clarified in this way.

Method:
Measured data from the control system have been collected and transferred via an OPC UA interface (OLE for process control – unified architecture). With custom software the values could be acquired and saved in a database. Combining and unifying the data from the internal control and the external metering systems a comprehensive view on the conditions of the system is given. Thermodynamic states of the silicone oil are computed by using the formulations in the Refprop library based on Colonna, Nannan and Guardone. The observed characteristic is compared to the expected results from a condenser model.

Results:
Various mass flows, temperature levels and temperature spreads result in varying pressure levels in the condenser. The pressure level ranges from 90 mbar to 140 mbar at feeding temperatures between 72 °C and 85 °C. High mass flows on the secondary side, respectively low temperature spreads, result in lower pressures. These lead to higher electric efficiencies due to higher pressure differences across the turbine. The findings give several conclusions for an economic operation of ORCs. Under normal operation conditions the overall influence of the condenser conditions sum up to one percentage point in electric efficiency. The question of higher efficiencies versus increasing pump power in the district heating network is discussed.

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OPTIMIZATION OF SUBCRITICAL AND TRANSCRITICAL ORC'S FOR LOW TEMPERATURE HEAT SOURCES

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ABSTRACT

Many types of low temperature (100-150°C) heat sources exist: waste, geothermal, solar, ... Classical, water-based power cycles cannot convert this heat into electricity efficiently. For these heat sources an Organic Rankine Cycle (ORC) is the better choice. In this paper, the thermodynamic optimization of ORC's for low-temperature heat sources is discussed and transcritical cycles are compared to subcritical cycles.

In the literature, different efficiencies (energetic, exergetic, ...) are defined. For economic reason, it is concluded that the total plant efficiency should be maximized and not the cycle efficiency as is often done in the literature. This is because the latter efficiency does not take into account the heat source cooling.

On our search for optimum plant designs, we investigated both subcritical and transcritical ORC's. The advantage of the latter cycle is that the fluid does not pass through the two-phase region during heating, so a better fit between the working-fluid heating curve and heat-source cooling curve is achieved. Less irreversibilities are generated in the heat exchange and higher efficiencies can be obtained.

The simplest ORC configuration is compared to cycles with a recuperation heat exchanger and to cycles with turbine bleeding. It is concluded that these two extended cycles are only useful when a limit on the heat-source-outlet temperature exists.

The optimum working fluid depends strongly on the heat source inlet temperature and the optimum cycle is often of the transcritical type. With a careful choice of the working fluid exergetic plant efficiencies of 50-60% can be achieved.

Due to the low temperature of the heat source, both the plant and cycle efficiency decrease strongly with increasing condenser temperature and pinch-point-temperature difference. So for low-temperature heat sources, a low condenser temperature and low pinch-point temperatures are even more important than in classical power plants.

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SUITABILITY OF SILOXANES FOR A MINI ORC TURBOGENERATOR BASED ON HIGH SPEED TECHNOLOGY

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ABSTRACT

Most of the Organic Rankine Cycle (ORC) power systems currently on the market features an electrical power output in the range 100 kWe – 5 MWe. However, there are many energy conversion applications where an ORC energy converter with an electrical power capacity of ca. 10 kWe is attractive. Examples are heat recovery from prime movers, concentrated solar power, small-scale cogeneration of heat and power (e.g. for domestic use). In all these applications the thermal source is at moderate or high temperature. One of the key issues in designing a small-scale ORC turbogenerator is the selection of a suitable working fluid.

Siloxanes have been successfully adopted in high-temperature ORC power plants for larger power capacities (400 kWe – 2 MWe). The main focus of this study is the evaluation of eight siloxanes as working fluid for a small-capacity ORC turbogenerator based on a high-speed technology.

High-speed technology refers to the concept of a compact hermetic component containing the turbine, the generator, and the feed pump coupled to the same shaft, rotating at high speed (typically more than 20 000 rpm) and using the working fluid in the liquid phase to lubricate the shaft bearings. The siloxanes considered in the study are D4, D5, D6, MM, MDM, MD2M, MD3M, and MD4M. Toluene is included in the analysis as a reference working fluid.

The effects of adopting different siloxanes on the thermodynamic cycle configuration, conversion efficiency, and on the turbine and component design are studied by means of computations. The working fluid parameters which are most influential are the critical temperature and pressure, and the molecular complexity, and, related to them, the condensation pressure, density and specific enthalpy over the expansion which affects the optimal design of the turbine. The fluid thermal stability is also extremely relevant in the considered applications.

The results of this study provide valuable information for the design of efficient ORC systems in the tens-of-kW power range utilizing siloxanes as working fluids. Further research will be centered on technological issues, such as material requirements, process component design, as well as safety and reliability issues.

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PRELIMINARY DESIGN OF ORC TURBOGENERATORS FOR WASTE-HEAT RECOVERY IN AUTOMOTIVE APPLICATIONS

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ABSTRACT

This presentation documents recent work performed within a cooperative project funded by the Austrian funding agency involving TU Graz, TU Delft and two European OEMs targeted at investigating options for converting the thermal power discharged by automotive engines via flue gases and the cooling system into mechanical/electrical power. The efficiency of reciprocating engines of cars and trucks has arguably reached its maximum limit and only marginal gains can be obtained by improving on currently adopted technologies. These engines discharge to the environment approximately 66% of the fuel energy content as thermal energy. The energy is available at different temperature levels depending on the type of engine: in car engines the temperatures range from 300 °C to 900 °C for the exhaust gases, and from 90 °C to 110 °C for the cooling system; in truck engines the two heat sources with the highest potential are the exhaust gases with temperatures ranging from 200 °C to 400 °C but thermal energy is available at even higher temperatures (280 °C to 580 °C), if also the heat from the exhaust gas recirculation (EGR) system is recovered. It is apparent that there is still a large fraction of the primary energy that is still untapped and the potential overall energy efficiency gain offered by effectively recovering wasted thermal power is very large [1]. The principle is already widely exploited in stationary power plants, while application on board of vehicles is very challenging and no commercial application exists. The current energy scenario has resumed strong interest into automotive heat recovery systems, much like it happened in the 70's as a consequence of the first oil crisis [2].

This work is focused on one of the possible solutions to the technical problem of heat recovery for car and truck engines, namely a compact ORC turbogenerator using a siloxane as the working fluid. Two paradigmatic examples of operating conditions taken from existing automotive propellers are considered, one for a truck engine and one for a car engine. The design envelope is explored in terms of working fluid selection, thermodynamic cycle configuration, preliminary turbine and heat exchangers design, taking into consideration all the stringent requirements imposed by the automotive application. A Rankine power system using water as the working fluid is taken as a benchmark and the challenges related to adopting water as the working fluid are discussed. The results of simulations are analysed in order to provide initial guidelines and the most promising routes to successful implementation are outlined.

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PRELIMINARY DESIGN OF A LJUNGSTROM-LIKE CENTRIFUGAL TURBINE FOR ORC APPLICATIONS

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ABSTRACT

Nowadays there is a general agreement that a substantial increase in the share of energy produced in a decentralized way is a desirable perspective for future sustainable societies. As a consequence, small-scale power plants are candidates to play a relevant role in the future distributed energy scenario [1]. Among the technologies that are suitable for high-efficiency conversion of thermal power into electricity in the small to medium power range, Organic Rankine Cycle turbogenerators stand out in terms of reliability and cost-effectiveness. It is well known that, as the size of a power plant reduces, the cost of the conversion engine (typically a turbo-expander) represents an increasing part of the total investment. The use of organic compounds as working fluids leads to relatively simple plant configurations and to design compact and reliable turbines. In common ORC applications the turbine is inherently characterized by a low enthalpy drop that is usually disposed in a low number of stages (even a single stage for radial turbines, or a few stages for axial turbines). These two peculiar aspects result in a very high stage expansion ratios, that, combined with the typical low speed of sound of organic fluids, induces strong supersonic phenomena. As a consequence the turbine maximum efficiencies are in the range of 80-85 % for the largest units [2]. The development of turbines with better performances in terms of efficiency and controllability is therefore a key-theme in the field of ORC: aim of the present work is the critical evaluation of a Ljungstrom-like multi-stage centrifugal turbine whose architecture could have substantial advantages over traditional solutions [3]. Due to the absence of experience and specific literature, a wide-spectrum design procedure has been conceived. A lumped parameter code has been initially developed, on the basis of initial project assumptions, machine design criteria, such as the Mach number at outlet section, and available models for losses evaluation. The results of the 0-D code are then verified with the new throughflow solver of zFlow, a quasi 3-D CFD-based code for turbomachinery applications coupled with the FluidProp package for accurate properties calculation [4]. The calculation method is proven to be a valuable tool to efficiently select a small number of preliminary machine's designs for the proposed architecture as well as for axial machines, where consolidated experience and experimental data are not available. Furthermore this represent an effective way to determine a baseline configuration for subsequent more detailed optimizations. The overall procedure is finally applied to a 100 kW multi-stage turbine using the siloxane D4 as working fluid. The results are extensively discussed by a comparison with available data from existing machines.

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MICRO-COGENERATION BASED ORGANIC RANKINE CYCLE (ORC) SYSTEM IN A DISTRICT HEATING NETWORK: A CASE STUDY OF THE LAUSANNE CITY SWIMMING POOL

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ABSTRACT

District heating distributes heat and hot water to residential, commercial and public buildings over a large urban area. In many European cities, the heat distribution system is designed to deliver hot water at a different temperature levels in order to meet the various thermal requirements of the customers. A high-temperature loop delivers water at around 160-200°C and a low temperature loop at around 90-120°C. In case of a particular need of steam, for example in a hospital, the high-temperature (HT) water is flashed at the customer's site and the low-pressure steam is then distributed. There are often many other end-use consumers which are connected to the HT system, but they only need low temperature heating and/or hot water (e.g. below 55°C).
As an example, for the typical situation of the Mon-Repos Swimming pool of Lausanne, Switzerland, the HT heating system is operated by the "Services Industriels de Lausanne – SIL", the Heat & Power utility company, at around 170°C, but it is used for the generation of low temperature sanitary water and to heat the pool water at around 26°C.

In this context, the use of ®ENEFCOGEN^{GREEN} unit by Eneftech Innovation SA of Nyon, Switzerland, and based on an ORC micro-cogeneration system can provide substantial benefits and savings. The system generates electricity at the customer's site using the heating network as the energy source, and also serves the need for low-temperature heating. The main features and operation of a modular 15 KWe unit installed at the swimming pool in Lausanne are presented. The system runs for 7500 hours per year and saves approx 23,000CHF in terms of grid electricity previously purchased from the utility company.

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LOW GLOBAL WARMING FLUIDS FOR REPLACEMENT OF HFC-245fa AND HFC-134a IN ORC APPLICATIONS

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ABSTRACT

Organic Rankine Cycle system designs that operate with non-flammable hydrofluorocarbon working fluids such as HFC-134a (1,1,1,2-Tetrafluoroethane) and HFC-245fa (1,1,1,3,3-Pentafluoropropane) have been operating in the field for a number of years. Their growing use in geothermal, engine and industrial heat recovery organic Rankine cycle applications is noteable. These systems have demonstrated environmental benefits that validate their current and future use. Even so, there is great interest among system OEMs, equipment end-users, regulatory agencies, and the public to embrace new low global warming working fluid technologies. Honeywell has developed a number of candidate fluids that can serve as replacements for HFC-134a and HFC-245fa in refrigeration, air-conditioning, foam expansion, aerosols, and organic Rankine cycle applications.

The two fluids that can serve as replacements for HFC-134a are hydrofluoroolefins HFO-1234yf (2,3,3,3-Tetralfuoroprop-1-ene) and HFO-1234ze (trans-1,3,3,3-Tetrafluoropropene). These two fluids are being commercialized for a number of applications. A third fluid, that is a potential replacement for HFC-245fa, is a candidate to replace HFC-245fa in organic Rankine cycle applications. The environmental and thermophysical properties of the fluids are reviewed. The theoretical thermodynamic efficiency, turbine size, speed, and mach numbers of the new fluids are compared to HFC-134a and HFC-245fa. Conditions for the organic Rankine cycle are those reflecting geothermal organic Rankine cycle applications. In the case of HFC-134a and potential replacements, both sub-critical and supercritical cycles are considered.

HIGH-POTENTIAL WORKING FLUIDS FOR NEXT-GENERATION BINARY ORC

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ABSTRACT

A Department of Energy funded study of high-potential working fluids for Organic Rankine Cycles (ORC) for use in Enhanced Geothermal Systems (EGS) has been conducted. The worked completed to date, in coordination with AltaRock Energy, Inc., characterized the performance of high-potential working fluids for EGS resource temperatures. From an available list of more than 17,000 pure components, 35 working fluids were identified as high-potential. In addition to the numerous fluids that were screened from commonly available sources, additional fluids were screened from vendors that are less common or even not on the market yet. An additional 3 working fluids were included for comparison to the current state-of-the-art.

The performance of the working fluids was evaluated in a subcritical ORC, supercritical ORC, and trilateral flash cycle and compared to the performance in baseline subcritical ORCs. The primary advantage of the supercritical cycle over the subcritical cycle is a better match between resource cooling curve and working fluid heating curve. The lack of constant temperature evaporation allows the heat source to be cooled to a lower temperature despite a similar pinch point as in a comparable subcritical cycle leading to greater utilization of the geothermal resource. The topics that will be presented include a cycle performance comparison and its impact on traditional working fluid (R134a, 245fa, n-butane and n-pentane) resulting in a 30-50% increase in net power output.

This material is based upon work supported by the Department of Energy's Geothermal Technologies Program under Award Number DE-EE0002769.

A FAST TWO-STEP EVALUATION OF FLUIDS FOR MICRO ORC-CHP SYSTEMS WITH VARYING RETURN FLOW TEMPERATURES

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ABSTRACT

ORC Application for CHP can be considered as state of the art for large biomass boilers. The organic Fluid is therefore evaporated by means of a heat carrier. In a heating condenser the remaining heat from the ORC-system is transferred to a heating system.
In smaller block heat and power systems a use of an ORC is also possible. In this study different fluids are compared for different heat carrier and return flow temperatures of an ORC system.
In order to evaluate the system in a practical way, a two-step approach for the benchmarking of the suitability of different fluids is done.

In a first step, the thermodynamic potential is compared. For each combination of temperatures, isentropic efficiencies for the expansion machine as well as the feed pump are set to a fixed value. Afterwards specific boundary conditions in terms of return flow temperature in the heating condenser and heat carrier temperature in the evaporator inlet are set and optimal operation pressures and temperatures are calculated for each fluid. As optimized parameter the net power output of the system is used. The result gives an overview over which fluid is thermodynamically best for selected applications.

In a second step, constructive aspects coming along with different fluids are rated. For a fast assessment of the constructive effort and therefore the cost of the system, specific parameters as heat exchanger surface and volume flow rate are compared.
A power-independent comparison is obtained by calculating relative deviations of the constructive parameters from the optimal system of the first step optimization.
Furthermore the improvements of the systems by means of the use of a recuperator are investigated. Although theoretically improvements in efficiency and net power output can be achieved, real effects as pressure drop across the component needs to be considered in detailed planning as it decreases the technical power of the expansion machine. Moreover the cost of an extra component coming along with increasing efforts for piping and casing does not necessarily lead to cheaper power related specific costs.
By means of this two-step approach a fast evaluation of an ORC system is possible. Not only thermodynamic aspects, but also cost-related aspects can be rated and taken into account for next steps towards the realization of such a system.

The same approach for the rating of an ORC system is done in another investigation presented at the conference [1].

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HEAT TRANSFER FLUIDS - EXTENDED FLUID LIFE AND IMPROVED PLANT SAFETY THROUGH HTF SYSTEM DESIGN AND MONITORING

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ABSTRACT

ORC technology power plants using heat transfer fluids (HTF) as organic heating media are widely recognized as highly reliable and safe. Key factors responsible for the huge growth of this industry include: waste heat availability, feed-in incentives and bankable technology.

The success of the ORC sector is related to a quick return on investment which is directly linked to a continuous and trouble free plant operation thus maximizing incomes while keeping operational costs minimized.

In such context heat transfer fluids play an essential role representing a component that is in contact with both the heat source and the ORC module. Control of the HTF in-service quality can help to monitor operation conditions of the whole plant and facilitate corrective actions ahead of problems.

All heat transfer fluids are subject to degradation, which means modification of its original molecular composition can occur. Over time, thermal stress of the fluid may result to the extent it will not be able to safely and efficiently convey the heat from the source to the user. Excessive fluid degradation can lead to higher maintenance works and reduced fluid life, thus increasing the investment return time. Reasons for this excessive degradation may include choosing a fluid with less than adequate thermal stability, operational problems or procedures in the plant, or defects in heater or system design.

An accurate HTF system design and regular monitoring of fluid conditions will help to prevent unexpected system troubles and unsafe operating conditions thus enabling operators to provide timely solutions and begin corrective actions.

The requirements of an ORC plant require specific properties of the HTF used in this technology. Therminol® heat transfer fluids have been used from the start of ORC power production until today. The proven track record of these fluids contributes to reliable and smooth plant operations.

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SPEEDS OF SOUND OF SILOXANES AS WORKINGS FLUIDS IN ORGANIC RANKINE CYCLES

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ABSTRACT

Heat recovery systems, such as organic Rankine cycles (ORC), play an important role for the efficient use of fossil as well as of renewable fuels. Performance improvements of ORC processes are based on the technical development of the hardware and on the selection of appropriate working fluids. The selection of suitable working fluids is made on the basis of their thermo-physical properties and safety requirements, considering the characteristics of the heat source. Thus, efficiency increases for technically well advanced ORC plants require reliable and accurate thermo-physical property data on working fluids.

One group of ORC working fluids are the siloxanes, which belong to the wider class of organosilicone compounds. In particular, hexamethyldisiloxane (HMDS) appears to be an eligible candidate for becoming a widely used working fluid for high-temperature processes. However, the current lack of accurate thermo-physical data for siloxanes may lead to sub-optimally designed cycles and processes. Therefore, the measurement of such data is necessary.

Thermal properties in the homogeneous fluid region, together with the speed of sound and the vapor pressure are used to generate accurate equations of state (EOS) that describe the entire range of fluid states. “Properly designed multiparameter equations of state are able to represent thermodynamic properties of a certain substance within the accuracy of the most accurate experimental data” [2]. This work aims at closing the gap with respect to the speed of sound of HMDS.

The measurement mechanism of the apparatus is based on the puls-echo technique and operates up to 150 MPa in the temperature range between 250 and 600 K [1]. While emitting a high frequency modulated burst signal by a piezoelectric quartz crystal, which is positioned between two reflectors in the fluid, the speed of sound is determined by the traveled distance divided by time the signal propagates through the fluid.

For designing and constructing an ORC plant, knowledge on the speed of sound is particularly relevant for the expansion in the turbo-machine. E.g., single stage radial flow turbines rely on supersonic expansion in an upstream Laval nozzle to transform the enthalpy of the superheated working fluid vapor into kinetic energy before interacting with the turbine-wheel. The mass flow rate in Laval nozzles is directly related to the speed of sound. Even small inaccuracies in the underlying data can decrease the performance of the turbo-machine significantly.

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A NOVEL MICROJET HEAT EXCHANGER FOR DOMESTIC ORC UNIT

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ABSTRACT

The authors are at the moment involved in a large scale national project with the objective of developing a commercially available ORC CHP unit for domestic applications. This technology is also likely to be fully mature much earlier than other promising technologies such as Stirling engines and fuel cells based ones. Apart from the completely new design of the expansion machine, which presents by far the most significant challenge, the installation should be equipped with highly efficient and small heat exchangers such as evaporator and condenser. An example of a novel concept of such device is studied in the present paper.

The authors acquired knowledge and gained experience in the topic of ORC prototyping by constructing and investigating the prototype micro power plant [1]. They have also developed their own prototype microjet heat exchanger constructed using the quite attractive minichannel technology [2]. Its main part consists of 28 steel membranes with cut microchannels. Their length is 2.5 mm, width - 200 µm and depth - 100 µm, respectively. The membranes were sandwiched between the plates made of aluminum alloy. The total heat transfer surface was equal to 0.0072 m^2. The membranes and plates have had holes, through which the working media could flow and exchange the thermal energy. In each of the circuits there were 1120 microchannels.

In the paper the idea of such heat exchanger is shown together with the flow and thermal experimental results of the prototype. Two flow cases are studied, namely water-water and air-air. In case of measurements of such complex geometries recording of wall temperatures is impossible and hence determination of heat transfer coefficient difficult. Therefore the Wilson technique was used for determination of the heat transfer coefficient. The results of accomplished measurements are satisfactory with the view of developing effective heat exchangers.

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POTENTIAL OF WATER-SPRAYED CONDENSERS IN ORC PLANTS

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ABSTRACT

Heat rejection is a crucial issue in the design and operation of an Organic Rankine cycle, since more than 75% of inlet thermal power must be typically released to the ambient. Dry air condensers are often the preferred option, since no water is required for their operations. For this reason, they are selected for those ORC plants which operate in areas where large amounts of cooling water are not available.

One limit of dry condensers is their performance decay when ambient temperature increases above the design one, especially in locations where relevant daily and seasonal temperature variations occur. The effect is a reduced net power output of the ORC plant during hot hours, either due to the enhanced condensing temperature (and the consequently lower turbine expansion ratio) or the increased fans consumption (when regulated to keep a condensing pressure closer to the design one).

In order to reduce the negative effects of high ambient temperatures, LU-VE Contardo has developed the DRY and SPRAY® series, where condenser can work both in conventional "dry operation" with dry fins, or in "wet operation" mode with water sprayed onto the fins. The evaporation of the water dramatically increases the capacity of the unit, allowing to increase the net power production. It must be highlighted that most of the water sprayed onto the fins evaporates off. This means that it is not necessary to fit a drain tray beneath the unit to collect and recycle the sprayed water, excluding the possibility of any build-up of impurities in the water and the proliferation of legionella.

The ambient transition temperature from dry to spray operation is a design option which must be optimized on the basis of technical and economical considerations, taking into account the cost of the water, the price of the electricity in each condition and the maximum operating hours limit under spray operation.

The aim of the present work is the assessment of the potential of a water-sprayed condenser in ORC applications. Starting from the project of an ORC condenser for geothermal application operating with R134a, the benefits of the water-spray solution are discussed. The increased thermodynamic performance of the ORC cycle at different ambient conditions are calculated by means of an accurate numerical model, using thermodynamic properties from Refprop® code. The economic benefits at different ambient temperatures for different water cost and electricity price, which are very site dependent, are also calculated to provide a rather complete picture of the potential of this innovative option for heat rejection.

EFFICIENCY IMPROVEMENT IN PRE-COMBUSTION CO_2 REMOVAL UNITS WITH A WASTE-HEAT RECOVERY ORC POWER PLANT

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ABSTRACT

In the transition period leading to electricity generation fully based on renewable energy resources, fossil-fuel power plants need to be equipped with CO_2 removal units. An ongoing research project involving Nuon-Vattenfall, TU Delft, and ECN, is aimed at the development of pre-combustion CO_2 removal technology from an integrated coal gasification combined cycle (IGCC) plant in the Netherlands [1]. A fully instrumented pilot plant of the CO_2 capture unit has been built at the Buggenum IGCC power station and is being commissioned for further studies and experiments. The removal of CO_2 from the syngas is very energy demanding and therefore technical solutions to reduce the efficiency penalty in thermal power plants must be investigated. This study concerns the feasibility of recovering low-grade thermal energy from the CO_2-capture process by means of an Organic Rankine Cycle power plant. In comparison to geothermal applications, which are widely documented in the literature [2,3], the heat source in this case is a syngas-water mixture which is cooled from a temperature of 130-140 °C and condenses due to the heat transfer to the ORC evaporator. First, the application of commercially available ORC units is explored by means of steady-state simulations. The plant composed of commercially available ORC units is simulated and taken as a benchmark for a tailor-made ORC power plant. The working fluid has an important influence on system performance and therefore the effect of selecting a fluid from the hydrocarbons and refrigerants families are investigated, targeting the maximum net power output. In addition to pure fluids, also two-component mixtures are investigated in a subcritical ORC cycle configuration. The use of mixtures as working fluids in ORC systems allows for a better match of the temperature profiles in the evaporator and the condenser [4], due to the temperature glide associated with phase-transition, leading to lower irreversibilities within the heat exchanging equipment. In order to further improve the thermal coupling of the cooling heat source to the heating of the working fluid, a supercritical ORC configuration is also studied. The three ORC configurations (commercial ORC, customized subcritical & supercritical ORC) are analyzed in terms of net power output, second law efficiency and component-based exergy destruction.

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TWO STEP OPTIMIZATION APPROACH FOR INCREASE OF ENGINE-ORC EFFICIENCY

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ABSTRACT

Due to their high electrical efficiency (up to 47 %), internal combustion engines (ICE) are widely used as independent power producers. In order to further increase the electrical efficiency, an Organic Rankine cycle (ORC) can be applied for waste heat recovery (WHR) of the ICE.

The recoverable engine waste heat is usually available at two different temperature levels: 300 °C to 400 °C (exhaust gas) and 90 °C (engine cooling water). The integration of both heat flows and especially the integration of the cooling water heat is a certain challenge for ORC operating with one specific working fluid which is usually optimized to just one temperature level. Therefore only few examples of the recovery of both heat flows can be found both in literature and as existing power stations.

This paper presents a two step optimization approach in order to increase the overall system efficiency of an engine-ORC combined cycle by means of the integration of the heat flows at both temperature levels.

In a first step the variable cycle parameters both in the topping and the bottoming cycle (e.g. fluid evaporation pressure and temperature of the cooling water) will be defined and evaluated for different working fluids (R245fa, pentane, MDM among other) within the boundary conditions given by the technical feasibility. Furthermore the application of a recuperator is investigated since recuperation and the integration of low temperature heat are often competing efforts. The effect of higher pressure losses throughout the recuperator has to be taken into account as well. This step is aimed at the definition of a set of working parameters, which leads to an optimal system configuration for each working fluid. The optimization parameter is the net electrical power output of the system.

Within the second step important constructive aspects of the engine-ORC are rated for the selected fluids. A fast indication of the expenditure of each power-optimized system can be generated by the evaluation of specific constructive parameters such as heat exchanger surfaces and volume flow rates. Based on these design parameters a power independent comparison can be obtained by calculating the influence of relative deviations of the constructive parameters from the optimal system on the net electrical power output.

By means of this two-step approach a fast assessment of an ORC system both under thermodynamic and cost-related considerations is possible. Both aspects are necessary for the next steps towards realization of the system.

The same approach for the evaluation of an ORC system is used in another investigation presented at the conference [1].

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EFFICIENCY OF ORGANIC RANKINE CYCLE: POTENTIAL AND LIMITATIONS

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ABSTRACT

Organic Rankine Cycle (ORC), sometimes referred to as “Binary power generation systems,” are typically used to exploit low- and medium-temperature geothermal and recovered energy resources. There are numerous technical variations of such plants using different organic fluids, as well as Kalina and Trilateral cycles.
Optimizing the efficiency by matching the cycle to the heat source:
This presentation will compare theoretical cycle efficiency, field measured and net power output and performance for the different heat sources and cycle configurations.
The maximum available energy produced as work for electricity from any heat source is specified by the second law of thermodynamics. Because the rate of the sensible heat carrying fluid is not infinite, its temperature decreases as it transfers the heat to the motive fluid in the heat engine. Thus, the overall process must be envisioned as a summary of an infinite number of infinitesimally small engines. Any heat exchange increases the irreversibility i.e.: reduces the efficiency. A temperature heat transfer diagram illustrates the differences in the temperature drop between a Steam Rankine Cycle and an Organic Rankine Cycle. Because of the lower heat capacity of organic liquids and their much smaller latent heat of vaporization, these fluids let too much smaller losses of availability in the utilization of the low- or medium-temperature predominantly sensible heat streams.
The process of designing a geothermal or waste heat recovery power plant can be considered one of matching and optimization. We have a source and a sink of heat of certain characteristics and the problem is to match them with the working cycle, match the working cycle with the working fluid, and match the working fluid with the expander. What matters most is the optimization of the whole system, involving the well-known process of trading-off a loss or gain.
Examples will be given showing the impact of different factors on the net power delivered to the grid.

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TO RECUPERATE OR NOT TO RECUPERATE - ORC CYCLES COMPARED TO IDEAL CYCLES

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ABSTRACT

The performance of real power cycles for heat source in the temperature range from 100°C to 300°C is studied in this paper. A reference is made to four ideal power production cycles: Carnot, Reversible Heat Engine (RHE), Triangular and Lorenz.

The real cycles are assumed to have infinite heat exchanger area, and it is as well assumed that cooling fluid is produced by external means, without being a parasite of the power plant.

The binary cycles studied are ORC with a single high pressure level as well as two pressure levels, a saturated Kalina cycle and a supercritical cycle. Single and double flash geothermal power cycles are included as well. A few different working fluids are considered for the ORC cycles, and a few different ammonia concentrations for the Kalina cycle.

The produced power for these cycles from the same source is then compared and a range of superiority for each cycle presented. The effect of recuperation on the produced power as well as on the calculated efficiency is shown.

Finally the influence of finite heat exchanger area is analyzed and an estimate of the cooling fluid generation parasitic power made both for air and wet cooling tower system.

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