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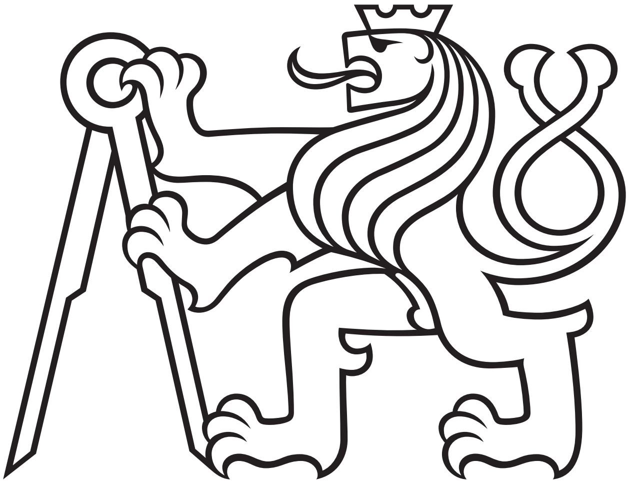

DOCTORAL
THESIS
STATEMENT

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

FAKULTA STROJNÍ

ÚSTAV energetiky

TEZE DISERTAČNÍ PRÁCE

Absorpční oběh pro produkci práce založený na solných roztocích pro využití nízkopotenciálního tepla

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Doktorský studijní program: Strojní inženýrství

Studijní obor: Energetické stroje a zařízení

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&

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Teze disertace k získání akademického titulu "doktor", ve zkratce "Ph.D."

Praha únor 2022

Název anglicky: Absorption power cycle with aqueous salt solution for low temperature heat utilization

Disertační práce byla vypracována v prezenční formě doktorského studia na Ústavu energetiky Fakulty strojní ČVUT v Praze.

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Oponenti:

Teze byly rozeslány dne: ....

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v zasedací místnosti č. 17 (v přízemí) Fakulty strojní ČVUT v Praze, Technická 4, Praha 6

před komisí pro obhajobu disertační práce ve studijním oboru Energetické stroje a zařízení.

S disertací je možno se seznámit na oddělení vědy a výzkumu Fakulty strojní ČVUT v Praze, Technická 4, Praha 6.

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Contents

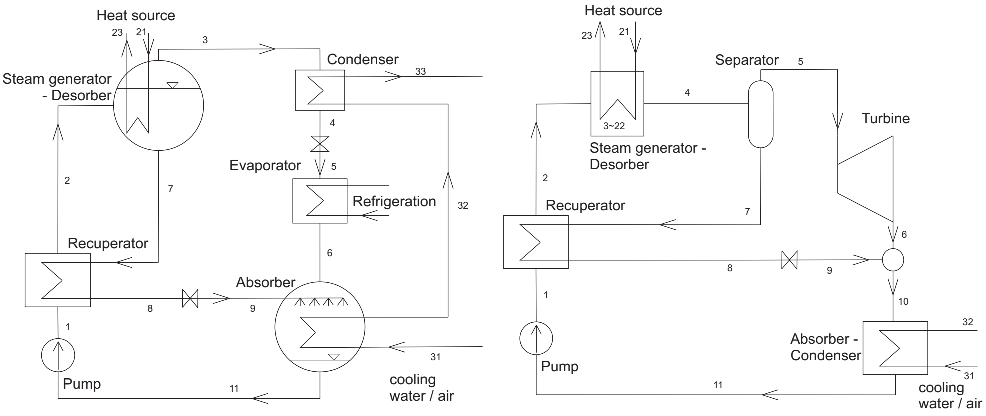
Chapter 1

Introduction & absorption power cycles review

Utilization of the low temperature and waste heat resources, especially at temperature below 200°C and in decentralized applications at the industrial sites, is field of research and development holding a large and mostly untapped potential [1, 2, 3]. Effective utilization of this heat could contribute to significant savings of primary energy sources. The conversion systems require technologies different than those used in conventional power production and for industrial, applications belong among the decentralized energy systems.

Cycle efficiency is not the most important parameter in the waste heat recovery, but the power production is [4, 5]. To get this value, cycle efficiency is multiplied by the amount of heat that can be extracted from the heat source. A heat source utilization efficiency is therefore used. The ideal cycle for this case is a trilateral (Lorenz) cycle, not Carnot cycle, as will be also demonstrated later. Parasitic load, mostly associated with secondary fluids for the heat input and heat rejection, can also largely affect the net power output [6, 7].

Organic Rankine cycle (ORC) with subcritical parameters is the most commonly employed technology for distributed heat to power systems. It has been widely documented and is widely used [8, 9], therefore is considered as a benchmark to novel explored systems. Alternatives with prospect of better performance, include supercritical ORC, zeotropic ORC, other fluids with temperature glide in absorption power cycles (APC), trilateral ORC (or organic flash cycle), inverted Brayton cycle, Stirling cycle etc. Each of them has potential benefits but also brings challenges. The heat can be also utilized by thermally activated chillers. In some cases, combined production of power, cooling and eventually heat (cogeneration and trigeneration) may be beneficial.



(a) (b)

Figure 1.1: Process flow diagrams of a) simple absorption cooling cycle and b) absorption power cycle.

1.1 Absorption power cycle concept

When the working fluid is a (zeotropic) mixture of two components with different boiling points, the actual boiling point has a temperature glide. Reports have been made on cycles utilizing this feature simply to obtain a temperature profile better matched to the heat source [10]. In the absorption process, there is further advantage of the different temperature levels at which the absorbent interfaces with the absorbed fluid at the same pressure, providing options for cooling. The typical simple cooling cycle and a simple APC for comparison are shown in Figure 1.1.

The author's review with full length in the thesis is a one of a kind work traces the origins of consideration of alternative APC working fluids and many previously overseen works from other researchers. Maloney and Robertson were among the first to study absorption power cycles using an ammonia-water mixture as a working fluid, but because of the thermal boundary conditions considered (using a desorber and absorber of the same design as in the typical cooling cycle), they found no significant thermodynamic benefit [11, 12]. Later, in several patents [13, 14], Kalina described a cycle with a slightly different configuration that exploited the temperature change throughout the evaporation and condensation process. In the cycle, the concentration of working fluid is controlled separately for evaporation and for condensation (by distillation). In the theoretical field, the Kalina cycle brought a revolution in the exergetic efficiency of resource utilization. The cycle has been partly commercialized. Numerous following theoretical works have explored various applications and system modifications.

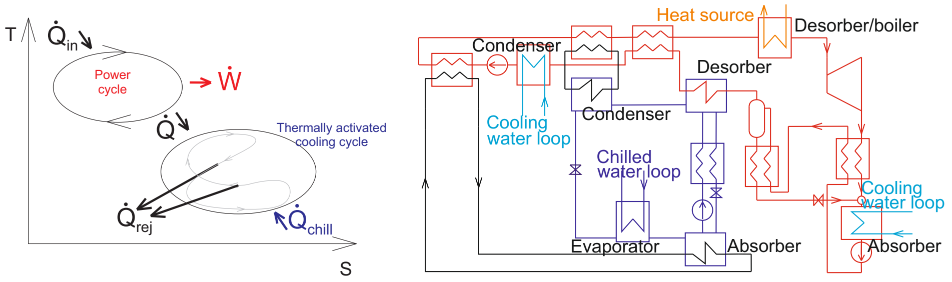
The first proposal for the use of aqueous salt solutions in absorption power cycles came from the previously mentioned study of Maloney and Robertson [11] in 1953 in which LiCl-water was mentioned as an alternative to water-ammonia. The first known consideration of a LiBr solution as a working fluid can be found in solar fuel-assisted power cycle from 1988 [15]. In 1991, several modifications of LiBr/LiCl/KOH aqueous-solution absorption power cycle were patented [16]. In 1995 was calculated cycle that uses a solution of LiBr:ZnBr:$CaBr_2$ and H_20 with an upper steam generator temperature of 70°C [17], the cycle has an efficiency of 6%, whereas a comparable steam cycle has only 2%. Operation at very low pressures is noted.

A basic energy and exergy analysis of Garcia-Hernando et al. [18] in 2013 renewed interest in cycles using salt solutions. The authors investigated the same basic scheme as in Figure 1.1b with a LiBr solution. A substantial increase in the exergetic efficiency of the cycle (not utilization) was identified when compared with the reference Rankine cycle while comparable results were obtained with ORC. An exergo-economic study [19] compared LiBr APC with a Rankine cycle and NH_3-H_2O APC using the specific exergy costing method, though arguably inapplicable to waste heat recovery and decentralized systems. LiBr APC had the highest efficiency; very low pressures and high volumetric flows logically disqualified it in an economic analysis (costing functions for large plants with hundreds MW scale). Lastly, the potential of salt solution-based APCs was included in a chapter on the Kalina cycle [20], remarking the potential of salts and presence of superheated vapour after its separation from solution. There are furthermore several works on APC with other working fluids than water-ammonia mixture or salt solutions [21, 22].

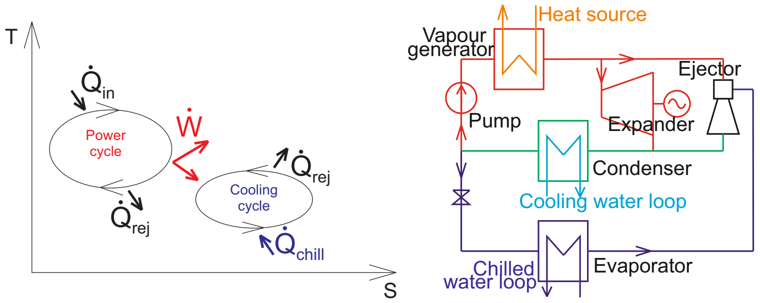
1.2 Review of absorption power and cooling combined cycles

In the combined cooling and power systems the sorption chillers are the most common thermally activated systems. When focusing on deeper integration for combined cooling and power (CCP) cycles, they have been discussed review works [12, 23]. The range of the CCP systems based on thermodynamic cycles found in the literature, regardless of the often high level of complexity, can be by by author of the thesis classified into four categories, outlined in Figure 1.2.

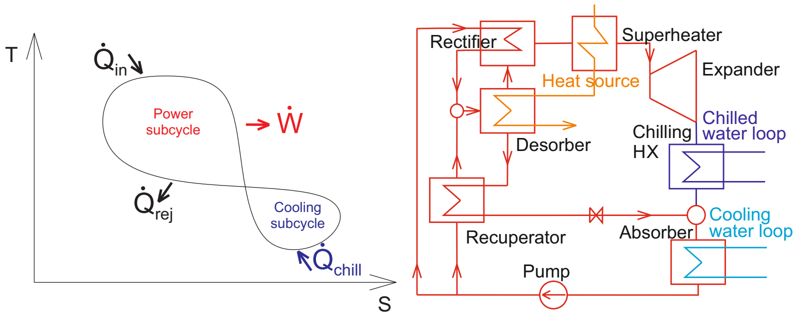
Only the branched concept is further elaborated in this summary. The simple form of the cycle comes from [26]. This configuration provides flexibility by routing vapour to the expander or chiller branch. Such a system has been experimentally analysed [27] with water–ammonia fluid (and implementing rectifier). A mixture of ammonia and salts has been proposed in [28, 29]. Regardless of apparent advantage of combining salt solution APC and chiller in this feasible configuration, such system has not been reported in the literature.



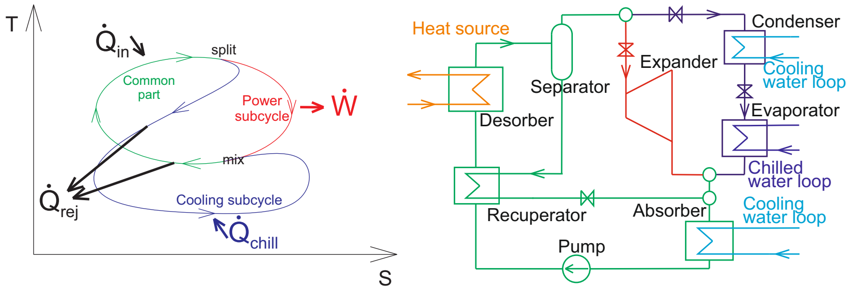
(a) T-s Diagram (b) Example Schematic



(c) T-s Diagram (d) Example Schematic



(e) T-s Diagram (f) Example Schematic



(g) T-s Diagram (h) Example Schematic

Figure 1.2: Schematic *T*-*s* and process diagrams of CCP systems with: **(a-b)** two separate cycles coupled by heat (example redrawn from [24]), **(c-d)** two separate cycles coupled by work (ex. from [25]), **(e-f)** single-branch thermodynamic cycle (ex. from [12]), and **(g-h)** two-branch thermodynamic cycle

1.3 Working fluids

Previous research had mostly focused on cycles using a water-ammonia mixture. Aqueous solutions of salts as LiBr, known from absorption chillers, are considered less. Other fluids are seen exceptionally and include amyl acetate-CO_2 or alcohol mixtures [21, 22] for APC. For cooling or APCC cycles these are ammonia-salts mixtures with either lithium nitrate or sodium thiocyanate [12, 23] or ionic liquids or organic fluids such [30, 31, 32]. Ionic liquids can be paired with various absorbates. [33] This work is focused mainly on potential of aqueous salt solutions, where the absorbent salt (LiBr) is non-volatile. The relationship between concentration, temperature and phase composition can be depicted using a Dühring plot to show boiling-point elevation. Example for a cooling cycle and the below-calculated APC is shown in Figure 1.3.

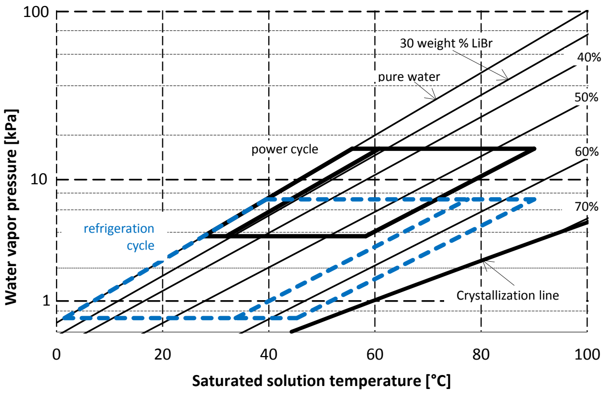


Figure 1.3: A Dühring diagram for a LiBr aqueous solution with APC and cooling cycle, both with a highest temperature of 90°C.

1.4 Experimental and commercial APC

No experimental APC with salt solution has been reported in the available literature before author's work. Experience is limited to water-ammonia mixture. Kalina cycle was partly commercialized with most of the units in MW scale but poor reliability. Problems with commissioning and operation, corrosion [34, 35] or very high pressures [35] were reported. Unterhaching and Husavik plants were decommissioned early [36]. The second experimental system is the Goswami APCC, explored in detail in dissertations [37, 38, 39] as a unit with thermal input of about 10 kW in hot water and electrical superheater. Purpose of the systems was as a proof of concept which successfully demonstrated reaching of sub-ambient temperatures. The cooling effect was however lower than predicted due to low expander efficiency and departure of measured values from modelled thermodynamic equilibrium.

Chapter 2

Prospective components design

In order to be able to successfully design the proposed APC, a review for consideration on construction of absorption systems and their major components of the cycle is performed and presented in the thesis. One of the key aspects of design of heat exchangers is the temperature glide of the bulk temperature in the phenomena of desorption and absorption. It is often taken as a given fact for both water-ammonia and LiBr-water systems [40]. The available literature failed to provide experimental confirmation of the actual temperature profile in the heat exchangers with the temperature glide during phase change. The available information for commercial Kalina plants are limited to statements of boiling taking place in a Shell & Tube or plate type heat exchanger and absorber being of a plate heat exchanger type. This is regardless of a number of theoretical studies on the Kalina cycle. Similar is the situation regarding LiBr systems and the phenomena of desorption and absorption. Actual temperature profile has either not been measured or the obtained temperature change was minimal [41, 42]. Limited experimental information reporting the actual temperature profile (but not within absorption/desorption) and usually a decrease in heat transfer coefficients can be taken from studies of zeotropic refrigerant mixtures as in [43].

Regardless these shortcomings, the range of experience and possibilities with components and whole absorption systems is very high in absorption cooling. Absorber design is identified as the crucial point of absorption heat engines with a phenomenon of simultaneous mass and heat transfer. Several designs has been developed, their summary for absorption heat pumps is given in [41] while the most common absorber and desorber heat exchanger design is of shell & tube type. Falling film type of absorber can be considered as a standard solution, especially for commercial absorption cooling systems with horizontal tube bank. Adiabatic, bubble, flat plate and membrane absorbers are among the alternatives.

Regarding the choice of suitable pump type, a work of author's group [44] reviews different types of pumps for small volumetric flowrate in ORC systems. Gear pump appears to satisfy well many requirements and it was also the pump choice after several trials in experimental Goswami cycle [37].

An expander is an essential component for power cycles regarding both cost and efficiency. An argument for the choice of the impulse turbine is made based on a prospect of a cost-effective turboexpander, assuming the utilization of additive manufacturing (AM) technologies. A detailed review of AM in turbomachinery is performed in the thesis and author's review works in [VN1, VN2]. Generally it is unlikely that the micro turboexpanders in decentralized units (not only and necessarily APC) are going to be ever produced in large series. Especially for waste heat recovery, customization is key for quality performance. A possibility to effectively tailor the turboexpander design to the desired operating conditions of the cycle is a necessity. Cost-effective manufacturing of even single-piece produced customized turbines rotors and stators has some interesting possibilities via additive manufacturing (AM). In low temperature APC, the expected low blade loading stress and low operating temperatures suggest even use of polymeric plastic materials for nozzles and rotor buckets. Zywica et al. discussed the possibilities of heat resistant plastics for a high-speed microturbine for a domestic ORC system. [45, 46] Based on the literature review as well as on in-house tests, an overview of AM applicability for micro turboexpanders was created and presented in Table 2.1.

Table 2.1: Summary of AM technologies for small turbines

Technology	**Possible applications**	**Materials**	**Max. T**	**Advantages**	**Drawbacks**
FDM	Low demand parts, other parts with limits	(Ultra) ABS, PETG, composites	~100 °C	Cheap, widely available	Rough surface in as-printed, need of supports, non-uniform properties
SLS	Any part	Nylon, carbon, TPU, PP	~80 °C	Cheap, no support, good accuracy	Limited T ~ 80 °C
SLA	Stationary parts, rotor with limits	Resins	>200 °C	Good resolution and surface quality	Most expensive plastic method, needed supports, fine features and tolerances are a problem
DMLS	Flow components	Metals (steel, Al, Ti)	>1000 °C	Most available metal AM technology	Expensive, sensitive to fine-tuning, Rough surface in as-printed, need of supports
MJF	Any part	Nylon based	~80 °C	Cheap, no support, best tolerances, fastest	Limited T ~ 80 °C; domain only of company HP
EBM	Flow components	Metals (steel, Al, Ti)	>1000 °C	Fast, well-tuned properties	Very expensive

Chapter 3

Goals of the thesis

Bases on the thorough review, LiBr aqueous solution (and generally salt solutions) used typically in absorption chillers may hold a significant thermodynamic and technical potential for power production as the Kalina cycle has. Possibilities of these absorption power cycle (APC) systems with salt solution working fluids have in the past, however, been only rarely theoretically investigated. Furthermore, no experimental work has been found to explore the technical feasibility of such concept. The goals of the thesis can be therefore summarized as follows:

- Find theoretical benefits and range of prospective applications
- Upon the theoretical potential, prove technical feasibility of the APC by:
    - Designing and building APC as a proof-of-concept
    - Demonstration of operability of APC and its components, including turboexpander featuring additively manufactured components
    - Provide comparison between theoretical and real operation of key system's components, especially regarding temperature glide and expander feasibility
- Based on system operation, suggest actual range of applicability and suggested heading of future salt solution APC development

Chapter 4

Theoretical cycle investigations

An interesting possibility and many research gaps were identified in the literature review regarding the salt solution APC performance. First, there was performed an analysis of performance potential for waste heat recovery, performed for a range of parameters and including a comparison to various alternatives or sensitivity of performance to cycle parameters. These results were published mainly in author's works [VN3, VN4]. Then, three case studies show the specific APC potential in selected applications including low temperature solar thermal system, application as a bottoming cycle or CCS systems waste heat recovery [VN5, VN6, VN7, VN8] (details included only in the thesis). The concept of a combined power and cooling system with well controllable ratio between the two products has been considered in author's work [VN5] and then in detail investigated in [VN9].

4.1 Methods

Many previous studies focused on potential of performance improvement by increasing complexity of the cycle configurations. This work aims at providing a thorough investigation of simple layouts that have a potential for actual applications, so that it can be later supported by an experimental study. The layout of baseline absorption power cycle is illustrated in Figure 1.1b. Additionally heat rejection systems with parasitic load are considered. To assess the performance of the proposed APCs with various working fluids with respect to other options, several reference cycles are chosen and modelled. The cycles used for comparison are mostly based on the Rankine cycle in either simple or recuperated configuration.

When the APCC is investigated, a schematic arrangement of the investigated configuration is represented in Figure 4.1.The principle follows the APC, only a splitter divides the steam flow into the two branches based on the required ratio between power and cooling, defined as SR (splitting ratio). The reference ORC-VCC system consists of an organic Rankine cycle VCC where portion of expander power production is used for compressor input.

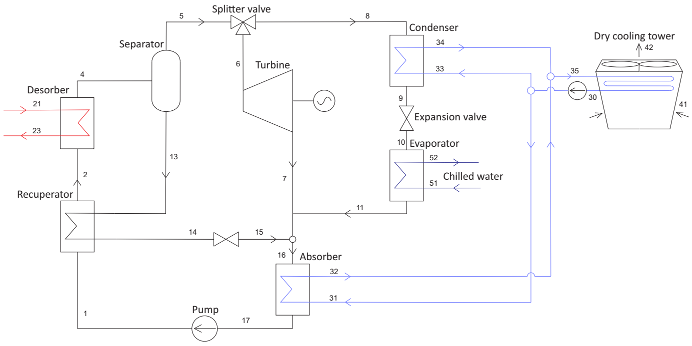


Figure 4.1: Schematic diagram of the proposed combined cooling and power cycle

Most of the theoretical investigations are based on pinch point analysis, which gives a limit to heat transfer in heat exchangers. The system of balance equations of all the states accounting for every single component and including necessary fluid properties is developed. Rotating components as expanders, pumps, compressors or a fan for dry cooler are calculated using isentropic efficiency.

As there are in many models present iteration loops and as optimization and sensitivity analyses are required, the models are built and solved using the software EES (Engineering Equation Solver). Alternatively software AspenPlus is used in cases, where a suitable mixture fluid property formulations are not present in the EES, nor are they available in the literature to additionally implement them. All HXs are considered to have a counter flow configuration. Partial evaporation and condensation processes in the mixtures, marked further as desorption and absorption, are assumed to occur at variable temperatures of the temperature glide as the concentration of the less volatile component changes in the liquid phase.

In the waste heat recovery and generally with open loop heat sources, there is not important just a single efficiency parameter as the maximum cycle efficiency usually doesn't reflect the point of maximal power output. Furthermore for clear assessment of the performance, efficiency is calculated both according to the first law of thermodynamics (energy efficiency) and according to the second law (exergy efficiency). The efficiency is also calculated as gross (excluding heat rejection auxiliary power requirement – parasitic load) and net (including all parasitic loads). As the efficiency of the cycle does not directly correspond to the power output and as the optimum parameters for either are typically different, heat source utilization efficiency is calculated alongside the cycle efficiency. Efficiency of APCC can be divided into the efficiency of power production and the COP of the chiller, again with respect to the first or second law of thermodynamics, with respect to cycle or heat source utilization and gross or net. Note that the power production efficiency may be negative when the cycle power production drops below zero for a higher chiller output.

4.2 Power cycle results

At the beginning it is suitable to show the thermodynamic limits of ideal cycles. For that were selected several ideal cycles, first, trilateral cycle neglecting pinch point and heat rejection fluid temperature rise (TC). Then Lorenz cycle, denoted as LC1, reflecting the temperature rise of heat rejection fluid but still neglecting minimal temperature differences. Lorenz cycle with respected the minimal temperature differences is denoted as LC2. For illustration is added a Carnot cycle (CC). To illustrate technically feasible cycles, ideal Rankine cycles with steam (RC) and two organic fluids - isobutane (ORC1) and MM (ORC2) are added. Figure 4.2 provides an illustration of the cycles in a modified TS diagram (corresponds also to QT diagram). The cases with CC, RC and ORC efficiency depends on their temperature and pressure levels and thus these are optimized.

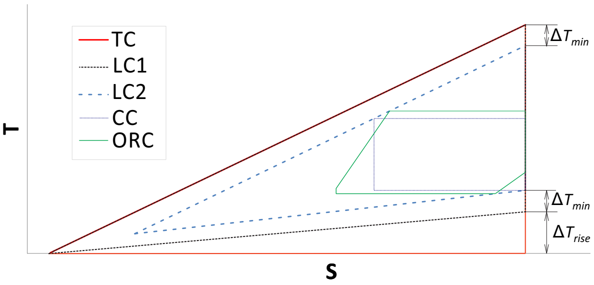
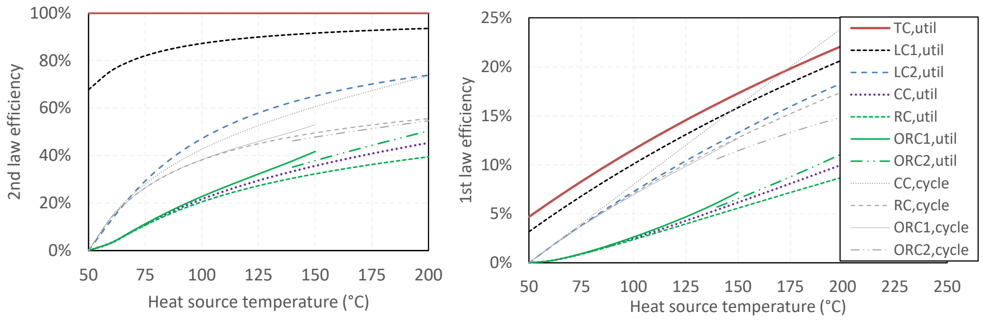


Figure 4.2: Illustrational TS diagram of several ideal cycles investigated for waste heat recovery

The resulting values can be considered as gross regarding the performance indicators. The efficiency values (of the optimized cycles) are plotted with respect to heat source temperature. A 2^{nd} law efficiency is in Figure 4.3a. Note that CC is inferior to ORC. Below 50°C heat source the cycles considering pinch point cannot be working, efficiency is zero. Rising tendencies are attributed to a decreasing relative effect of the pinch point and related irreversibilities. For illustration are additionally plotted notably higher efficiencies considering only the cycle, which illustrate the importance to distinguish between the utilization and cycle efficiencies. Figure 4.3b shows, how the previously presented values translate into the values of the 1^{st} law efficiencies.



(a) (b)

Figure 4.3: Exergy (2^{nd} law) (a) and energy (1^{st} law) (b) efficiencies of ideal thermodynamic cycles in WHR application

4.2.1 Detailed parameters of the cycles

A temperature-entropy ($T - s$) diagram of the cycle for selected typical WHR conditions is in Figure 4.4. It shows the variable evaporation (desorption) and condensation (absorption) temperatures together with the temperature rise caused by adiabatic absorption in the beginning of the absorption-condensation process. A cycle with these parameters has also been drawn into the Dühring plot in Figure 1.3. Compared to the cooling cycle, the APC optimized for utilization efficiency has the advantage of having the working fluid further from the crystallization barrier. A major difference from previous studies [20, 18, 19], which focused more on cycle-only efficiency, was observed with respect to solution concentration. The weak solution concentration at the utilization-optimized parameters was significantly lower (approximately 30% of salt) and the change of concentration was also higher. The reason for such behaviour is found in the prioritizing higher temperature glide of the phase change over the highest mean heat-input temperature.

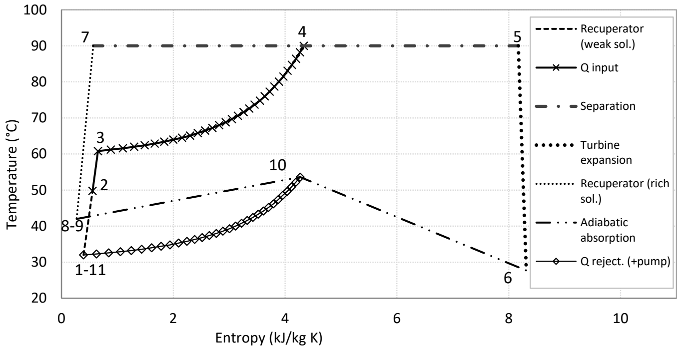
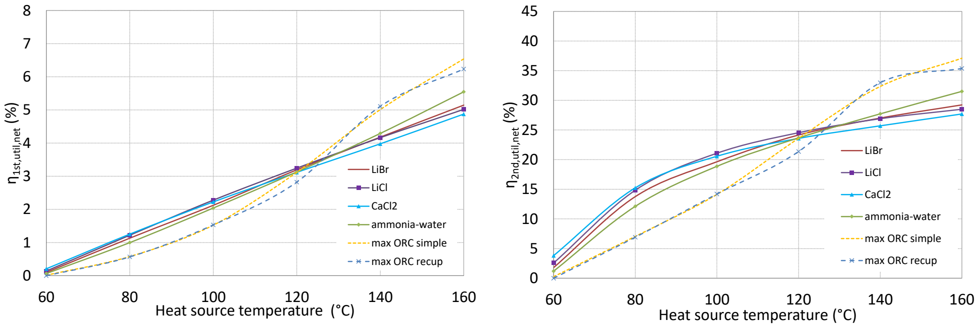


Figure 4.4: A temperature-entropy (T-s) diagram of the LiBr cycle at 100°C and cooling tower.

4.2.2 Heat source utilization general analysis

Utilization efficiency corresponding to power output is the key performance indicator for open loop heat sources instead of only cycle efficiency (η_{cycle}). Therefore, maximal net energy efficiency of heat source utilization was searched for in the APC models, optimizing the absorption temperature and pressure (together define the concentration of the weak solution) and high pressure in the system together with temperature (define the concentration of the solution at the end of desorption). The efficiency of the reference cycles is optimized with respect to the evaporation temperature and the condensing temperature. Cycles with recuperation are considered only in cases possible within the given boundaries (available heat for recuperation within the limits of the minimal temperature difference in recuperative HX). The working fluids chosen for explored cases are for RC2 water, R143a, R152a, methanol, ammonia, R290 and R1234yf; for RC3, these are isobutane, n-butane, cyclohexane, RC318, HFE7100, R245fa and MM.

The results for the maximized first-law net efficiency of heat source utilization ($\eta_{1st,util,net}$) for APCs and for the reference Rankine cycles are shown for ACC in Figure 4.5a. Alternatively, the results for the net second-law efficiency of heat source utilization ($\eta_{2nd,util,net}$) are shown in Figure 4.5b. It is important to notice what effect the heat rejection auxiliaries' power requirement has on the cycle efficiency. Although gross efficiency may still be at reasonable levels, this parasitic load takes almost all of the power output of a 60°C heat source. Heat source temperatures below approx. 110-120°C appear as the prospective domain of APCs, as they can deliver more power than the Rankine cycles.



(a) air cooled condenser

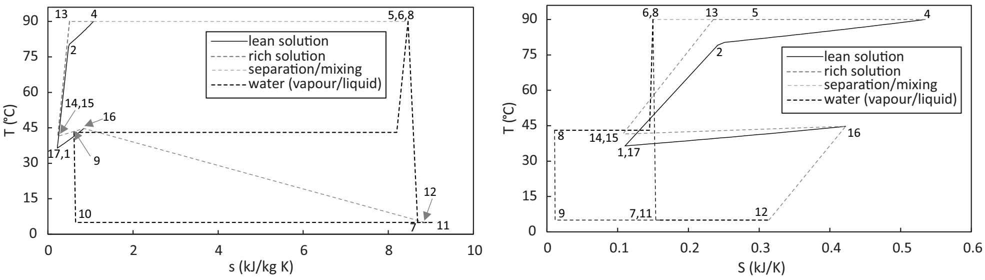
(b) air cooled condenser

Figure 4.5: Maximum net heat source utilization energy (first law) efficiency ($\eta_{1st,util,net}$) (a) and exergy (second law) efficiency ($\eta_{2nd,util,net}$) (b) for the APCs and for the reference Rankine cycles with ACC heat rejection methods.

In order to compare other possible working fluids such as ionic liquids or potential of zeotropic and supercritical ORCs, a shorter investigation presented also in author's work [VN4]. The results (detailed in the thesis) confirm with the previous analysis a simple Rankine cycle as a better choice at higher temperatures while lower temperatures are a domain of cycles using working fluid mixtures. The best performance at low temperature has the water-LiBr APC, closely followed by the zeotropic ORC and methanol – heptanol APC.

4.3 Combined absorption power & cooling cycle

The absorption power and cooling combined cycle (APCC) from the previous figure is suggested as a combination of the APC concept into the existing technology. The parameters are presented when the heat source inlet temperature of 90°C and outlet 85 °C, with a splitting ratio 0.5. Figure 4.6 shows T–s and T–S diagrams of the APCC. The cycle efficiency is mainly affected by the cooling output, while the exergy efficiency is affected by the power output. The APCC, in comparison with the ORC–VCC system, provides nearly double chiller capacity while having at the same time an approximately 25% higher net power output. The power requirement of the auxiliary equipment is similar for both cases.

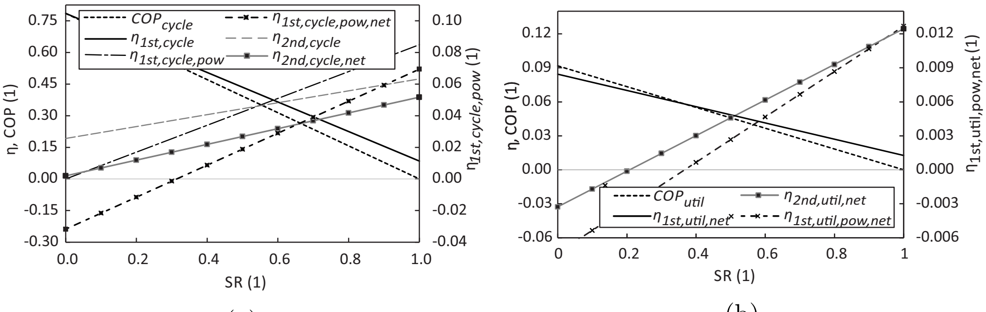


(a) (b)

Figure 4.6: Temperature entropy diagrams of the combined cycle for the baseline conditions for specific entropy (a) and absolute entropy (b) of the working fluid.

Impact of the splitting ratio SR on the performance indicators is significant and is shown in Figure 4.7a. As expected from the SR definition, all the considered parameters depend linearly on the splitting ratio. However, the results clearly illustrate the disproportion between the quantity and quality of the products—cooling output and electricity. The energy efficiency is largely affected by the cooling output because the absolute value of the electrical output is low, while the situation is nearly the opposite for the exergy efficiency.

To maximise the utilisation of a heat source, fixing its outlet temperature is not suitable. The values of optimized utilisation efficiency and COP are shown for both systems in Figure 4.7b. The trends are similar to that of the efficiency with respect to the transferred heat, but the values are significantly lower because the cycles can utilise only a small portion of the heat from the heat source.

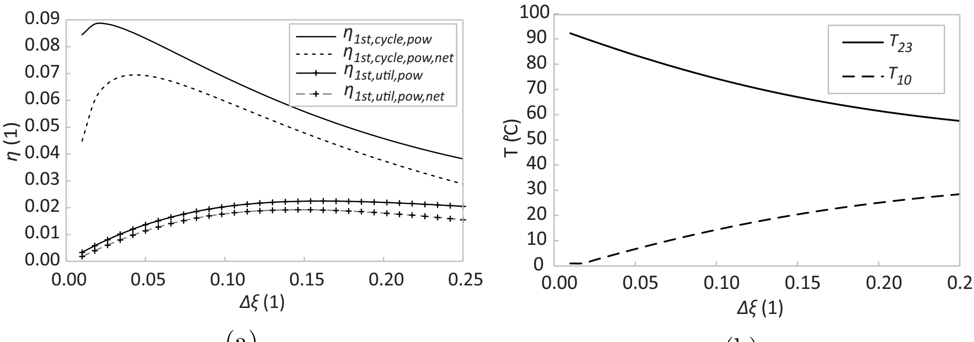


(a)

(b)

Figure 4.7: Sensitivity analysis of APCC performance with respect to the splitting ratio, for cycle parameters (a) and utilization parameters (b).

The operating conditions of APCC and APC for waste heat recovery differ mostly regarding the optimal concentration level and concentration difference. There is a fixed concentration of the APCC lean solution given by the heat rejection temperature from the absorber and the absorber pressure given by the required evaporator temperature. Figure 4.8 shows the effect of the concentration difference in the power cycle (SR = 1) when the rich solution concentration and absorber outlet temperature are constant (heat source outlet temperature and absorber pressure are no longer fixed). The cycle efficiency has a maximum point at a low concentration difference near the APCC nominal point. The utilisation efficiency has a maximum higher concentration differences. The evaporator temperature rises with the concentration difference, which is the reason this regime is suitable for power production, but not very suitable for the chiller regime.



(a)

(b)

Figure 4.8: APC system (SR=1) parameters at varied concentration difference for higher heat recovery from the heat source: cycle and utilization efficiency (a) and heat source outlet and evaporator temperature (b).

CHAPTER 5

Experimental development of the absorption power system

Two experimental systems of APC with LiBr solution were designed. The first was made primarily to test flow boiling with temperature glide during the phase change. Its design and operation led to several dead-ends. The second test rig was built as an entire LiBr solution APC with expected nominal power output around 300 W. The results are reported primarily for the second one – whole APC unit, as it was more successful.

Before the experimental systems design, first sizing considerations of the author described in [VN10] has shown a preliminary technical feasibility of design of two sizes of an APC system, 20 kW and 500 kW nominal power output. A concept of the first test rig has been proposed by author in [VN11] and then is described in actual configuration with obtained results in [VN12]. The fundamental objective was an experimental verification of the temperature profile (glide) along the desorber and absorber length during the phase change along with observation of related flow boiling two phase flow but the tests have shown only a limited feasibility of the adopted approach.

A new experimental system was proposed after only limited success with the first test rig as a fully operational APC unit, according to the schematic in Figure 5.1. Its design, described in detail in author's work [VN13], is to serve as a proof of the whole concept as well as of specific components (e.g. 3D printed turboexpander). Therefore, the parameters were selected conservatively and partly similar to ones of absorption chillers, rather than according to theoretical results for the most efficient WHR system. Design of the overall system is then depicted in Figure 5.1. Net designed power output respecting the own power consumption in the system is 0.26 kW. This yields a 1^{st} law efficiency of the cycle of 1.3% (net utilization 1^{st} law efficiency 0.12%).

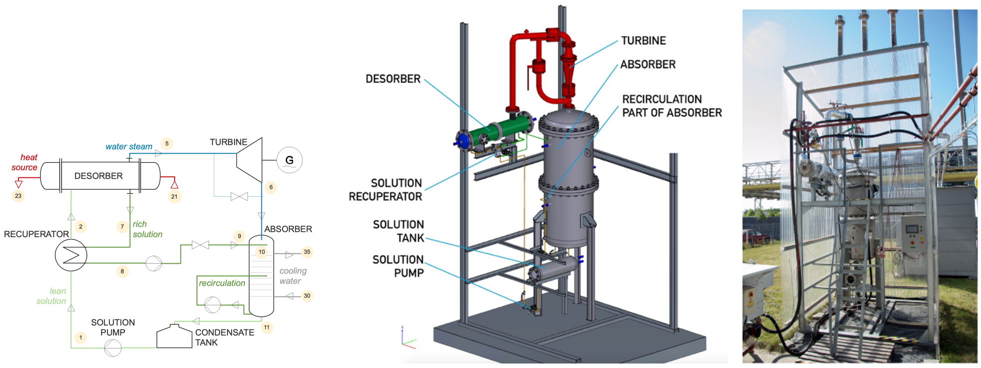
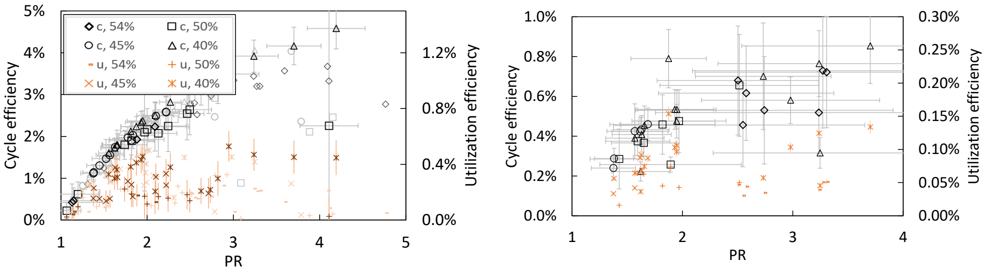


Figure 5.1: Overall design of the experimental APC unit (Red coloured components are for vapour branch, green for LiBr rich solution piping and light brown colour for LiBr lean solution piping)

The experiments with the 1^{st} testrig turned out to serve as a verification whether a suitable flow pattern in the designed desorber can be achieved and can be found in [VN12]. As the system was not completely air tight, in order to prevent corrosion, experimental campaigns were performed with demineralized water at decreased pressure various flow patterns were observed but their nature, mostly due to oscillating nature and high pressure drop, has proven unfeasible for APC. Operation of the 2^{nd} testrig was successful, with the first results provided in [VN14] and more detailed analysis of the results being in [VN15, VN16]. The tests were performed for ranges of charged solution concentration. The heat source was a hot water, thermal output of biomass-fired ORC micro-cogeneration units. Due to the internal settings of the ORC units and heat losses in the heat input pipes, the heat maximal source temperature was typically only around 75°C. The heat sink was provided by a cooling water loop which rejected the heat into the air in a dry cooler.

Reference for the utilization efficiency was taken as cooling water inlet temperature. Only the gross efficiency (excluding all parasitic load and also cycle pumps) was at the end evaluated. The APC was in most of the time operated with the bypass valve and in order to assess the potential of the cycle, an achievable expander efficiency η_{turb} of 65% has been assumed. When the turbine was in operation, produced electricity is then used to evaluate actual system efficiency.

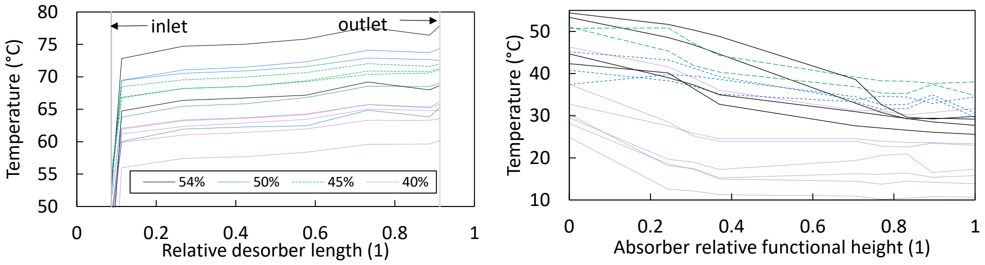
Uncertainty analysis of the systematic error is performed for the cycle parameters with resulting values mostly in the order of often dozens percent (complex method to obtain mass flow rate). The cycle and utilisation efficiency for all selected and analysed steady states and assumed expander efficiency of 65% (or rather efficiency potential) are plotted in Figure 5.2a as a function of the cycle pressure ratio (PR) and distributed according to the charged LiBr concentration (40-54%). The operation states recorded as more accurate are highlighted here with rich colour. The second graph (Figure 5.2b) shows the same parameters but for actual expander electrical power output. Further results are presented in the thesis.



(a) (b)

Figure 5.2: Cycle and utilisation efficiencies as a function of cycle pressure ratio and charged LiBr concentration, (a) with the hypothetical 65% expander efficiency, higher accuracy states in bold and (b) measured parameters with the plastic turbine

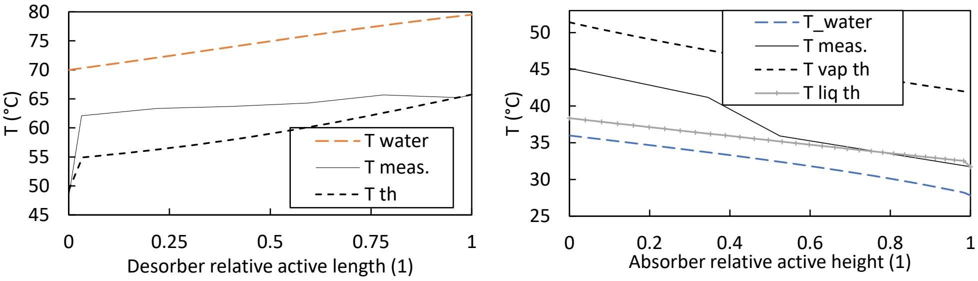
One of the objectives of the experiments was to evaluate the actual temperature glide during the non-isothermal phase change during desorption and absorption. This glide for several selected operation states is shown for both desorber and absorber in Figure 5.3. The measured temperature in the desorber corresponds to the boiling solution as the probes are placed under the liquid level. The recorded glide is significantly lower than predicted yet still measurable.



(a) (b)

Figure 5.3: Measured temperature glide profiles in desorber and absorber (absorber 0 corresponds to top part with vapour inlet)

For a selected case out of the ”more accurate” states, an analysis of parameters and comparison with design models, when the operation parameters are fitted back into it, is performed. The design model was partly modified for off-design calculations. Interestingly, at the analysed conditions, the desorber has better heat transfer performance than in reality. Even though the actual LiBr concentration difference and temperature glide are smaller, the cycle can in extract more energy from the heat source. Absorber performs worse where the model predicts notably lower pressure (better efficiency). A correction factor to the overall heat flux in desorber and mass transfer coefficient in absorber has been determined and the model was extended to solution subcooling at the absorber outlet. Figure 5.4 compares the measured Q-T diagrams to the ones from the corrected model. Solution temperature rises faster than required and remaining temperature glide during the phase change is moderate. The pinch point shifts to the saturated lean solution. In the absorber, the vapour temperature corresponds to the saturated solution; the solution on the tube surface is subcooled. Another deviation from the cycle models is a lower vapour superheat than corresponds to the saturated mixture temperature. Mostly constant temperature difference between the actual and the theoretical values (regardless of mass flow) suggests a phenomenon that causes departure from the thermal equilibrium.



(a) (b)

Figure 5.4: Comparison of measured temperature glide profiles in desorber and absorber with the corrected model

Chapter 6

Experimental development of expanders

First there were developed several air turbines, which served as the initial proof of concept of the adopted approach in turbine development and (additive) manufacturing. To show the general approach across the explored turbines, design of the first air turbine and a photograph of the assembled central part are shown in Figure 6.1.

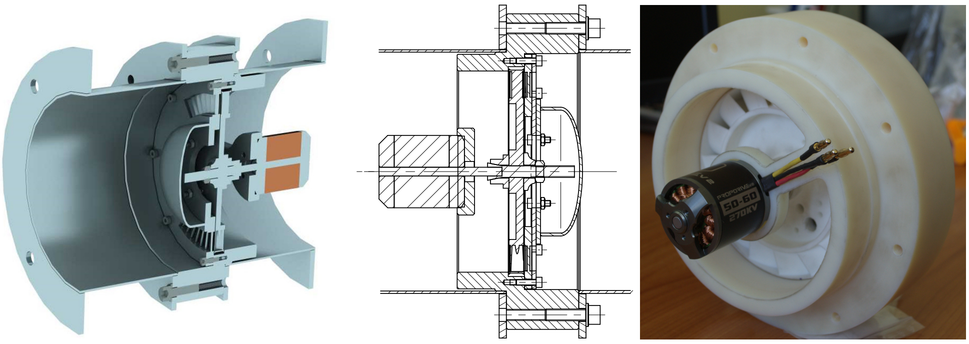


Figure 6.1: Design of the air turbine for tests of AM components and photograph of its assembled central

Design and perfromance of the developed air turbines, both axial and radial and all using 3D printing for manufacturing of flow paths, is documented in works [VN17, VN2, VN18, VN19]. Note that the design is mostly based on 1D loss models and parameters for larger steam turbines from [47, 48, 49] as better approach was not at the time available. As a selection of the results, a trial run with nominal and double admission for best configuration with components manufactured by SLS method (and no post-processing, as printed state of surface) is presented in Figure 6.2. Here it is very interesting, that the design model fairly accurately predicts the performance.

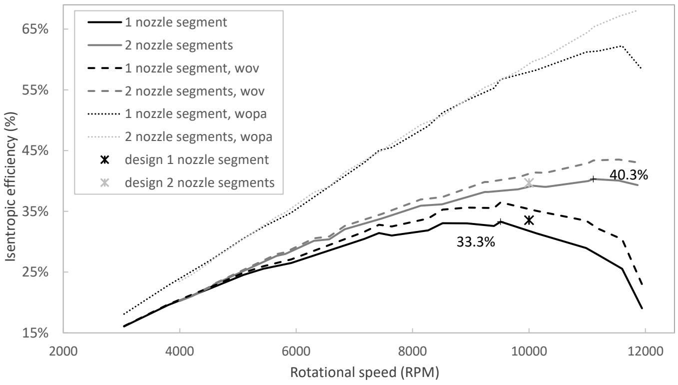


Figure 6.2: Effect of the partial admission on selected turbine configuration, comparison with design model and comparison of related loss models for PR about 1.4 (“wov” as without ventilation according to [VN2], “wopa” - without partial admission from design model).

The working fluid in the APC expander is a pure, naturally superheated, steam. The design PR is 2.2, thus slightly supersonic. Regardless the very low mass flow rate, the isentropic volumetric flow after the expansion is about 0.2 m^3s^{-1}, which justifies use of dynamic expander. The APC turbine results are reported in author’s work [VN14, VN16]. Unlike in air turbines, here was varied both the turbine inlet pressure as well as the outlet pressure. Summary of experimental efficiency characteristics is in Figure 6.3 (only the states selected as more accurate). During the operation, a resonance frequency and related vibrations caused that the maximal turbine speed was only 8000-9000 rpm (design 15 000 rpm, optimal 30 000 rpm). Even with the poor surface quality, the efficiency is mostly within boundaries provided by different loss models. This shows a high prospect of the plastic 3D printed concept with better engineering than was adopted for this proof of concept.

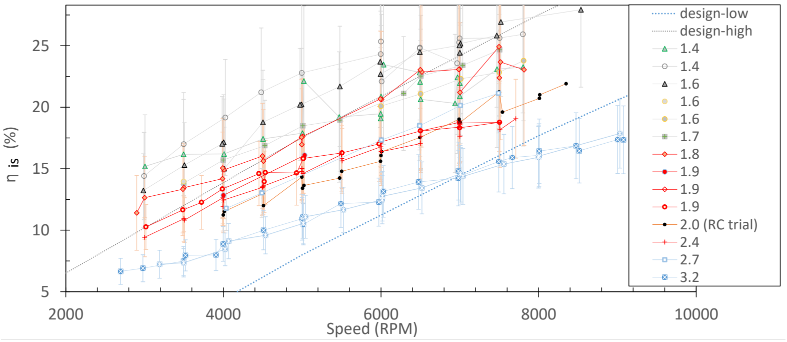


Figure 6.3: Measured turbine characteristics from APC operation for states with higher accuracy

Chapter 7

Conclusion

In summary, the concept of APC with salt solutions as LiBr was found to be until author's works aside of many researchers' interest, even though it provides many opportunities. Comprehensive theoretical investigation based mostly on pinch point analysis found its potential as superior for low temperature and distributed applications. Following on that, it has been proven experimentally as technically feasible in form of the world's first LiBr APC unit operating at the Czech Technical University in Prague. The theoretically most prospective application, WHR, proved however to underperform compared to the expectations with smaller and less suitable temperature glide. This is contrary to common assumption in many theoretical studies and should be taken into account. Possibility of cost effective polymer additively manufactured turboexpanders has been suggested and also proven as technically feasible. Further engineering optimization beyond the presented proof of concept system gives potential for its high efficiency. The most feasible application now appears as turbine integration into LiBr absorption chillers for cogeneration APCC systems, analysed theoretically also in this thesis. Since the presented unit and its components have been built in a way to ensure successful operation, rather than the thermodynamically best possible performance, there are many aspects that can be improved now. For such tasks, this thesis can serve as starting point with solid fundamentals in field of salt solution APC, APCC as well as 3D printed turboexpanders for small distributed energy systems.

Author's publications related to the thesis

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Resumé

Absorpční cykly byly navrženy nejen pro chlazení, ale také pro výrobu energie, jako je známý Kalinův cyklus využívající směs vody a čpavku. Použití jiných pracovních kapalin však zůstalo stranou hlavního proudu výzkumu. V této práci je konkrétně navrženo použití vodných roztoků solí, jako je LiBr, který se používá v absorpčních chladicích zařízeních. Kromě perspektivních termodynamických výhod jsou tyto soli netoxické, což přináší i výhody pro životní prostředí. Práce se rovněž zaměřuje na technickou proveditelnost konfigurací a celých systémů.

V první části práce je proveden komplexní přehled alternativních pracovních kapalin pro absorpční energetické cykly (APC). Následné teoretické zkoumání založené na analýze pinch pointů ukázalo největší přínosy solných APC v nízkoteplotních aplikacích (pod cca 120 °C), především pro rekuperaci odpadního tepla (WHR). Srovnání bylo provedeno s Rankinovými cykly s řadou pracovních kapalin a konfigurací, jakož i s jinými APC. Druhá aplikace APC byla zkoumána jako kombinovaný energetický a chladicí systém, kde solné roztoky mohou přinést zjednodušení proti některým vodním čpavkovým systémům. Překonává pracovní kapalinu voda-čpavek i srovnávací ORC s chladičem s kompresí par. Analýzy zahrnují parazitní zátěž, která může mít u nízkoteplotních systémů podobný jmenovitý výkon jako výkon expandéru.

Podle přehledu literatury nebyl dosud zaznamenán provoz APC s roztokem soli. Proto se tato práce pouští také do experimentálního úkolu, aby ověřila technickou proveditelnost. Byla navržena a postavena první ověřovací jednotka APC s roztokem LiBr na světě o jmenovitém tepelném příkonu 20 kW a výkonu pod kW. Experimentální práce poukazují na konkrétní aspekty technického návrhu s ohledem na předpoklady teoretických modelů. Byl změřen teplotní skluz při změně fáze a porovnán s teoretickými hodnotami. Předchozí koncepce desorbéru pro vysoký skluz se experimentálně ukázala jako neproveditelná, zatímco technicky proveditelná koncepce poskytuje nízké hodnoty. V absorbéru je nutné výrazné podchlazení roztoku a intenzita absorpce je nižší, než se předpokládalo. Na druhé straně je přestup tepla v desorbéru oproti modelům vyšší, a pára oddělená od roztoku je přirozeně přehřátá v důsledku zvýšení bodu varu roztoku. Při teplotě zdroje tepla pod 90 °C dosáhla maximální hrubá elektrická účinnost cyklu 0,8 % a výkon přibližně 150 W. S lepším návrhem turboexpandéru však existuje potenciál pro maximální účinnost cyklu téměř 5 % a účinnost využití zdroje tepla kolem 0,5 % při daných provozních podmínkách.

Specifická část experimentální práce je zaměřena na vývoj turboexpandérů. Vzhledem k tomu, že páry v APC mají nízký tlak (obvykle několik až desítek kPa na vstupu do turbíny) s vysokým objemovým průtokem, jsou turbíny použitelné místo objemových expandérů i pro výkony pod jeden kW. Nízké teploty dále umožňují použití polymerních materiálů a aditivní výrobu. Tato koncepce s motorem s permanentními magnety jako generátorem se ukázala jako cenově efektivní řešení. Nejprve bylo vyvinuto a testováno několik konfigurací vzduchových turbín. Následně byla pro jednotku APC použita turbína s rotorem a průtočnými částmi statoru vyrobenými z nylonu pomocí 3D tisku z prášku. S isoentropickou účinností mezi 15-25 % slouží řešení pro ověření konceptu, přičemž další vývoj může výrazně zlepšit parametry.

Napříč prací je kladen důraz na technickou realizovatelnost. Mírné teoretické zvýšení parametrů často v praxi nestojí za přidanou složitost systému, obzvlášť v decentralizované energetice. Výsledky práce nastiňují reálnou oblast využití APC, omezeně pro využití odpadního tepla, ale zajímavé kombinovaný systém výroby elektřiny a chlazení.

Summary

Absorption cycles have been proposed not only for cooling but also for power generation, such as well-known Kalina cycle utilizing water-ammonia mixture working fluid. Use of other working fluids has however stood aside of mainstream research. Specifically, using aqueous salt solutions, such as LiBr found in absorption chillers, is proposed in this work. Except for prospective thermodynamic benefits, the salts are non-toxic, bringing also environmental benefits. Focus of the work is also on technical feasibility of the configurations and whole systems.

As a first part of the thesis, a comprehensive review of the alternative working fluids for absorption power cycles (APC) is performed. Following theoretical investigation based on pinch point analysis has shown the largest benefits of salt APC in low temperature applications (below about 120°C), mainly for waste heat recovery (WHR). The comparison has been performed with a Rankine cycles with a range of working fluids and configurations as well as other APC. Second application of APC was investigated as a combined power and cooling system, where salt solutions can bring a simplification against some water ammonia systems. It outperforms water-ammonia working fluid as well as benchmark ORC with vapour compression chiller. The analyses include a parasitic loads, which can have at low temperature systems a similar power rating as the expander output.

According to the literature review, operation of no salt solution APC has ever been reported. Therefore, this work embarks also on an experimental task to validate technical feasibility. World's first LiBr solution APC proof-of-concept unit has been designed and built with 20 kW nominal thermal input and sub-kW power output. The experimental works point out at specific aspects of the technical design with respect to the theoretical models' assumptions. Temperature glide during phase change has been measured and compared to

theoretical values. Previous concept of desorber for high temperature glide was experimentally proven unfeasible, while technically feasible one provides low temperature glide. In the absorber, significant subcooling of the solution is required and absorption rate is lower than predicted. On the other hand, desorber heat transfer is higher than predicted and steam separated from the solution is naturally superheated due to boiling point elevation. With the heat source temperature below 90°C, the maximum gross electrical cycle efficiency reached 0.8 % and about 150 W. However, with a state of the art turbo-expander, there is a potential for maximal cycle efficiencies of almost 5 % and heat source utilisation efficiencies around 0.5 % at the explored operating conditions.

Specific part of the experimental work is focused on turboexpander development. As the vapour in the APC is at low pressure (typically several to dozens kPa at turbine inlet) with high volumetric flowrate, turbines are feasible instead of volumetric expanders even for sub kW power output. Low temperatures further suggested use of polymer materials and additive manufacturing. This concept, with permanent magnet motor as a generator, was shown as a cost effective solution. First, several configurations of air turbines were developed and tested. Following, a turbine with rotor and stator flow components made of nylon by powder bed fusion has been used for the APC unit. With isentropic efficiency between 15-25 % it serves as a proof of concept, while further engineering development can significantly improve the performance. Need for simplicity of designed system is indeed stressed throughout the work. Slightly better theoretical performance is often practically not worth of added complexity. The overall results outline possibilities of actual applicability; limited for waste heat recovery but decent for combined power and cooling system.