



Performance of ammonia–water based cycles for power generation from low enthalpy heat sources



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ABSTRACT

Cost efficient power generation from low temperature heat sources requires an optimal usage of the available heat. In addition to the ORC (Organic Rankine Cycles), cycles with ammonia and water as working fluid show promising results regarding efficiency. Due to their non-isothermal phase change, mixtures can adapt well to a liquid heat source temperature profile and reduce the exergetic losses. In this analysis thermodynamic calculations on the layouts of two existing ammonia–water cycles are compared: a geothermal power plant based on a Siemens' patent and a modified lab plant based on a patent invented by Kalina (KCS-34). The difference between the two cycles is the position of the internal heat recovery. Cycle simulations were carried out at defined boundary conditions in order to identify optimal operation parameters. For the selected heat source of 393.15 K (hot water) the ammonia mass fraction between 80% and 90% results in the best performance in both configurations. In general, the layout of Siemens achieves a slightly better efficiency compared to the KCS-34. Compared to an ORC using R245fa as working fluid, the exergetic efficiency can be increased by the ammonia/water based cycles by approximately 25%.

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1. Introduction

Power generation from low temperature heat sources including geothermal heat or waste heat from processing industries typically yields rather low energy efficiency. The efficiency of a thermal power cycle is mainly determined by the temperature difference between the heat source and the heat sink. In order to generate power with low enthalpy cycles more efficiently, the exergetic losses during the heat transfer must be minimized. Besides the well-known Organic Rankine Cycle (ORC), a similar cycle, the so-called “Kalina Cycle” is used as binary cycle.

Several literature sources see the Kalina Cycle as a promising cycle for increasing the power output efficiency of low temperature heat source based cycles [1–5]. The working fluid of the Kalina Cycle is a zeotropic mixture, usually a mixture of ammonia (NH₃) and water (H₂O). The use of such a mixture leads to a sliding temperature during isobaric evaporation and condensation and

appears to adapt better to single phase heat sources (industrial waste heat, geothermal heat, biomass heat) and heat sinks.

The Kalina cycle is named after Dr. Alexander Kalina who invented it [6]. Since 1982 Kalina patents his inventions on a variety of embodiments of thermal cycles for different temperature applications varying from rather simple systems to very complex and more expensive systems [7].

Until today, only few cycles have been realized. Among the first projects are a demonstration plant (Canoga park) in the USA and two waste heat recovery Kalina plants in Japan [1]. In Europe, three Kalina cycles using geothermal heat for power generation exist as of today (2015) to the knowledge of the authors. The first one is a Kalina plant in Húsavík, Iceland. This 2 MW plant is based on the Kalina cycle system called KCS-34 that was published in a European patent application by Kalina in 2001 [8]. In this patent, four different embodiments are described. The Húsavík plant presents case three, which is a simplified embodiment with no extracted stream [9]. The other two are located in Germany, in Unterhaching and Bruchsal, both of which have been built by Siemens from 2007 to 2009 [10,11]. Their cycle layout is very similar to the simplest embodiment of KCS-34. The layout of this cycle differs from the original KCS-34 by the internal heat exchangers and was published

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in a patent by Siemens in 2006 [12]. In some articles this cycle is referred to as Kalina SG-1 [13]. Thus, the cycle is called “KC SG1” in this paper. While the Siemens configuration recovers heat from the expanded steam and the bypassed liquid, the KSC-34 only utilizes the bypassed liquid. According to [12], the mechanical and electrical energy output can be increased slightly compared to the KSC-34. Besides the existing patent no published information can be found regarding the performance of the Kalina cycle implemented in Bruchsal and Unterhaching compared to the simplified KSC-34. The KSC-34 is not only applied for applications of power generation, but can also be used in a modified configuration as absorption/desorption refrigeration process. An existing lab plant is operated by Makatec. The difference compared to the existing Kalina plants is the concentration of NH_3 . The power plant in Bruchsal operates with a mass concentration of about 90% NH_3 , Húsavík with 82% [9], while the Makatec’s cooling process only uses 25% and 50% in its cycle.

The aim of this study is a thermodynamic comparison between the KSC-34 and the KC SG-1. The analysis includes a detailed review of zeotropic mixtures ($\text{NH}_3/\text{H}_2\text{O}$) as working fluid in a thermal process, as well as thermodynamic calculations based on energy and mass balance equations. In order to make the cycles comparable, boundary conditions for the heat source, heat sink and the efficiency of the auxiliaries are defined. Due to the different NH_3 concentrations used in the geothermal Kalina plants and the cooling cycle of Makatec’s lab plant, each cycle is calculated for concentrations of 25%–100% of NH_3 . The analysis focuses on the influence of the NH_3 concentration and the operation pressures. Cycle performances are compared based on their second law efficiencies.

2. The binary mixture $\text{NH}_3/\text{H}_2\text{O}$ as working fluid

$\text{NH}_3/\text{H}_2\text{O}$ is a so-called zeotropic mixture of two components with different boiling points leading to a sliding temperature profile during isobaric evaporation and condensation. At ambient pressure conditions the boiling point of NH_3 is 240 K, while the boiling point of H_2O 373.34 K. When a liquid $\text{NH}_3/\text{H}_2\text{O}$ mixture is heated up to its boiling point, mainly NH_3 will start to evaporate reducing the fraction of NH_3 in the liquid, which leads to an increasing boiling temperature. When a gas is cooled to the dew point a higher amount of H_2O will condense, leaving an NH_3 enriched gaseous mixture with a lower dew point. The ratio between NH_3 and H_2O is an important factor impacting on the cycle and influences the following parameters:

- Evaporation temperature/pressure profile
- Condensation temperature/pressure profile
- Mass flow of the vapor in the turbine

The sound estimation of thermodynamic properties is a prerequisite when investigating these effects.

2.1. Properties of $\text{NH}_3/\text{H}_2\text{O}$ mixtures

As basis for the calculation with $\text{NH}_3/\text{H}_2\text{O}$ mixtures, knowledge of key thermo-physical properties of the mixture is required. These include thermodynamic properties (mainly enthalpy and entropy) and transport properties (mainly viscosity and thermal conductivity) of the fluid. Since $\text{NH}_3/\text{H}_2\text{O}$ mixtures have been used in absorption heat pumps and refrigerators for years, the mixture is well known. However, for power cycle calculations, knowledge of the properties of $\text{NH}_3/\text{H}_2\text{O}$ which are valid for higher pressures and temperatures are required.

In the simulation tool two alternatives for the calculation of the properties of $\text{NH}_3/\text{H}_2\text{O}$ mixtures have been integrated. One is based on Ibrahim and Klein [14] and the other refers to the software REFPROP, version 9.0, of NIST [15] Using the equation of state of Tillner-Roth and Friend [16] for calculating the properties of $\text{NH}_3/\text{H}_2\text{O}$ mixtures.

Fig. 1 presents in a T, ξ -diagram the comparison of saturation points calculated with the two alternative correlations. The lines depict the data of REFPROP and the dots are calculated result data of the Thermoflex software. The orange line represents the dew and bubble lines at 0.5 MPa, the blue line the dew and bubble lines at a higher pressure of 2 MPa.

According to [17] both estimates differ slightly. As presented in Fig. 1 the difference occurs mainly in the gas phase at an NH_3 mass fraction above 90%. Since calculations using the REFPROP formulation are time consuming, the following calculations are done with the correlations based on Ibrahim and Klein.

2.2. Thermodynamic characteristics of $\text{NH}_3/\text{H}_2\text{O}$

The isobaric phase change the mixture $\text{NH}_3/\text{H}_2\text{O}$ occurs non-isothermally and mostly non-linear. The temperature profile during evaporation or condensation of $\text{NH}_3/\text{H}_2\text{O}$ mixtures with different mass fractions and the pure fluids are presented in Fig. 2 in a T, h -diagram at a constant pressure of 2 MPa.

The non-linear behavior of the sliding temperature profiles of evaporating mixtures in the graph is not only valid for the presented pressure of 2 MPa and has an impact on the exergetic losses during heat transfer. In comparison, pure fluids have a constant temperature during phase change.

Unlike the isothermal phase change of pure fluid, this specific behavior of mixtures allows the process to take advantage of desorption and absorption characteristics [18]. The high and low process pressure level can be influenced in order to achieve optimal operating conditions. Figs. 3 and 4 demonstrate this phenomenon. Two $\text{NH}_3/\text{H}_2\text{O}$ mixtures of 90% NH_3 and 93% are compared during evaporation and condensation. In an evaporator at a maximum process temperature of 393.15 K total evaporation of a 90% NH_3 mixture leads to a pressure of 1.5 MPa, while a 93% NH_3 mixture can totally evaporated at a higher pressure of 2 MPa. On the other hand,

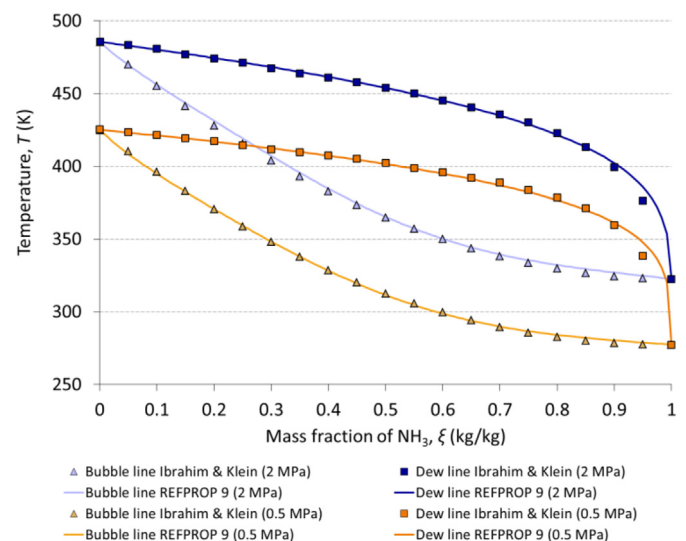


Fig. 1. Dew and bubble lines of the correlation of Ibrahim & Klein [14] and REFPROP 9 in comparison [15].

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