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Performance analysis of an evaporation process of plate heat exchangers installed in a Kalina power plant

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ABSTRACT

In geothermal power generation, ammonia-water (NH_3-H_2O) mixtures are considered as working fluids in order to improve efficiency from low enthalpy heat sources.

During the evaporation process, the NH_3-H_2O working pair as zeotropic working fluid has the advantage to evaporate not isothermal temperature but over a temperature glide to adapt better to the heat source temperature profile.

By today, there is a lack of performance data from operational generation units available in literature that can be used for scientific works based on computational calculations to compare with.

In this paper the data logs from the evaporation process of the geothermal power plant are analyzed in order to review the evaporator's performance. Data had been gathered for a period of 5 years and three key performance parameters were defined: pressure drop, vapor fraction and heat transmission capacity. The main parameters that influence the performance are the temperatures, pressures and flow rates. It turned out, that the NH_3 mass fraction plays only a minor role within the evaporation process.

1. Introduction

In low temperature regions like Germany Organic Rankine Cylces (ORC) or Kalina Cycles are applied for geothermal power generation. The brine does not drive the turbine directly, but the heat is transferred via heat exchangers to a binary cycle. These binary cycles are similar to a regular Rankine Cycle, but differ in the working fluid. While the working fluids of an ORC are organic media like hydrocarbons or refrigerants, the Kalina process is operated with a zeotropic mixture of NH_3 and H_2O. The use of a zeotropic mixture leads to a non-isothermal temperature profile during the phase change and therefore to a better adaption of the geothermal heat source to the working fluid. The two-phase flow of zeotropic mixtures during this evaporation process has been studied in several publications.

Experimental investigations show, that the boiling process of zeotropic mixtures leads to a significant reduction of the heat transfer coefficient compared to pure fluids with similar physical properties [1–5]. For calculations of the heat transfer of a mixture it is not sufficient to apply the correlation of pure fluids by adapting only the corresponding properties of the mixture. In addition to the heat transfer, also the mass transfer of the mixture influences the heat transfer coefficient [6]. While modelling the design of heat exchangers, this effect needs to be taken into account.

The boiling heat transfer of the mixture NH_3-H_2O is investigated in literature both experimentally and through computer simulations. Inoue et al. compare in Ref. [7] the existing correlations [8–12] with experimental data measured on a horizontal heated wire. The results show that the boiling heat transfer for pure NH_3 can be well predicted based on available correlations. The correlation for the heat transfer coefficient of NH_3-H_2O partly shows high deviations from measured data [7]. Arima et al. [13] also carried out experiments on the heat transfer coefficient of NH_3-H_2O. Their conclusion is that the boiling heat transfer coefficient decreases with the increase of the NH_3 mass fraction between 0 and 0.3 and increases between 0.5 and 0.9. An interesting aspect is that at an NH_3 mass fraction of 0.95 the heat transfer is slightly higher than for the pure NH_3. The experimental study on forced convective boiling of ammonia-water mixtures in a vertical smooth tube of Khir et al. [14] compared measured data with correlations and received the best result with the modified correlations of Mishra et al. [15], with an error of $\pm 12\%$. These publications illustrate that the prediction of the heat transfer of the binary

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mixture NH_3-H_2O is both challenging and complex.

For the Kalina cycle both types of heat exchanger - plate and shell-and-tube - are installed in the existing plants. The heat exchangers applied at the geothermal Kalina plant that is analyzed in this study, are corrugated plate heat exchangers. Abu-Khader summarizes in Ref. [16] the recent technical improvements of the plate heat exchangers. Even though most applications are liquid-liquid plate heat exchangers, a positive performance trend for plate heat exchangers related to evaporation and condensation processes can be observed [16]. The main advantages of plate heat exchangers compared to tube bundle heat exchangers is the compact design and their flexibility of adapting the heat exchange surface by increasing or decreasing the number of plates. Due to their welded or sealed construction, however, operational pressures and temperatures are limited and the pressure drop is higher compared to a bundle heat exchanger.

The heat exchange of zeotropic mixtures in plate heat exchangers has been investigated in few studies only. Mainly Tàboas et al. studied the flow boiling heat transfer of an NH_3-H_2O mixture in a plate heat exchanger [17–19]. Their first publication [17] analyzed the boiling behavior in a plate heat exchanger by experiments. At a constant mass fraction of NH_3 of 42% the effect of mass flux, heat flux and pressure on the boiling heat transfer coefficient are determined. Besides the vapor quality, the study determines the mass flux as the main parameter influencing the heat transfer. For lower mass fluxes only nucleate boiling occurred, while for higher mass fluxes also convective boiling effects are observed. The influence of the NH_3 mass fraction is analyzed in Ref. [18]. For vapor qualities up to 0.22, the NH_3 mass fraction in the range from 0.42 to 0.62 has no considerable impact on the heat transfer. Tàboas et al. compare the heat transfer and pressure drop measurements with correlations from literature in Ref. [19]. They introduced their own correlation for predicting the heat transfer coefficient, achieving a prediction of 98% in an error range of ±20% for nucleate and conductive boiling. Besides Tàboas only two further publications are found discussing the topic of NH_3-H_2O plate heat exchangers. Ventura observed that literature correlations for the heat transfer coefficient mismatch with his experiments [20]. Okamoto et al. analyzed local heat transfer coefficients for NH_3 at mass fractions between 90% and 100% [21] .

Until today, no detailed performance analysis of the evaporation process in corrugated plate heat exchangers in plants that are operated with NH_3-H_2O has been published yet. Worldwide only a few Kalina power plants are under operation and no operation data has been published. This study focuses on the monitoring of the performance of the evaporator in an existing Kalina power plant. Effects of fouling, scaling, size and parameter influence on the performance of the evaporation process will be analyzed by using defined key performance indicators. Also, the challenges of data analysis caused by fluctuations of the system or changing parameters during operation are reported.

2. The Kalina's cycle layout

Already in 1953, Maloney and Robertson published a study on NH_3-H_2O heat power cycles, being skeptical about performance improvements associated with this working fluid [22]. In the early 1980's, Kalina patented a variety of cycle configurations with zeotropic mixtures as working fluids. Depending on the heat source and its temperature the applications vary from simple to very complex systems [23–29]. For geothermal power generation the layout called KCS-34 has been realized in Husavík, Iceland [29], which refers to the European patent [30] of Kalina from 2001. Based on a patent of Siemens [31], two similarly constructed plants have been built in Germany. The layout differs slightly from the simplest embodiment of the KCS-34, since the location of the internal heat exchanger is different. In this study the evaporation process of one of the Kalina plants built by Siemens is analyzed. The layout is presented in Fig. 1.

The geothermal heat source evaporates the zeotropic mixture in the evaporator. There are two evaporators installed in parallel in the analyzed Kalina plant. Under the operation conditions the

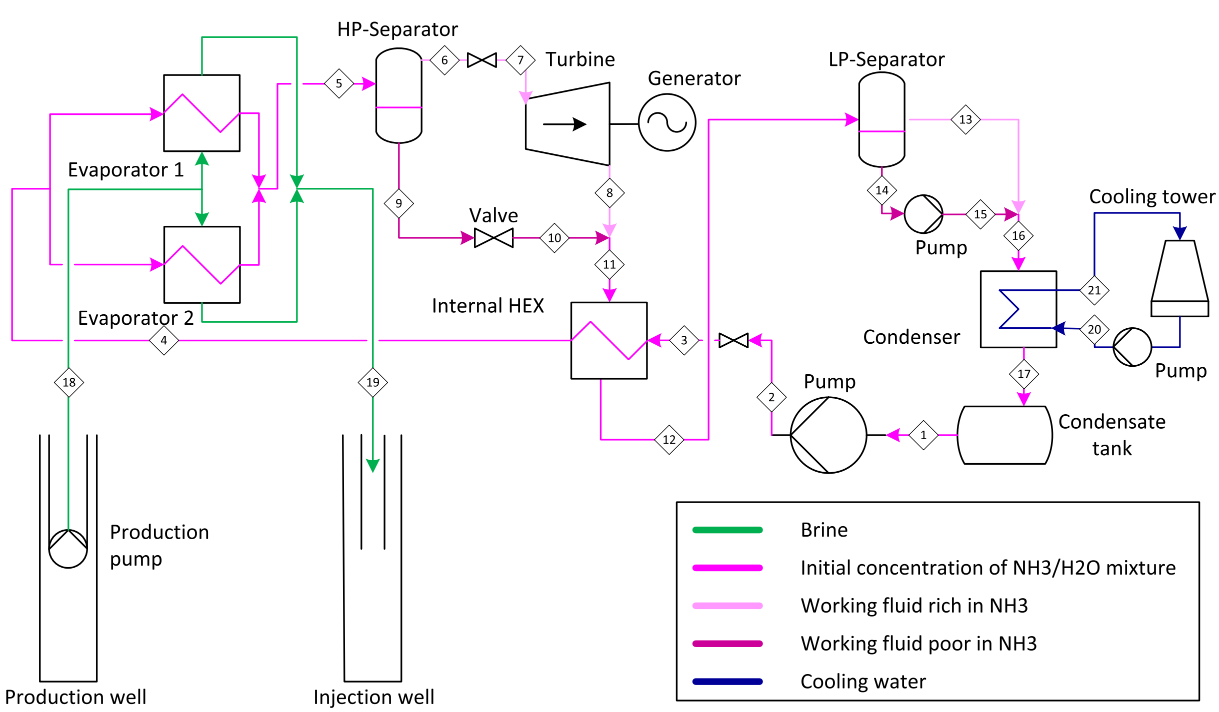

Fig. 1. Layout of the Kalina Cycle of a 550kW$_{el}$ geothermal power plant.