

Research Article

Investigation of Separator Parameters in Kalina Cycle Systems

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Abstract

Kalina cycle is useful for generating power from the waste heat or low temperature geothermal resources. The Kalina cycle systems use ammonia and water mixture as working fluid. The basic arrangement of an ammonia-water based power generating system consists of heat recovery vapor generator, separator, turbine, condenser, pump, heat exchanger, mixer and throttling device. Due to the non-isothermal nature of boiling of ammonia and water mixture, the evaluation of performance of such systems becomes tedious. The functional forms for obtaining the properties of ammonia-water mixture at different pressure, temperature and concentration are presented. Since the separator parameters are considered as the key parameters which influence the performance of the power plant, the behavior of two-phase ammonia and water mixture in the separator is investigated at different process conditions. The results are presented in the form of graphs and can be used for the development of new configurations of Kalina cycle system.

Keywords: Ammonia-water mixture, Equilibrium properties, Separator parameters, Vapor fraction.

1. Introduction

In order to increase the efficiency of the power generating systems, many new thermodynamic cycles have been investigated and developed in the past three decades. There is an increased curiosity to design cost-effective, efficient and reliable energy conversion systems for the utilization of low temperature heat sources which might have otherwise not utilized. The power cycles using binary mixture of ammonia and water as working fluid have favorable characteristics for generating electricity from low-temperature heat sources. The gain in efficiencies over the Rankine cycle particularly in the medium to low temperature range makes the ammonia-water cycle ideal for industrial waste heat, geothermal and co-generation power generating applications. In the ammonia-water based power generating system heat is transferred to the ammonia and water mixture either through the heat exchangers or boiler tubes. The ammonia-water mixture entering the separator exists both in vapor and liquid form. This means that the saturated vapor coexists in equilibrium with the saturated liquid and as such the concentration of ammonia in the liquid phase and in the vapor phase is different. The hot high pressure vapor mixture is then passed through a conventional steam turbine to generate power. The Kalina cycle is the most popular power cycle which utilizes ammonia and water mixture as the working fluid and is capable of generating electricity from a low-temperature heat source efficiently. Due to the feasibility

of binary and ternary working fluids in the power cycle for the utilization of conventional and non-conventional sources of energy, researchers are putting more efforts for the development of such power generation systems.

The analysis of ammonia-water mixture based power generation systems require the availability of thermodynamic properties of ammonia-water mixture at various conditions of pressure, temperature and concentration. Ziegler and Trepp have used Gibbs free energy equation and described an equation of state for the thermodynamic properties of ammonia and water mixture (Ziegler and Trepp 1984). The data on properties of ammonia-water mixture up to 316 °C and 210 bar was extended by El-Sayed and Tribus (El-Sayed and Tribus, 1985). By fitting critically assessed experimental data a set of five equations describing vapor-liquid equilibrium properties of ammonia-water mixture are presented. These equations are intended for use in design of absorption processes and avoid iterations (Patek and Klomfer, 1995). Nag and Gupta have used the Peng-Robinson equation for the vapor-liquid equilibrium (Nag and Gupta, 1997). The feasibility of vapor generation and absorption condensation process has been presented experimentally by Tamm and Goswami (Tamm and Goswami, 2003). Srinivas and Gupta have studied the heat recovery from the gas turbine exhaust with Kalina bottoming cycle and highlighted the advantage over the steam bottoming cycle (Srinivas and Gupta, 2010). Ganesh and Srinivas have identified the strong solution concentration as a key parameter and presented the performance characteristics

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for low temperature Kalina power plant using solar energy (Ganesh and Srinivas, 2012).

It has been identified that the separator parameters are the key parameters which influence the performance of the binary working fluid based power generating systems. The separation process of the ammonia-water mixture in the separator with respect to varied operating conditions is not well reported in the literature. The objective of the current work is to analyze the performance of ammonia-water mixture in the separator of power generating system so as to facilitate the development of new configurations of the power cycle. The parameters chosen for investigation in the current work are pressure, temperature, vapor fraction and vapor concentration.

2. Property data

The properties of binary mixture depends upon the three parameters i.e. pressure, temperature and concentration. The thermodynamic properties of ammonia-water mixture are computed using Gibbs free energies (Feng and Goswami, 1997). The specific enthalpy of the ammonia-water mixture in liquid and vapour phase is obtained from equations 1 and 2. It is assumed that the superheated ammonia-water mixture in the vapor phase above the saturation temperature of water behaves as an ideal solution.

$$h_{mix}^l = xh_{NH_3}^l + (1-x)h_{H_2O}^l + h^E \quad (1)$$

$$h_{mix}^g = yh_{NH_3}^g + (1-y)h_{H_2O}^g \quad (2)$$

$$T_b(P, x) = T_o \sum_i a_i (1-x)^{m_i} \left[\ln \left(\frac{P_o}{P} \right) \right]^{n_i} \quad (3)$$

$$T_d(P, y) = T_o \sum_i a_i (1-y)^{m_i} \left[\ln \left(\frac{P_o}{P} \right) \right]^{n_i} \quad (4)$$

$$y(x, P) = 1 - \exp[aP^b x + \left(c + \frac{d}{P}\right) x^2] \quad (5)$$

3. Separation of ammonia-water binary mixture

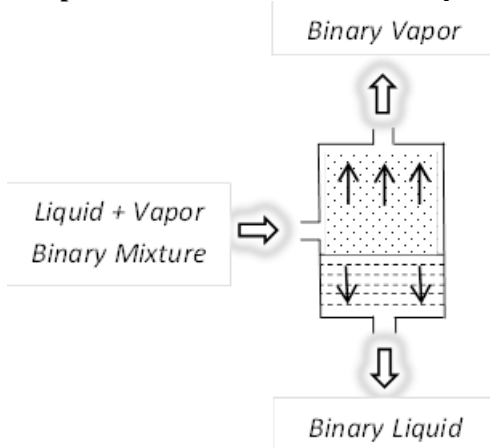


Fig. 1 Separation of liquid and vapor ammonia-water mixture in separator.

The separation of liquid and vapor ammonia-water mixture is shown in figure 1. The ammonia-rich vapor mixture flows through the top and the weaker liquid mixture flows through the bottom.

Once the heat is supplied to the mixture of ammonia-water in the boiler or heat recovery vapor generator, the

temperature of the mixture increases steadily and the mass fraction of the solution remains constant till the start of the evaporation. The temperature at which the first vapor bubble appears is known as bubble point of the solution at that pressure and concentration. Upon further heating the temperature rises continuously and finally at one particular temperature the last drop of liquid vaporizes. The temperature at which the last drop of liquid vaporises is known as dew point temperature.

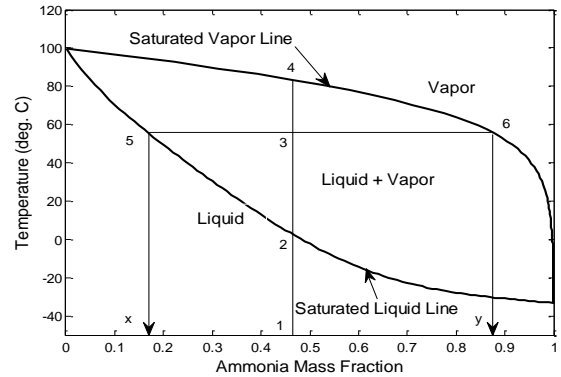


Fig. 2 Temperature-Composition diagram for ammonia-water mixture at 1.013 bar

The values of bubble point and dew point are calculated for different ammonia concentrations from 0 (pure water) to 1 (pure ammonia) keeping the pressure constant. The equilibrium temperature vs. concentration curve can be obtained by joining all the bubble points and the dew points. Figure 2 shows the variation of bubble point and dew point temperatures of ammonia-water mixture at 1.013 bar. The loci of all the bubble points are called the bubble point line or the saturated liquid line and the loci of all the dew points are called the dew point line or the saturated vapor line of the mixture at that pressure.

At any considered pressure and the temperature ranging from saturation temperature of pure water and dew point temperature T_d of the mixture, the water component is assumed to be in a meta-stable vapour state. Similarly in the liquid region, between the saturation temperature of pure ammonia and the bubble point of the mixture T_b , a meta-stable liquid state for ammonia is assumed. In the region where $T_d > T > T_b$, the ammonia mass fraction of the saturated vapor mixture is y and the saturated liquid mixture is x . In the liquid region, below the bubble point of the mixture T_b , a Gibbs excess function for the departure from ideal-solution behaviour is assumed (Kalina 1983). The region between the bubble point line and the dew point line is the two phase region in which the vapor and liquid coexist in equilibrium. The bubble point and dew point temperatures of the ammonia-water mixture are calculated from the equations 3 and 4 (Patek and Klomfar, 1995). The ammonia concentration in vapor phase is obtained from equation 5 (Soleimani, 2005). The concentration of vapor and liquid will be different in the two phase region. From figure 2 the mass and energy balance equations are obtained as follows.

Mass balance:

$$M_1 = M_2 + M_3 \quad (6)$$

$$M_1x_1 = M_2x_2 + M_3x_3 \tag{7}$$

Energy balance:

$$M_1h_1 = M_2h_2 + M_3h_3 \tag{8}$$

The vapor fraction in the separator is the ratio of mass of vapor to the mass of the two-phase mixture at the inlet. by lever rule

$$VF = \frac{\text{length 1 to 3}}{\text{length 2 to 3}} = \frac{M_3}{M_1} \tag{9}$$

from equations 7 and 8

$$VF = \frac{M_3}{M_1} = \frac{x_1 - x_3}{x_2 - x_3} = \frac{h_1 - h_3}{h_2 - h_3} \tag{10}$$

The ammonia-water mixture is heated in the heat recovery vapor generator in such a way that the exit condition lies in the two phase region. The two phase mixture is then fed to an adiabatic separator where the saturated vapor and the saturated liquid are separated. Figure 3 depicts the separation of ammonia-water mixture.

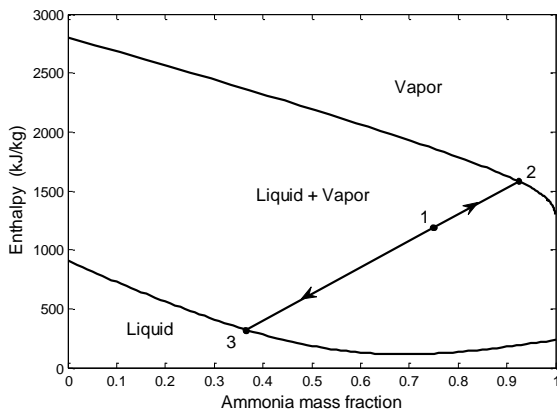


Fig. 3 Separation of two-Phase ammonia-water mixture at 35 bar, 125 °C and 0.75 inlet concentration.

Point 1 represents the state of the mixture at the inlet of the separator. As the performance of the ammonia-water based power plant is predominantly influenced by the separator parameters, the separator Pressure, temperature, vapor concentration and vapor fraction are chosen for investigation. Among these four parameters while one parameter is fixed, the other three are varied and the influence of these parameters on the separation process is analyzed.

4. Analysis of separation process

The variation of ammonia concentration in vapor mixture, liquid mixture, two-phase inlet mixture, vapor fraction, separator temperature and enthalpy of Vapor mixture at different operating conditions are evaluated separately.

4.1 Influence of separator pressure on concentration in vapor mixture

The variation of concentration in vapor mixture at fixed separator temperature between the pressures ranging from 20 to 70 bar is depicted in figure 4.

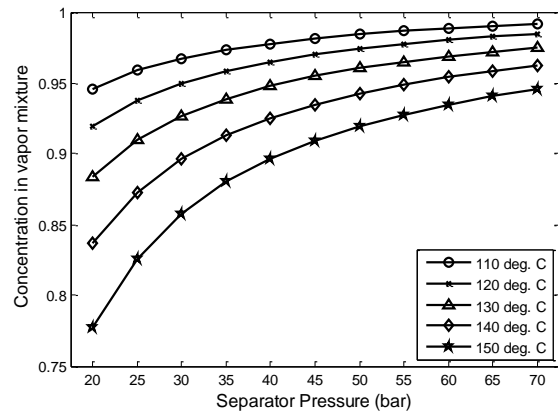


Fig. 4 Variation of ammonia concentration in vapor mixture with separator pressure

As more ammonia evaporates at higher pressure, the concentration in vapor mixture is found to be increasing with the separator pressure and decreasing with separator temperature.

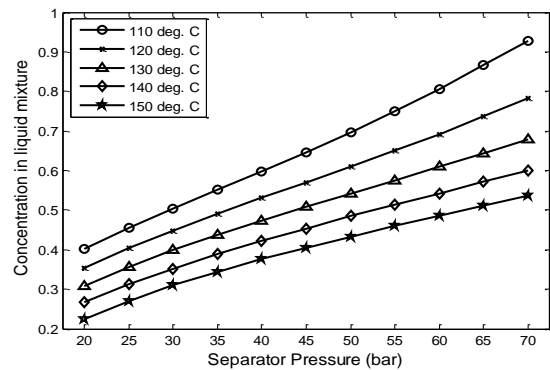


Fig. 5 Variation of Concentration in Liquid with Separator Pressure

4.2 Influence of separator pressure on concentration in liquid mixture

The variation of concentration in liquid mixture at fixed separator temperature between the pressures ranging from 20 to 70 bar is analyzed. The liquid concentration is found to increase with the separator pressure and decrease with separator temperature.

4.3 Effect of pressure on mixture concentration

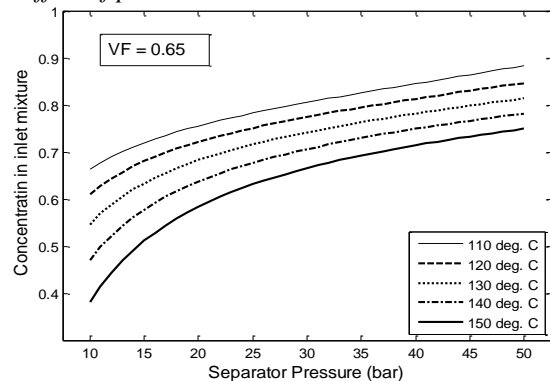


Fig. 6 Variation of mixture concentration with separator pressure

Figure 6 represents the variation of mixture concentration at the fixed separator temperature and between the pressures ranging from 20 to 60 bar when the vapor fraction is fixed. The higher separator pressure demands higher concentration in the inlet mixture and at elevated separator temperatures the concentration in the inlet mixture decreases.

4.4 Effect of pressure on separator temperature

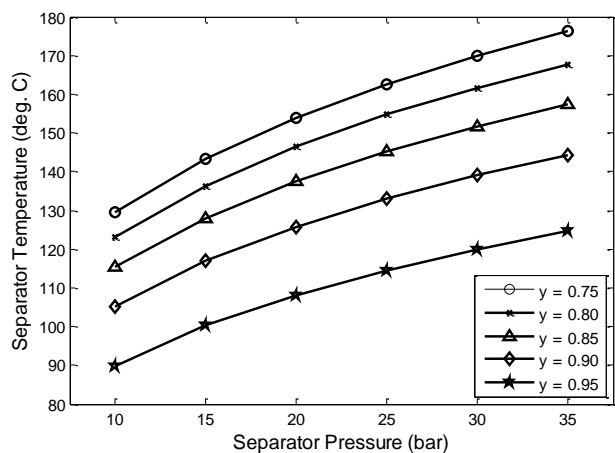


Fig. 7 Relation between separator temperature and its pressure

The separator pressure is a function of vapor concentration and separator temperature. The separator temperatures are evaluated at fixed concentration in vapor mixture and pressures ranging from 10 to 35 bar. It is found that the separator temperature rises with increasing separator pressure. The rate of evaporation of water in the mixture increases at elevated temperatures and therefore the concentration in vapor decreases with increase in separator temperature.

4.5 Effect of separator pressure on mixture Concentration

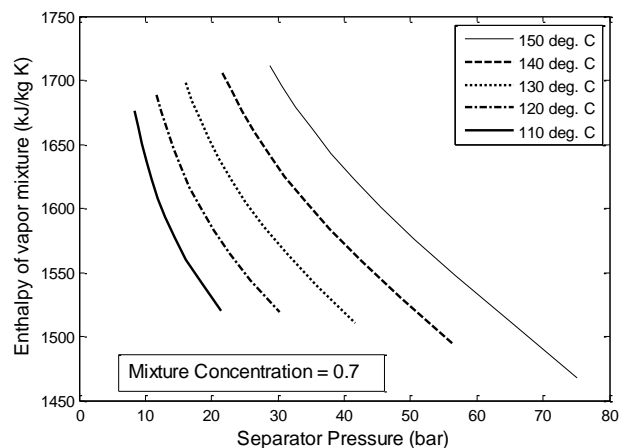


Fig. 8 Variation of Enthalpy of Vapor mixture with Separator Pressure

The concentration in the separator inlet mixture is fixed and the influence of separator pressure on the enthalpy of

the vapor mixture at fixed separator temperature is evaluated. The variation of enthalpy of vapor at pressures ranging from 10 to 75 bar is illustrated in the figure 8. The enthalpy of the vapor mixture decreases with increase in separator pressure. Also it is observed that the working fluid can be employed in wide range of pressure at elevated temperatures.

4.6 Effect of pressure on mixture concentration

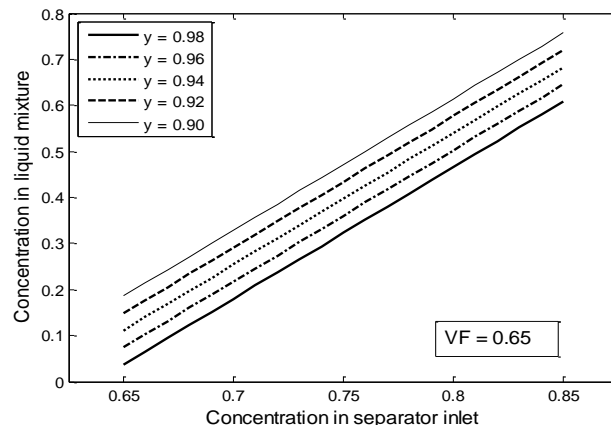


Fig. 9 Relation between separator inlet concentration and liquid concentration.

The effect of inlet mixture concentration on liquid mixture concentration at fixed vapor fraction and vapor concentration is analyzed. Figure 9 represents the variation of liquid concentration for separator inlet concentrations ranging from 0.65 to 0.85. As the concentration in liquid is the function of vapor concentration and vapor fraction, it rises linearly with an increase in separator inlet mixture concentration and also with increase in vapor concentration.

4.7 Effect of vapor concentration on liquid concentration

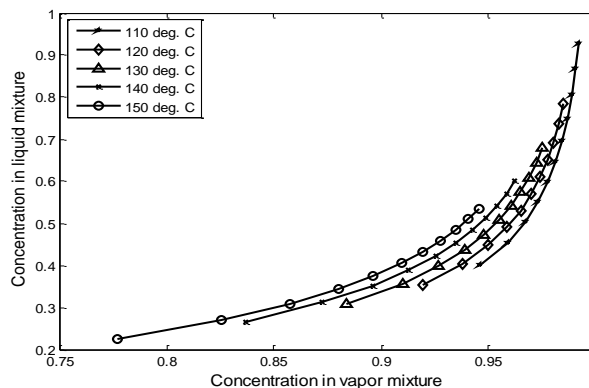


Fig. 10 Variation of liquid concentration with Separator Temperature

The relationship between liquid concentration and vapor concentration at constant temperature between the vapor concentrations ranging from 0.78 to 0.98 is depicted in the figure 10. An increase in liquid concentration is observed with increase in vapor concentration and separator temperature.

4.8 Effect of vapor concentration on vapor fraction

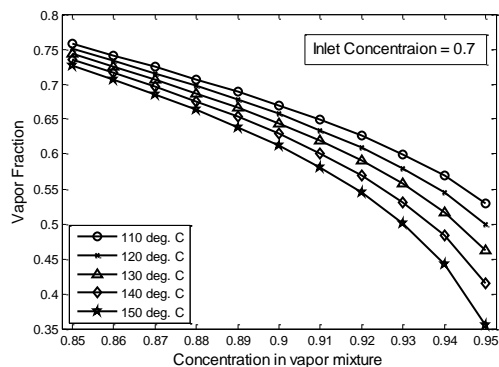


Fig. 11 Variation of vapor fraction with vapor concentration

The vapor fraction is evaluated from equation 10. The effect of vapor concentration on vapor fraction at fixed inlet concentration and temperature between the vapor concentrations ranging from 0.85 to 0.95 is shown in the figure 11. The vapor fraction decreases with increase in vapor concentration and separator temperature.

4.9 Effect of inlet concentration on vapor fraction

Figure 12 depicts the effect of inlet concentration on vapor fraction at fixed vapor concentration and temperature between 0.6 to 0.85 inlet mixture concentrations. The vapor fraction is found to be increasing with increase in vapor concentration and decreasing with an increase in temperature.

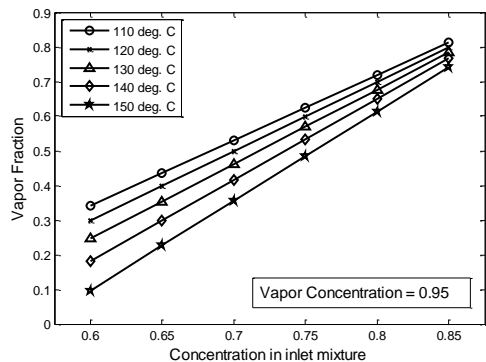


Fig. 12 Variation of vapor fraction with inlet concentration

4.10 Effect of inlet concentration on vapor fraction

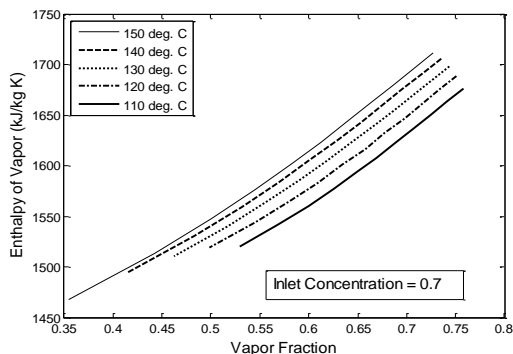


Fig. 13 Variation of Enthalpy of vapor with vapor fraction

The effect of vapor fraction on enthalpy of vapor at fixed inlet concentration and temperature between the vapor fractions ranging from 0.35 to 0.75 is depicted in the figure 12. The enthalpy of vapor increases with increase in vapor fraction and also with increase in temperature.

Conclusions

The energy and mass balance equations have been developed for separation process to evaluate the performance of two phase ammonia and water mixture in the separator at different combinations of pressure, temperature, vapor concentration and liquid concentration. The concentration of vapor and liquid phase increases with the increase in the separator pressure. With the increase in separator temperature, the concentration of vapor phase and liquid phase decreases at the fixed pressure and increases at the fixed concentration. With the increase in vapor concentration the liquid concentration also increases. In order to obtain higher vapor concentration, either the mixture concentration or the separator pressure is to be increased.

Nomenclature

- P* pressure, bar
- T* temperature, K
- VF* vapor fraction
- M* mass, kg
- h* specific enthalpy, kJ/kg
- x* ammonia mole fraction in liquid phase
- y* ammonia mole fraction in vapour phase
- a, c, d* coefficient
- Subscripts**
- mix* mixture
- o* reference state
- NH₃* ammonia
- H₂O* water
- Superscripts**
- l* liquid
- g* vapor
- E* excess
- b, m, n* constant

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