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Processes assessment in binary mixture plant

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Abstract
Binary fluid system has an efficient system of heat recovery compared to a single fluid system due to a better temperature match between hot and cold fluids. There are many applications with binary fluid system i.e. Kalina power generation, vapor absorption refrigeration, combined power and cooling etc. Due to involvement of three properties (pressure, temperature and concentration) in the processes evaluation, the solution is complicated compared to a pure substance. The current work simplifies this complex nature of solution and analyzes the basic processes to understand the processes behavior in power generation as well as cooling plants. Kalina power plant consists of regenerator, heat recovery vapor generator, condenser, mixture, separator, turbine, pump and throttling device. In addition to some of these components, the cooling plant consists of absorber which is similar in operation of condenser. The amount of vapor at the separator decreases with an increase in its pressure and temperature.

Keywords: Aqua ammonia; Heat recovery; Mixing; Separation.

1. Introduction

Thermodynamic solutions for basic processes involved in Kalina cycle have been solved and analyzed. The processes involved in this plant are adiabatic mixing, separation, pumping, regeneration, heat recovery, condensation, throttling and expansion. The mass and energy balances for the processes in components of Kalina cycle have been carried out. The components considered are mixer, separator, turbine, heat exchanger, evaporator, superheater and condenser.

The amount of vapor at the separator decreases with an increase in its pressure and temperature. Both have their individual merits and demerits. Recently research has been focused on these plants due to its flexibility in operation, environmentally friendly and alternative power generation. These cycles are well suited for recovering heat from low-grade waste heat. It has been identified that Kalina cycle is a suitable technology to recover heat from low temperature to medium temperature. The main thermodynamic advantage of the Kalina cycle is boiling/condensing process with variable temperature. Compared to the isothermal boiling/condensing processes in a Rankine cycle, the varying temperature during the heat transfer processes reduces the thermodynamic irreversibility of heat exchange process [1]. The low-grade waste heat cannot be used for steam production in a conventional steam cycle. The alternative way to generate electricity at low temperature is Kalina power system. This process maximizes the power output with a better heat recovery and without demand of additional fuels. Shankar Ganesh and Srinivas [2] developed the performance characteristics for low temperature Kalina power plant using solar energy.

The strong solution concentration has been selected as a key parameter in the reported work by the authors. But it restricts the vapor generation limits as it is function of strong solution concentration, liquid concentration and vapor concentration. Therefore to increase the range of variation, instead of strong solution concentration, vapor fraction has been selected as a key parameter in current investigation.

Without any problems, ammonia can be used in thermal power installations in a mixture with water. It is cheap and readily available, has no corrosive effect on iron and its alloys, and is soluble in water in any concentration [3]. Radial inflow turbines are ideal for binary cycles to get maximum isentropic efficiencies [4]. The processes investigation to understand the plant has not well reported in the literature. This work is useful to solve power alone [2], cooling alone [5] or power and cooling plant [6, 7] with simplified approach.

The main objective of the current work is to develop the processes to solve the power as well as cooling plant with aqua ammonia as a working fluid in a simplified approach. The current work is useful to the researchers in solving and developing new configurations for power generation as well as cooling generation.

2. Evaluation of basic processes

The following sections present the binary mixture processes and analyses to diagnose the processes clearly to assess the power and cooling plants.

2.1 Adiabatic mixing process

Figure 1 (a) and (b) shows the adiabatic mixing and separation processes for binary solutions. The mixing chamber is a device which mixes two different streams into one stream. In mixing and separation processes, the pressure assumed as remains constant. In adiabatic mixing, the final temperature depends on the temperature of constituents before mixing. The separation temperature during the process has been assumed constant.

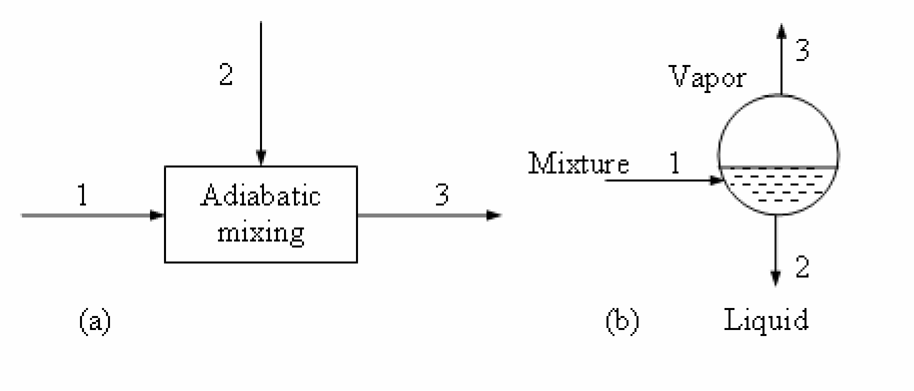

Figure 1. (a) Adiabatic mixing and (b) separation processes

Figure 2 shows the enthalpy-concentration diagram for adiabatic mixing process. Two streams 1 and 2 are mixed at state 3, which lies in two – phase region. The mixture obtained in the two phase region is a blend of compressed liquid and liquid-vapor mixture. As per the lever rule the distance between 1 and 3 is the ratio of mass at 2 to mass at 3 and between 2 and 3 is the ratio of mass at 1 to mass at 3.

The mass and energy balances for the mixing chamber are outlined from Eqs.1 to 5.

$$m_1 + m_2 = m_3 \tag{1}$$

$$m_1 x_1 + m_2 x_2 = m_3 x_3 \tag{2}$$

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \tag{3}$$

From Eq. (1), the mass at the outlet is calculated, and Eqs. (2) and (3) results the mixture concentration and mixture specific enthalpy at the outlet of the mixing chamber. From the enthalpy-concentration diagram of mixing streams (Figure 2), mixture concentration and mixture enthalpy have been calculated from the following equations.

$$x_3 = x_1 + \frac{m_2}{m_3}(x_2 - x_1) \tag{4}$$

$$h_3 = h_1 + \frac{m_2}{m_3}(h_2 - h_1) \tag{5}$$

The outlet concentration and enthalpy can also be calculated using the graphical method. The mixture temperature can be iterated from the enthalpy h_3.

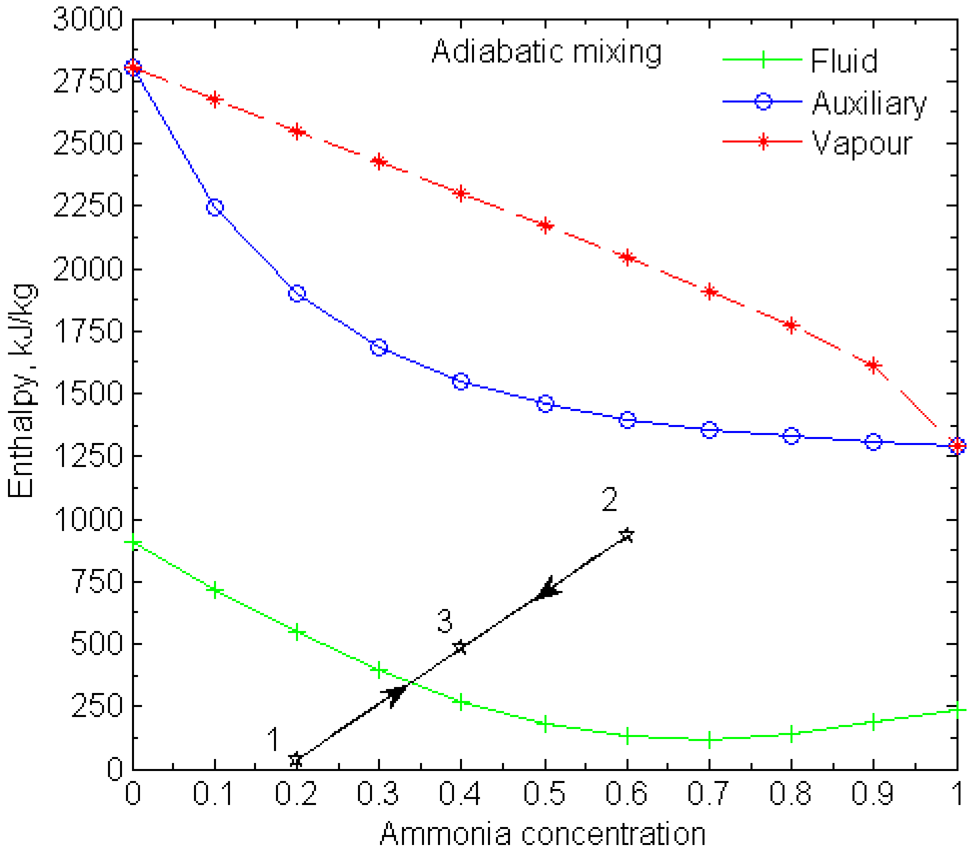

Figure 2. Adiabatic mixing of two streams on enthalpy-concentration diagram

2.2 Separation process

Separator is a device that separates the mixture at two-phase region in which the saturated vapor coexists in equilibrium with the saturated liquid. The concentration of the liquid and vapor in the separation chamber will be different.

Figure 3 shows the separation process in the enthalpy concentration diagram for binary mixture at 65% of vapor fraction. The line joining 1-2-3 is a constant temperature separation process. The liquid concentration of mixture is obtained by extending the constant temperature line up to the saturated liquid curve represented by point 2. Similarly the vapor concentration is obtained by extending the constant temperature line up to the vapor curve represented by point 3. The enthalpy at 2 is liquid enthalpy and at 3 is vapor enthalpy.

From the mass balance of separation process,

$$\mathrm{m}_1 = \mathrm{m}_2 + \mathrm{m}_3 \tag{6}$$

where m_2 and m_3 are liquid mass and vapor mass respectively.
From the lever rule, the vapor fraction in the separator is

$$F = \frac{x_1 - x_2}{x_3 - x_2} \tag{7}$$

The above equation can also be written as

$$\frac{m_3}{m_1} = \frac{x_1 - x_2}{x_3 - x_2} \tag{8}$$

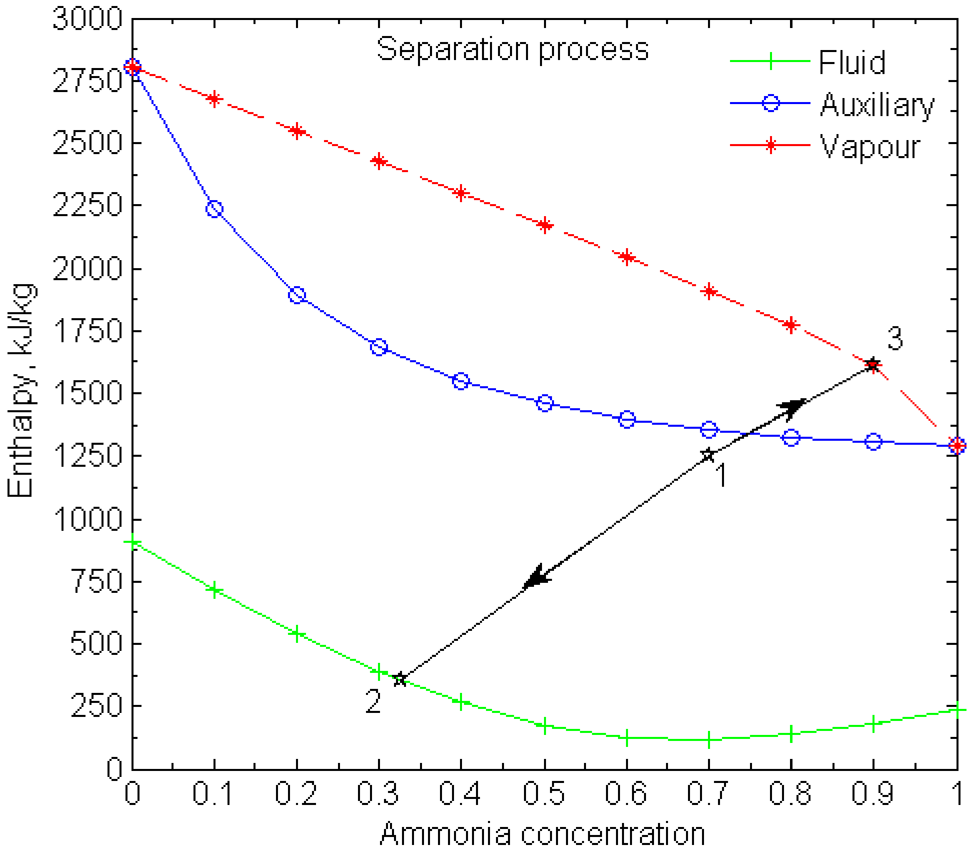

Figure 3. Separation of two streams on enthalpy-concentration diagram

From Eqs. (7) and (8), it can be understood that the liquid and vapor fractions in two phase region are inversely proportional to the distance between the mixture condition 1 and the vapor state 3 and saturated liquid 2 respectively as per the lever rule.

The separator parameters are considered as key parameters which influence the performance of the power plant. The parameters chosen for investigation in the separator are pressure, temperature, vapor fraction and vapor concentration. Out of these four parameters, one parameter has been fixed and the other three parameters are varied. The vapor fraction has been fixed as 65% to evaluate the influence of other parameters. In the succeeding sections the influence of these parameters on separation process has been analyzed. With the influence of each variable the changes in the enthalpy and concentrations are identified.

The separation can be solved either at known pressure and temperature or at known temperature and vapor concentration. At known pressure and temperature, the unknown vapor concentration can be determined. Similarly at known temperature and vapor concentration, unknown pressure can be determined. To solve the separation process, the separator inlet condition also to be required i.e. either separator inlet concentration or separator vapor fraction (mass of vapor to the total mass). The solution at given vapor fraction instead of at assumed separator inlet concentration gives more flexibility in parametric variation. Therefore, in current assessment, vapor fraction has been fixed instead of fixing separator inlet concentration.

2.2.1 Separation process with pressure variations at a fixed temperature, y = f (P, T)

Figure 4 is an enthalpy-concentration plot and shows the influence of separation pressure at a fixed vapor fraction of 65% and a separator temperature of 125 ºC. Since the vapor concentration is function of pressure and temperature, it has been determined at a variable pressure and a fixed temperature [8]. The separation pressure has been increased from 20-60 bar insteps of 10. The mixture at state 1 consists of both liquid portion and vapor portion. It is separated into liquid mixture (2) and vapor mixture (3). The resulted liquid concentration and vapor concentration increases with a diminishing rate, with an increase in separator pressure. The length (1-2) remains at 65% of total length connecting liquid and vapor curves. The mixture concentration also increases with diminishing rate with increase in the separator pressure at a fixed vapor fraction and temperature. On overall basis, the system demands high separator inlet concentration i.e. strong solution at high pressures to get the same amount of vapor fraction. If a vertical line has been assumed for constant separator inlet concentration in between the liquid and vapor curves, it results that, the vapor generation decreases and so vapor fraction with an increase in the separation pressure at a constant separator inlet concentration.

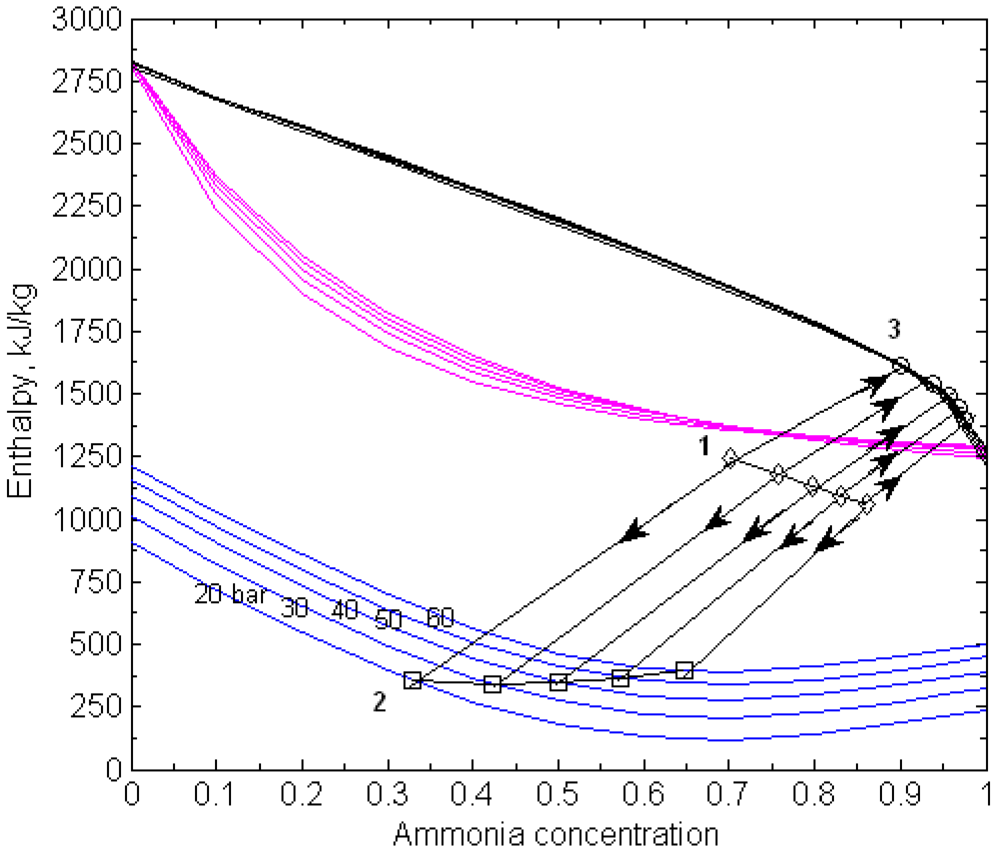

Figure 4. Influence of pressure on separation process at a fixed vapor fraction (65%) and separator temperature (125 ºC)

2.2.2 Separation process with temperature variations at a fixed pressure, y = f (P, T)

Figure 5 shows the enthalpy-concentration diagram with a change in separator temperature at a fixed pressure and vapor fraction. This process has been developed with a variable temperature at 65% of vapor fraction and 35 bar pressure. The resulted liquid concentration, vapor concentration and separator inlet concentration (concentration before separation) decrease with an increase in separator temperature at fixed vapor fraction and pressure. With a rise in separator temperature, the bubble point temperature and dew point temperature increases which decreases the related concentrations at a particular pressure and vapor ratio. On overall basis, low temperature results high vapor generation at a fixed vapor fraction and pressure.

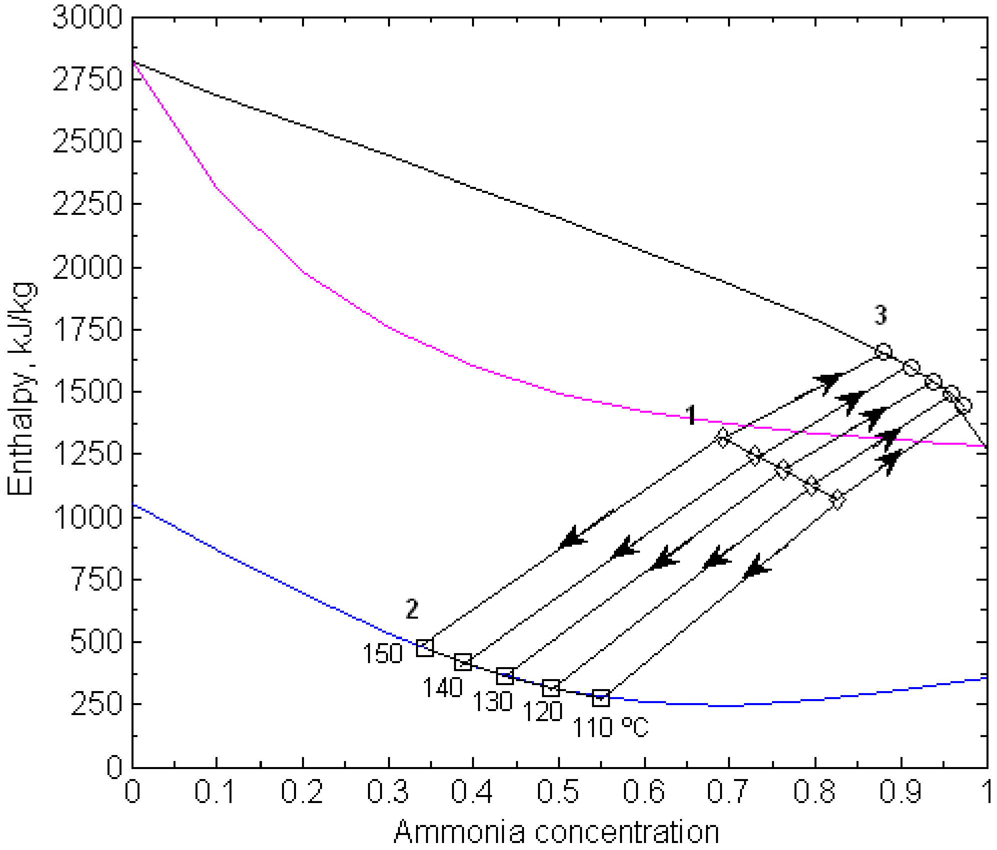

Figure 5. Influence of separator temperature on process outlet conditions at a fixed vapor fraction (65%) and pressure (35 bar)

2.2.3 *Separation process with vapor concentration variations at a fixed temperature, P = f (T, y)*

Figure 6 shows the enthalpy-concentration diagram with a change in vapor concentration at a fixed temperature and vapor fraction. The figure has been plotted at 65% vapor fraction and 125 ºC separator temperature. The separator pressure has been calculated at a fixed temperature and variable vapor concentration (0.86-0.94). The separator pressure has been increased with an increase in vapor concentration. The liquid concentration also has been increased with increase in vapor concentration. Similar to interpretation at Figure 4, high vapor concentration demands high separator inlet concentration to get the constant amount of vapor generation or the vapor generation decreases at a fixed separator inlet temperature. On overall basis, low vapor concentration results high vapor generation because of low pressure.

2.2.4 *Separation process with temperature variations at a fixed vapor concentration, P = f (T, y)*

Figure 7 shows the enthalpy-concentration plot with changes in separation temperature on process variations at 65% vapor fraction and 0.95 vapor concentration. As stated in previous sections, the pressure is function of temperature and vapor concentration. The resulted variations in separator concentration at inlet are low compared to the above results. The liquid concentration increases with increase in separator temperature. The lines converge at vapor line due to fixation of vapor concentration. As separator pressure is a function of temperature and concentration, with increase in separator temperature the pressure increases. If the separator inlet concentration is fixed, at lower temperature more amount of vapor can be generated.

2.3 Turbine expansion

The ammonia vapor turbine is a component for expanding ammonia vapor which is coupled to generator for electric work output. A mixture turbine can be used in decentralized power generation, cogeneration, trigeneration etc. Expansion in mixture turbine results nearly a saturated vapor at exit compared to wet steam in Rankine cycle, which requires protection of blades in the last few stages. Due to this reason, reheater is not essential for Kalina power turbine. With high pressure of vapor and low specific volume at exit of turbine, the size of the exhaust system could be comparably smaller than steam Rankine cycle.

$$W_t = m_1(h_1 - h_2) \tag{9}$$

where,

$$h_2 = h_1 - \eta_t \times \left(h_1 - h_2'\right) \tag{10}$$

Subscripts 1 and 2 are the inlet and outlet states, h_2' are the isentropic enthalpy at the exit condition. The exit enthalpy has been calculated from isentropic efficiency. With iterative procedure the temperature at the turbine exit is calculated after finding exit enthalpy [9].

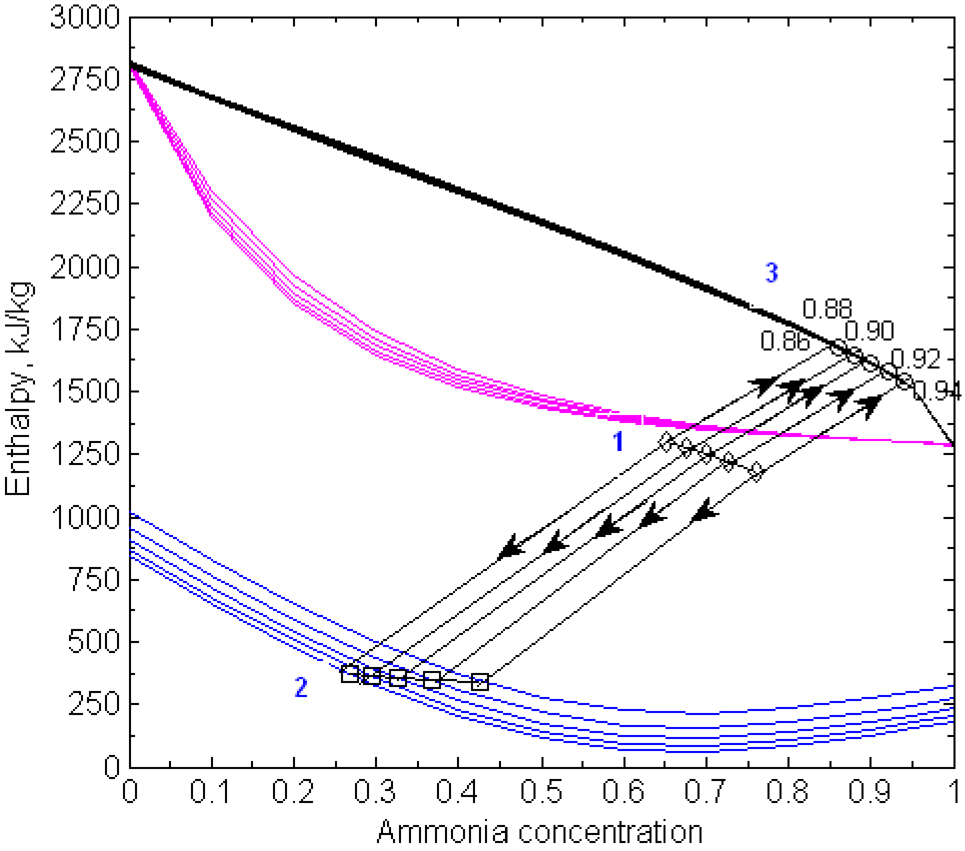

Figure 6. Influence of vapor concentration on separation process at a fixed vapor fraction (65%) and separator temperature (125 ºC)

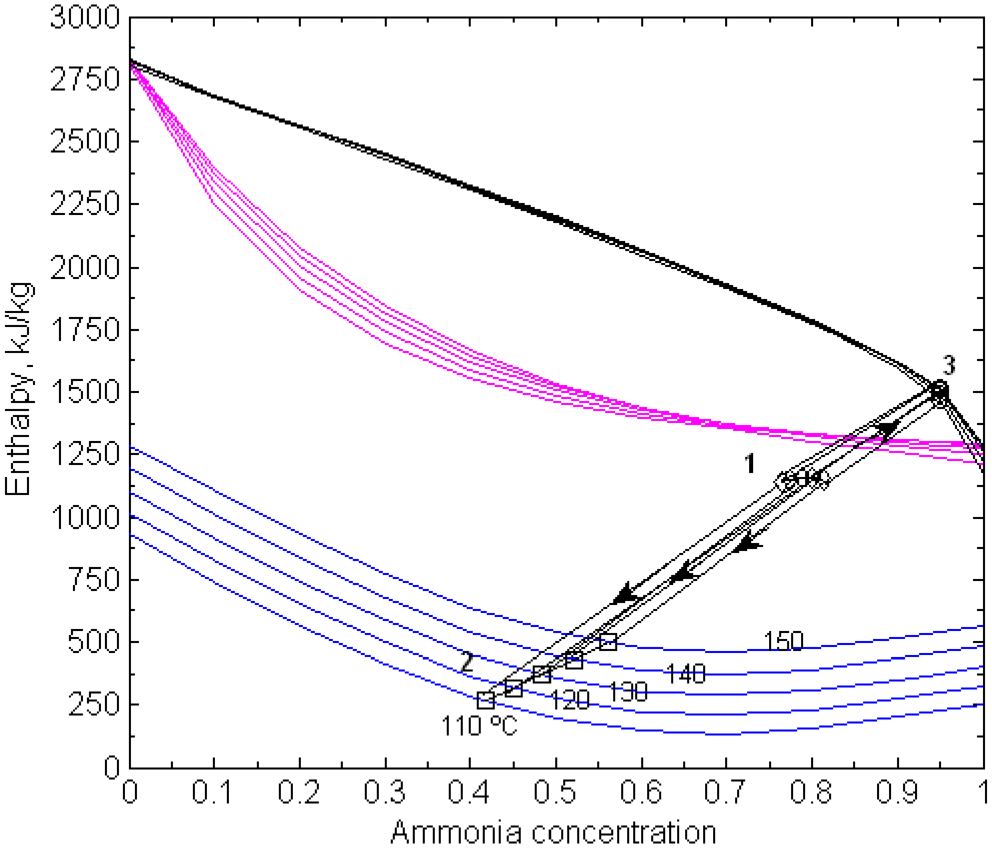

Figure 7. Influence of temperature on separation process at a fixed vapor fraction (65%) and vapor concentration (95%)

2.4 Heat exchanger

Kalina cycle power plant consists of different types of heat exchangers such as economizer, evaporator, superheater, low temperature regenerator, high temperature regenerator and condenser. In the evaporator section, the boiling takes place over a range of temperature. By virtue of varying boiling point, two components working fluid is able to match or run parallel to the hot fluid temperature line while recovering energy and hence the exit hot fluid temperature can be low. Ammonia-water mixture is a non-azeotropic mixture and non-isothermal. A pure substance boils at constant temperature and pressure, whereas non-azeotropic mixture boils at increasing temperature. With the constant boiling nature in the Rankine cycle the structural loss will be high. The temperature gap between the working fluid and heat source is high. Due to non-isothermal phase change of aqua ammonia a closer match between fluids has been observed. When the structural loss is reduced the driving force for the heat transfer is reduced, reduction in exergy loss.

Heat recovery vapor generator (HRVG) is a boiler in which heat from the hot source is utilized for generating vapor. HRVG consists of economizer, evaporator and superheater. A typical heat recovery used in Kalina power plant has been depicted in Figure 8. Economizers are heat exchange devices in which ammonia water mixture is heated up to its boiling point. It is used to preheat the working fluid by the hot source in the boiler.

At low temperature heat recovery, HRVG generated wet vapour where its temperature is maintained below the dew point temperature. A separator is required to remove the liquid portion from the liquid vapor mixture. Increase of high temperature heat recovery, directly superheated vapor has been generated. The heat source may be in the form of steam or hot gas from another process. In the evaporator the working fluid is passing through tubes surrounded by heat source stream, gaining heat and converted to vapor.

Superheater is a device in which the left portion of wet vapor or saturated vapor is converted to dry vapor. The superheated vapor is then expanded in the turbine. The efficiency of the cycle is increased with the utilization of superheated vapor.

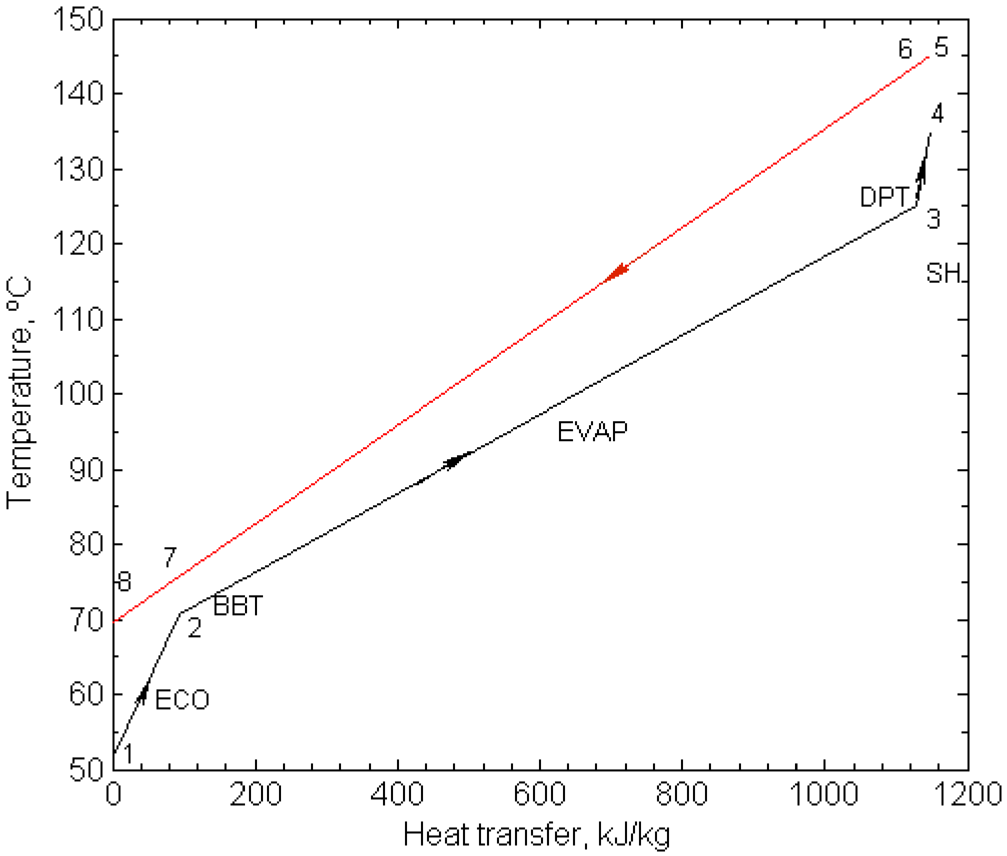

Figure 8. Temperature-heat transferred diagram for heat recovery vapor generator, BBT: bubble point temperature; DPT: dew point temperature; ECO: economizer; EVAP: evaporator; SH: superheater

2.5 Condenser

Like evaporator, the condensation of two component working fluid also occurs over a range of temperatures and hence permits additional heat recovery in the condensation system. The condenser pressure can be much higher in two component fluid cycle, and the cooling water temperatures do not impact the power output of the turbine as in Rankine cycle. Thermo-physical properties of mixture can also be altered by changing the concentration of one component. This helps to recuperate or regenerate energy in the condensation system. Modifications to the condensing system are also possible by varying the mixture concentration and thus more energy can be recovered from the hot fluid. More power can be generated if the sink temperature is low. In Kalina cycle at high condenser pressure condensation have been efficiently achieved which is not possible in the Rankine cycle. Condenser pressure in Kalina cycle depends on sink temperature and concentration of ammonia in the mixture. The output and efficiency of Kalina power cycle system will increase at low concentration in condenser.

2.6 Solution pump

The pump in the plant pressurizes the liquid stream and delivers to the subsequent components. From the energy balance, the pump work can be predicted.

$$W_p = \frac{m_1\left(h_2 - h_1\right)}{\eta_P} \tag{11}$$

where, η_P is pump efficiency.

3. Conclusion

The energy and mass balance equations have been developed for thermodynamic processes to evaluate the power and cooling cycles. The focus has been given on separation process due to its complexity and influence on performance. The influence of key parameters such as temperature, pressure, concentration and vapor fraction on the separation process has been analyzed. At increased separator pressure the liquid and vapor concentrations have been increased, whereas at increased temperature, the concentration in both phases decreased. At increased vapor concentration, pressure and liquid concentration has been increased. The increased pressure and temperature in separator decreases the vapor generation capacity. It increases the plant efficiency and power output with a decreasing rate due to the above mentioned reason.

Nomenclature

F	vapor mass fraction in separator	T	temperature, K
H	specific enthalpy, kJ/kg	TTD	terminal temperature difference, K
m	mass, kg/s	W	work, kJ
s	specific entropy, kJ/kg K	x	mass fraction of ammonia, kg/kg mixture

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