

Parametric Analysis of a Multiple Solution Concentration Operated Combined Power and Cooling Cycle with Internal Recuperation

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Abstract – In this paper, two different methods of combining ammonia-water based power and cooling cycle are discussed in terms of turbine work output, cooling output, overall exergy destruction and exergy efficiency of the cycle. The two cycles are connected either in parallel or series configuration, in which the cooling sub-cycle is fed on the waste heat recovered from the liquid condensate of power sub-cycle. In both configurations, the cooling sub-cycle is fed on the high solution concentration, whereas, the low solution concentration is either feed directly (in parallel configuration) or converted into intermediate solution concentration (in series configuration), before feeding to the power sub-cycle. The concentration difference in the entire cycle is maintained by assuring partial vaporization during both generation and recuperation of ammonia vapors. The cooling output produced in parallel circuit is marginally higher than the corresponding series circuit due to lower absorber pressure under similar operating conditions. However, the turbine work output of the series circuit is comparably higher as compared to parallel circuit due to higher solution concentration and mass flow rate. But, this higher solution concentration increases the exergy input, pump work and hence overall exergy destruction in series circuit as compared to parallel circuit. Nevertheless, due to higher product output, exergy efficiency of series circuit is higher. For unit mass flow rate, the turbine work output improves from 9.11 kW (in parallel circuit) to 23.77 kW (in series circuit), cooling output marginally reduces from 63.29 kW (in parallel circuit) to 63.27 kW (in series circuit), overall exergy destruction increases from 140.30 kW (in parallel circuit) to 182.05 kW (in series circuit) and exergy efficiency improves from 7.16% (in parallel circuit) to 11.94% (in series circuit), when operated for 185 °C heat source temperature, 0.15 split fraction (only in series circuit) and 0.30 kmol of NH₃ / kmol of sol basic solution concentration.

Keywords: ammonia-water; work output; cooling output; overall exergy destruction; exergy efficiency; basic solution concentration; heat source temperature, split fraction.

1. Introduction

The continuous generation of greenhouse gas emissions from the conventional energy related activities has motivated many researchers to develop systems that do not involve ozone depleting-working fluid. In view of the above energy challenges, the recent developments in the ammonia-water based thermal systems such as absorption based cooling [1], power [2], cogeneration [3] and trigeneration systems [4] attracted significant attention due to its cleaner approach. The ammonia-water system has a provision to club its standalone cycles into an integrated system. The thermal and exergy efficiency of one such integrated power and cooling system is found to be 24.24% and 8.16% times higher as compared to its parent standalone cycle operating under similar conditions [5].

It is clear from published literature that the integrated ammonia-water power cooling system requires extensive exploration. Liu and Zhang [6] proposed a splitting/absorption unit to adjust the ammonia concentration and mass flow rate of different streams during cogeneration. The modification leads to 23.3% increase in exergy efficiency as compared to standalone power refrigeration cycles. Zhang and Lior [7] studied parallel/series arrangement of ammonia-water operated power and refrigeration cycle, connected through a distillation column, for minimum exergy losses. Wang *et al.* [8] simplified the above parallel combination by eliminating the pump and condenser used before and after the turbine of the power sub-cycle. Jawahar *et al.* [9] proposed a Generator-Absorber heat eXchange (GAX) based cogeneration cycle, which has better thermal efficiency and Coefficient Of Performance (COP) (64% and 0.63) as compared to simple cycle (0.5 and 50%). Srinivas and Reddy [10] proposed a solar collector operated combined cycle with controlling facility for adjustable power and cooling output. Nearly equal amount of cooling and power is produced for 0.8 mass split ratio. Han *et al.* [11] developed a cogeneration experimental rig by sharing common generator, absorber, rectifier, pump, throttle valve and solution heat exchanger. The test rig generated 0.448 COP in cooling alone mode and had 3.98% heat source-to-power conversion efficiency. Wang *et al.* [12] clubbed the Kalina and the absorption refrigeration cycles through separators, feeding the latter cycle on the vapors recovered after the turbine work. It shows that increase in separator pressure or strong solution concentration, and decrease in separator temperature or turbine back pressure favours growth in efficiency of the

cogeneration cycle. Ghaebi *et al.* [13] proposed a combination of Kalina based combined cycle as a heat source with a Liquefied Natural Gas (LNG) based power cycle as a heat sink. The modified system shows great enhancement in overall efficiency as compared to Kalina cycle under similar conditions. Zhang *et al.* [14] added generator and rectifier before the evaporator in the refrigeration sub-cycle of cogeneration system, thus provided cooling temperature in ice making range as it is running on low-pressure absorber. Zhang *et al.* [15] re-modified the cycle mentioned in [14] to provide either air-conditioning capacity or ice making capacity in the refrigeration sub-cycle. For this, two convertible flow directions are provided to the refrigerant with the aid of valves. Singh and Das [16] evaluated the ammonia-water refrigeration cycle and conclude that the overall exergy destruction minimization leads to improvement in exergetic COP when the cooling load is fixed. Singh and Das [17] showed the conditional behaviour of overall exergy destruction minimization for cogeneration cycle. The overall exergy destruction minimization per unit cooling load and exergy input, leads to improvement in both power and cooling output. Shankar and Rivera [18] integrated two different cogeneration cycles, first is double pressure and second is triple pressure, in which the double pressure cycle is operated through only flashing and separation process and no heating is provided from any external heat source.

It is seen that there is no study on the parallel/series combination of the ammonia-water power and cooling cycle in which the cooling sub-cycle is fed by the hot liquid condensate of the power sub-cycle. The recovery of waste heat from the liquid condensate not only enables producing additional output in the form of cooling, but also reduces the exergy losses during the absorption process. Also, the cycle is simplified by maintaining partial vaporization in the generator and recuperator, and by using separator instead of distillation column. Here, a parametric study is framed to compare the suitability of above mentioned parallel/series combinations in terms of turbine work output, cooling output, overall exergy destruction and exergy efficiency of the cycle under different operating conditions.

2. Combined cycle construction and assumptions

The combined cycle demonstrated in this paper consists of a higher solution concentration operated topping cooling sub-cycle and intermediate/lower solution concentration operated bottoming power sub-cycle. The topping and bottoming sub-cycles are connected through recuperator, separator and absorber in two different configurations: either connected in parallel or in series. Both topping and bottoming sub-cycles are operated on common binary working fluid but with different solution concentrations. As simple separators are used for liquid and vapor separation, the operating pressure of the generator and recuperator is always maintained below to their corresponding bubble pressure. Only one external heat source with the aid of saturated steam is provided to the power sub-cycle, whereas the cooling sub-cycle is working on the waste heat recovered during recuperation. The line diagram of the parallel/series circuit is discussed below.

2.1. Parallel connected cogeneration circuit

The schematic diagram of the parallel cogeneration circuit is shown in Fig. 1. The power sub-cycle can be identified as 4–5–6–7–8–9–10–1 and the cooling sub-cycle as 14–15–16–17–18–1. Process 11–12–13 shows internal

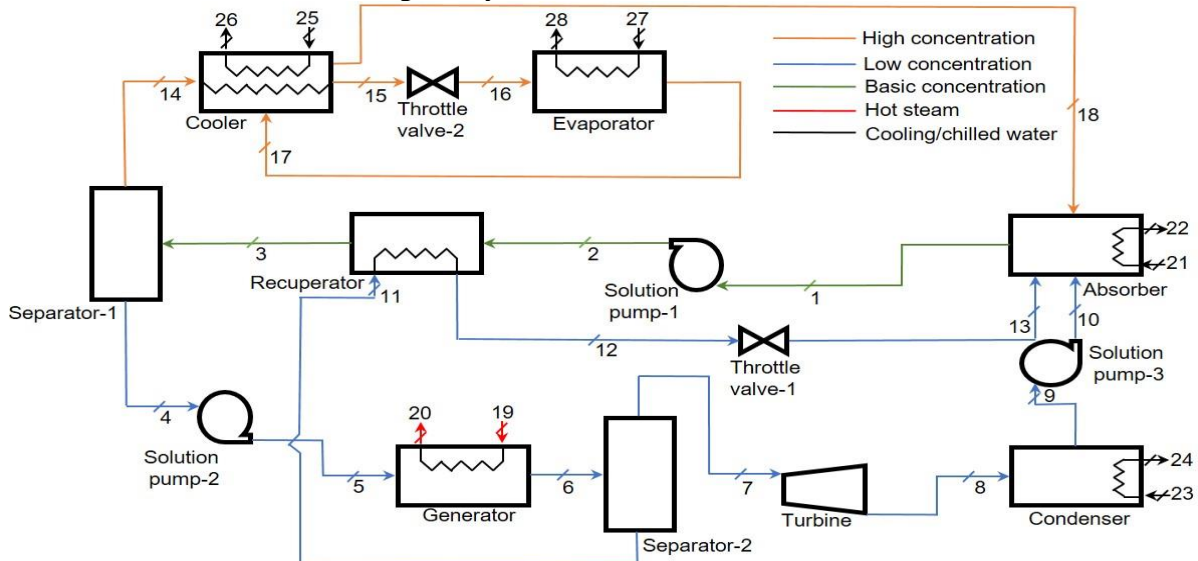


Fig. 1: Line diagram of the parallel circuit of combined power and cooling cycle

recuperation. Clearly, the cooling sub-cycle is operating on high vapor concentration as compared to the power sub-cycle. The parallel combined cycle has four different pressure levels during its operation. Also, it can be seen that the external heat source is added only in the generator of the power sub-cycle. Rest of the cycle is operated on the internal recuperation of the condensate heat of power sub-cycle.

2.2. Series connected cogeneration circuit

The arrangement of the series cogeneration circuit is shown in Fig. 2. The power sub-cycle can be identified as 16–17–18–19–20–21–1 and the cooling sub-cycle as 11–12–13–14–15. Path 22–23–24 represents internal recuperation.

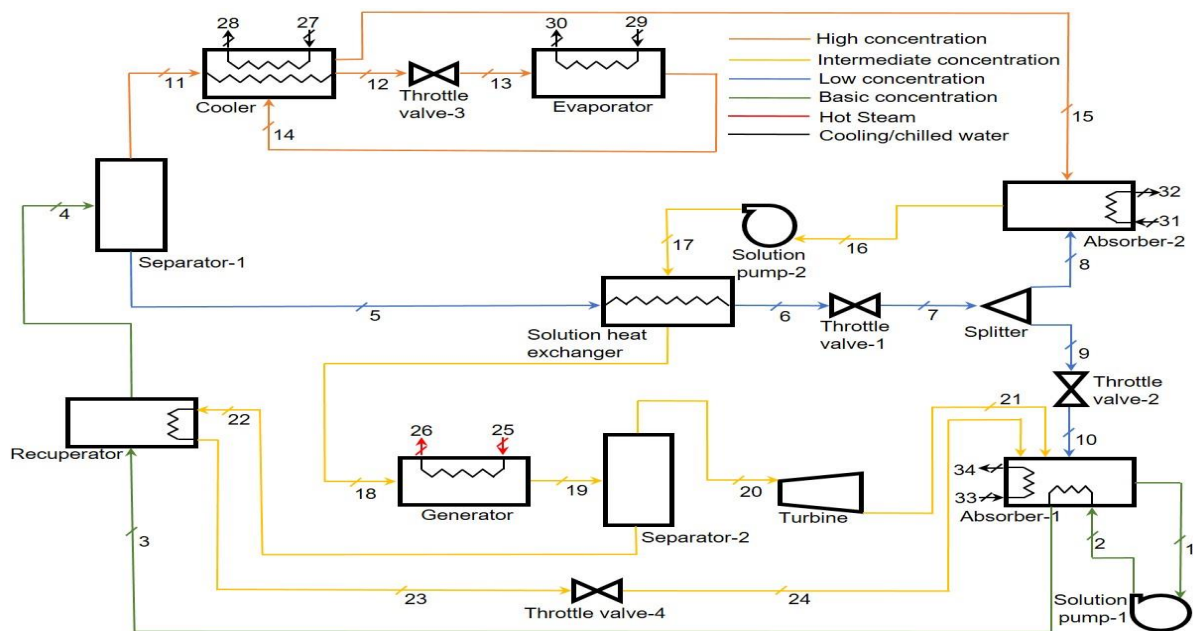


Fig. 2: Line diagram of the series circuit of combined power and cooling cycle

Here, the low concentration mixture from the separator-1 is divided into two streams by the splitter. One stream meets the high vapor concentration solution in the absorber-2 to form new intermediate solution concentration, while the second stream is sent to catch the turbine vapors in absorber-1. So, in series configuration, the cooling sub-cycle is working on high vapor concentration and power sub-cycle is working on intermediate concentration. The distribution of the streams by the splitter is quantified by split fraction, which is the ratio of \dot{m}_9/\dot{m}_7 , where \dot{m} represents mass flow rate at any location of the cycle in kg/s.

2.3. Estimation of thermal properties and assumptions

The thermodynamic analysis involves evaluation of specific enthalpy, specific entropy and specific physical exergy of the ammonia-water mixture at various locations of the cycle. The above mentioned thermal properties are evaluated in this paper by adopting the scheme proposed by Xu and Goswami [19]. The values of the assumed parameters considered in the analysis are mentioned in Table 1. Some other assumptions taken during the analysis are mentioned below,

- The system is evaluated under steady state environment. There is no pressure loss taken in the system except for the mixture flowing through throttle valve and turbine.
- Saturated conditions are assumed while calculating operating pressure in absorber and condenser.
- The operating pressure of generator and recuperator is maintained 20% lower than the corresponding value of their bubble pressure. This assumption is assumed to maintain the condition of partial vaporization while heating. One can choose any value of percentage as the overall trend of the output and performance parameters remain same during the analysis.
- The temperature of vapor and liquid condensate coming out from the rectifier is assumed to be the same.
- The temperature rise during internal heat recovery in cooler and absorber-1 (in series circuit only) is assumed as 10 °C [18].

Table 1: Details of the assumed parameters in the parallel/series circuit of power and cooling cycle configuration.

S. No.	Operating parameter name	Assumed values	Literature source
1	Ambient temperature	25 °C	[17]
2	Ambient pressure	1.01325 bar	[17]
3	Basic solution concentration	0.30 – 0.37 kmol of NH ₃ / kmol of sol	[8]
4	Ammonia vapor concentration at both separator exit	0.999 kmol of NH ₃ / kmol of sol	[16]
5	Heat source operating temperature	150 – 185 °C	[18]
6	Absorber exit temperature	5 °C above ambient temperature	[8]
7	Condenser/cooler exit temperature	5 °C above ambient temperature	[8]
8	Evaporator exit temperature	-5 °C	[8]
9	Inlet temperature of cooling water	27 °C	[16]
10	Exit temperature of cooling water	35 °C	[16]
11	Inlet temperature of chilled water	20 °C	[16]
12	Exit temperature of chilled water	10 °C	[16]
13	Strong solution flow rate	1 kg/s	[7]
14	Isentropic efficiency of Turbine	85%	[7]
15	Isentropic efficiency of solution pump	70%	[7]
16	Terminal temperature difference for generator	10 °C	[18]
17	Terminal temperature difference for recuperator	60 °C	–
18	Temperature difference for low concentration solution flowing in solution heat exchanger	30 °C	–

2.4. Performance parameters used in the analysis

Overall exergy destruction in the parallel/series circuit can be computed as [20],

$$\begin{aligned} \text{For parallel circuit : } & \left[\dot{m}_{19} (PE_{19} - PE_{20}) + \dot{m}_1 (H_2 - H_1) + \dot{m}_4 (H_5 - H_4) + \dot{m}_9 (H_{10} - H_9) \right] - \\ & \left[\dot{m}_7 (H_7 - H_8) + \dot{m}_{28} (PE_{28} - PE_{27}) \right] - \\ & \left[\dot{m}_{25} (PE_{26} - PE_{25}) + \dot{m}_{21} (PE_{22} - PE_{21}) + \dot{m}_{23} (PE_{24} - PE_{23}) \right] \end{aligned} \quad (1)$$

$$\begin{aligned} \text{For series circuit : } & \left[\dot{m}_{25} (PE_{25} - PE_{26}) + \dot{m}_1 (H_2 - H_1) + \dot{m}_{16} (H_{17} - H_{16}) \right] - \\ & \left[\dot{m}_{20} (H_{20} - H_{21}) + \dot{m}_{29} (PE_{30} - PE_{29}) \right] - \\ & \left[\dot{m}_{27} (PE_{28} - PE_{27}) + \dot{m}_{31} (PE_{32} - PE_{31}) + \dot{m}_{33} (PE_{34} - PE_{33}) \right] \end{aligned} \quad (2)$$

where, H represents the specific enthalpy in kJ/kg, PE the specific physical exergy in kJ/kg and the overall exergy destruction in kW.

Exergy efficiency of the parallel/series circuit can be calculated as [21],

$$\text{For parallel circuit : } \frac{\left[\dot{m}_7 (H_7 - H_8) + \dot{m}_{28} (PE_{28} - PE_{27}) \right]}{\left[\dot{m}_{19} (PE_{19} - PE_{20}) + \dot{m}_1 (H_2 - H_1) + \dot{m}_4 (H_5 - H_4) + \dot{m}_9 (H_{10} - H_9) \right]} \quad (3)$$

$$\text{For series circuit : } \frac{\left[\dot{m}_{20} (H_{20} - H_{21}) + \dot{m}_{29} (PE_{30} - PE_{29}) \right]}{\left[\dot{m}_{25} (PE_{25} - PE_{26}) + \dot{m}_1 (H_2 - H_1) + \dot{m}_{16} (H_{17} - H_{16}) \right]} \quad (4)$$

where, the exergy efficiency is expressed in percentage for better understanding.

3. Results

In this study, saturated steam is taken as a latent heat source for the generator. The system response is studied for different values of heat source temperature and basic solution concentration. Rest of the parameters are either assumed as fixed values, shown in Table 1, or are calculated from the assumptions mentioned previously. For series system, one more parameter, named split fraction, is involved during the analysis. The response of the parallel/series systems under identical input or assumed parameters is discussed below.

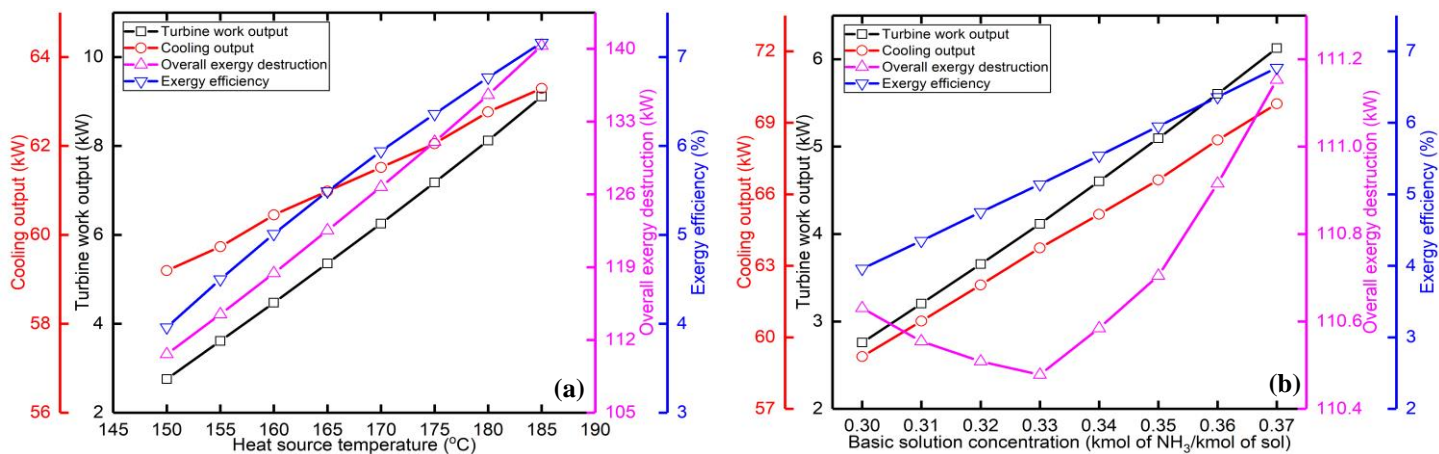


Fig. 3: Effect of (a) variable heat source temperature and (b) variable basic solution concentration on the performance of parallel combined power and cooling cycle

For parallel circuit running at constant basic solution concentration of 0.30 kmol of NH₃ / kmol of sol, in Fig. 3 (a) the increase in heat source temperature leads to increase in recuperator inlet temperature. This results in more evaporation of the basic solution in the separator-1, which increases vapor flow rate in the cooling sub-cycle and decreases the mass flow rate/solution concentration of the power sub-cycle. So, there is direct improvement in the cooling output as more vapors enter the cooling sub-cycle. On the other hand, the turbine work output increases due to rise in turbine inlet temperature/vapor flow rate passing the turbine. But, the turbine work output is very small as compared to increase in exergy input, which is due to decrease in low solution concentration in the power sub-cycle. Also, the pump work increases with increase in both generator and recuperator pressure, which is due to increase in heat source temperature. So, the increase in fuel input in the form of exergy input and pump work provides the main reason for increase in overall exergy destruction of the cycle. The exergy efficiency is although very small, because the increase in product output is very small as compared to increase in fuel input, but the product to fuel ratio increases due to higher increase in product output as compared to increase in fuel input. Also, it should be noted that the condenser back pressure is constant due to fixed turbine vapor concentration and condenser outlet temperature. Also, due to fixed basic solution concentration and absorber outlet temperature, the absorber pressure is also fixed.

For parallel circuit running at constant heat source temperature of 150 °C, Fig. 3(b) shows that the increase in basic solution concentration results in more evaporation in separator-1. This increase in mass flow rate is higher than the previous parallel circuit case in which heat source temperature was varied under constant concentration. Hence, the cooling output for variable basic solution concentration is higher as compared to previous parallel case of variable heat source temperature. Also, there is rise in the absorber pressure due to increment in the basic solution concentration of the system. This limits the amount of expansion in the throttle valve-2 or the cooling output of the cooling sub-cycle. On the other hand, the solution concentration of the power sub-cycle also increases with increase in the basic solution concentration but its mass flow rate decreases. The increase in solution concentration increases the mass flow rate of vapors at the entrance of the turbine operating at constant generator temperature. Thus, the work output of the turbine increases with increase in basic solution concentration. But, this increase in turbine work output is lower than the previous parallel case, as vapors are entering at fixed turbine temperature and the depreciation in the mass flow rate of low concentration solution is higher than the previous one. The increase in solution concentration of power sub-cycle also increases the generator pressure which slightly increases the demand of heat source/exergy input to maintain the same generator temperature. The pump work also increases due to increase in concentrations/pressures in both generator and recuperator. It can be seen from Fig. 3(b) that the overall exergy destruction first decreases and thereafter again increases with increase in the basic solution concentration. This variation is although on a very small scale and is due to the additional effect of exergy losses as seen in Eq. (1), which increases due to increase in mass flow rate in cooler and absorber, but this increase is later dominated by the exergy input and pump work. The exergy efficiency of the cycle is although less than the previous case, but it increases due to more improvement in both the outputs as compared to increase in exergy input and pump work of the cycle.

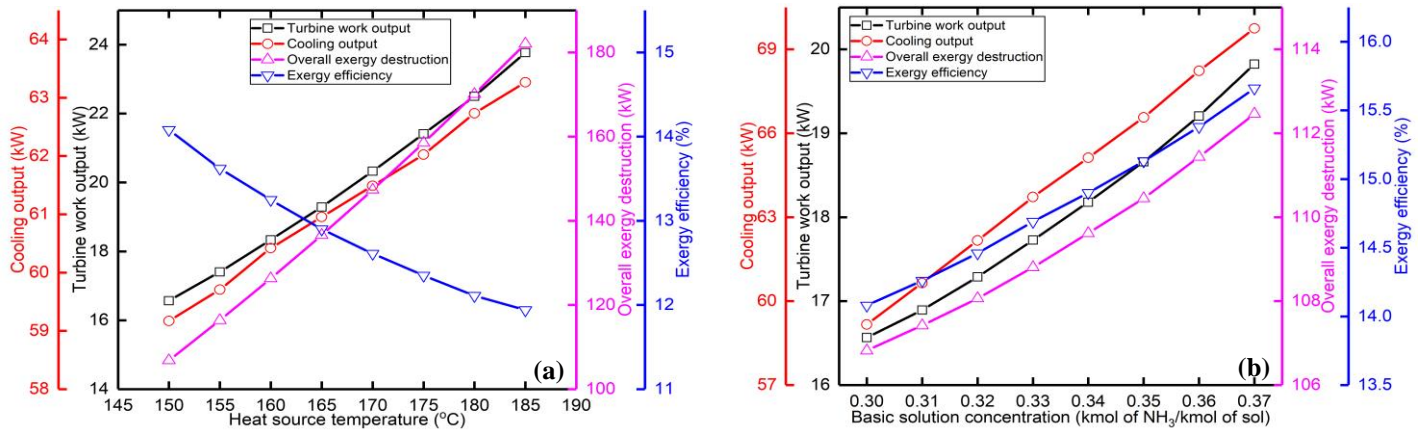


Fig. 4: Effect of (a) variable heat source temperature and (b) variable basic solution concentration on the performance of series combined power and cooling cycle

For series circuit, the increase in heat source temperature as depicted in Fig. 4 (a) leads to increment in vapor flow rate in the cooling sub-cycle, for constant basic solution concentration (0.30 kmol of NH₃ / kmol of sol) and split fraction (0.15). So, there is direct improvement in cooling output with increase in heat source temperature. But, in contradictory to parallel circuit under similar conditions, the absorber-2 pressure in series circuit is not constant and is slightly higher due to the addition of low concentration solution in it. This marginally reduced the cooling output of the series circuit when compared with parallel circuit under similar conditions. It is seen from Fig. 2 that the power sub-cycle is operating on intermediate solution concentration and its mass flow rate, which are increasing with rise in heat source temperature. This helps in significant improvement in turbine work output as compared to parallel circuit for the same heat source temperature. But, the intermediate solution concentration increases the generator pressure, which requires more exergy input and pump work (solution pump-2 in series circuit). The pump work of solution pump-1 also increases with increase in recuperator temperature or pressure. Thus, it leads to higher overall exergy destruction as compared to parallel circuit case operating under similar conditions. Here, the exergy efficiency of the cycle is although much higher than that of the parallel circuit operating under similar conditions, but it decreases with increase in heat source temperature. This is due to more increase in the pump work (especially of solution pump-2) and exergy input as both heat source temperature and intermediate solution concentration change in the power sub-cycle.

For series circuit operating under constant heat source temperature (150 °C) and split fraction (0.15), the increase in basic solution concentration (Fig. 4b) leads to higher increment in the vapor flow rate as compared to the previous series circuit case. Hence, the cooling output for variable basic solution concentration is higher as compared to previous series case of variable heat source temperature. But, there is also increase in the concentration of liquid condensate obtained in separator-1. This increase in low solution concentration leads to increase in absorber-2 pressure, which limits the expansion of vapors in throttle valve-3 of cooling sub-cycle. Due to this, the increase in cooling output is marginally lower than that of the parallel circuit due to more back pressure of absorber-2. Further, there is higher increase in both intermediate solution concentration (due to increase in low solution concentration) and its mass flow rate (due to increase in vapor flow rate of cooling sub-cycle) as compared to previous series case. This improves the mass flow rate of vapors at the entrance the turbine at fixed temperature. Thus, the work output of the turbine increases with rise in basic solution concentration. However, the increase in turbine work is lower than the previous case, as the vapors are entering the turbine at fixed temperature. Also, there absorber-1 pressure (in series circuit) is also increases with increase in basic solution concentration, which limits the expansion in the turbine. There is also increase in generator pressure and recuperator pressure with increase in basic solution concentration. But, this increase in generator pressure is lower than that of series circuit with variable heat source temperature, constant solution concentration and split fraction. So, there is increase in pump work, exergy input (to maintain constant generator temperature) and hence the overall exergy destruction of the cycle, with increases in basic solution concentration. Since the increase in pump work and exergy input is smaller than the previous series case, the exergy efficiency of the cycle here increases with rise in the basic solution concentration.

For series circuit, as the split fraction is increased for constant heat source temperature (150 °C) and basic solution concentration (0.30 kmol of NH_3 / kmol of sol), there is increase in intermediate solution concentration and decrease in mass flow rate obtained from the absorber-2. This is due to lesser portion of low concentration solution supplied to absorber-2. The increase in absorber-2 concentration increases the back pressure on the cooling sub-cycle and the vapor flow rate entering the cooling sub-cycle are constant due to no change in basic solution concentration and heat source temperature. This is shown by marginal decrease in the cooling output as shown in Fig. 5. Next, although there is increase in intermediate solution concentration for constant generator temperature, but the decrease in mass flow rate of the intermediate solution concentration overcomes the above effect. This results in decrease in vapor flow rate entering the turbine and hence the turbine work output decreases. Also, the decrease in mass flow rate of the intermediate solution concentration reduces the exergy input to the power cycle. But the increase in intermediate solution concentration leads to slight increase in the generator pressure, which demands more pump work. This decreasing trend of exergy input and slight rise in pump work is reflected by the decrease in overall exergy destruction of the cycle. As the cooling or work output is also constant against the decrease the exergy input. So, the exergy efficiency of the cycle improves with increase in split fraction.

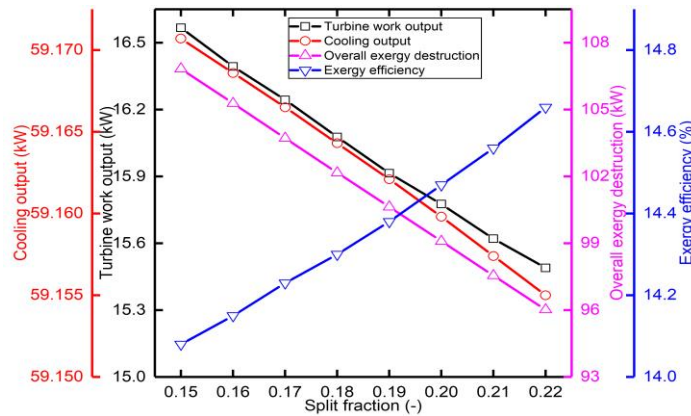


Fig. 5: Effect of variable split fraction on the performance of series combined power and cooling cycle

It becomes apparent that the series circuit generates appreciable turbine work output on the expense of marginal decrease in cooling output and considerable increase in overall exergy destruction. The work output (9.11 kW in parallel circuit and 23.77 kW in series circuit), cooling output (63.29 kW in parallel circuit and 63.27 kW in series circuit), overall exergy destruction (140.30 kW in parallel circuit and 182.05 kW in series circuit) and exergy efficiency (7.16% in parallel circuit and 11.94% in series circuit) is generated for unit mass flow rate, 185 °C heat source temperature, 0.15 split fraction (only in series circuit) and 0.30 kmol of NH_3 / kmol of sol basic solution concentration.

4. Conclusions

This paper discusses two different methodologies to club the ammonia-water based power and cooling sub-cycles where cooling is produced after the waste heat recovery from power sub-cycle through internal recuperation. In parallel configuration, it is seen that the rise in cooling output is higher at lower overall exergy destruction, when the basic solution concentration is variable instead of constant heat source temperature. But, the rise in turbine work output is higher when heat source temperature is increased instead of basic solution concentration, but that also increases the overall exergy destruction in the cycle. Moreover, the overall exergy destruction for varying basic solution concentration first decreases due to the additional effect of exergy losses considered and then increases afterwards due to higher increase in exergy input and pump work. The exergy efficiency always improves with change in heat source temperature or basic solution concentration. It is also seen that the turbine work output suffers significantly due to low solution concentration in the power sub-cycle of parallel circuit configuration. So, there is a need to improve the concentration of the solution which is fed to the power sub-cycle which is achieved in series circuit configuration. In series circuit, the cooling output suffers marginally as compared to the both corresponding cases of parallel circuit due to the back pressure generated in cooling sub-cycle. However, the turbine work output production is significantly improved in series circuit when compared with corresponding cases of parallel circuit. The overall exergy destruction in series circuit is higher as compared with the corresponding cases of parallel circuit. But, the higher output generated in series circuit over comes the increase in demand

of exergy input and pump work. This results in higher exergy efficiency in series circuit as compared with the corresponding parallel circuit. Again, the rise in turbine work output is higher in series circuit when the heat source temperature is varied instead of varying basic solution concentration and split fraction. But, that leads to more exergy destruction in the cycle, thereby resulting in decrease in exergy efficiency of the series circuit. The variation of split fraction shows that the series cycle should be run at lower split fraction so as to gain higher cooling and turbine work output for a particular heat source temperature and basic solution concentration.

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