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# Thermodynamic Modelling of a Vapor Absorption Cogeneration Cycle

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## Abstract

*Attempting towards sustainable development through the principles of cogeneration, proposal towards vapor absorption cogeneration cycle is presented with improved performance efficiency. MATLAB based simulations were done for utilization of condenser as heat rejecter and addition of reheater and other components to conventional absorption refrigeration cycle. The proposed combined heating and cooling cycle demonstrated optimum performance at ambient temperature of 20°C, heat input temperature of 170°C with 0.96 as weak solution concentration. The energy analysis presented total output of 1286.49kW, including process heat of 732.05 kW with cooling effect of 554.44 kW, with energy utilization factor of 1.193 at best conditions. The proposed cycle calls for further research and development aiming in favor of improvement in efficiency and better performance.*

**Keywords:** Modelling, simulation, cogeneration, vapor absorption, heating, cooling.

## Introduction

The level of awareness and cognizance for energy conservation and management among the people has increased rapidly in recent years. Urge for sustainable development, energy safeguarding and diminution of global warming has also encouraged the global level. With modernization and increased standard of living, people demand for comfortable life, but at economical price. This calls for upgradation of conventional systems and proposal of new technologies as well. Agarwal et al. suggests application of cogeneration principle, but the vapor compression refrigeration cycle requires significant amount of electricity and power[1]. Also, the use of R134a as working fluid poses threat to environment with very high global warming potential[2].

Focusing upon balanced progression of society and environment, cogeneration presents itself as a potential solution. Increased overall efficiency with minimal cost involvement has always been considered as prime objective of any technological development. Shankar and Srinivas presents an approach towards combined power and cooling based cogeneration using vapor absorption refrigeration systems[3]. Implementation of absorption system based heat pumps in kraft pulping process by Bakhtiari et al. presents strong advantages of absorption systems for sustainable development[4].

There has been varied use of fluids for vapor absorption refrigeration systems, including $NH_3$-$H_2O$, LiBr-$H_2O$, $NH_3$-NaSCN, $NH_3$-$LiNO_3$ etc. Comparing performance of absorption refrigeration systems utilizing ammonia-lithium nitrate, ammonia-water and ammonia-sodium thiocyanate as working fluids, although the variations in results are not notable, ammonia-water cycle has the least coefficient of performance. But, easy and cost-effective commercial availability of $NH_3$-$H_2O$ overshadows the small decrement in performance results. Also, the limitation regarding use of $H_2O$ as a solvent in working fluid for operation at temperatures below 0 °C promotes use of aqua-ammonia over it. As by Billiard, ammonia has strengthened its application as refrigerant in refrigeration systems[5].

In recent times, concept of heat recovery and energy utilization from conventional energy sources has greatly developed. This presents improved overall efficiency for both primary and secondary energy cycles. Srinivas et al. analysed model of a combined cycle with Kalina bottoming cycle and inferred increase in combined cycle efficiency compared to conventional cycle[6]. Analysis of absorption refrigeration system by Kalinoswki et al. powered with waste heat confirms the cost savings and potential development of the heat recovery cycles[7]. Thus, analysis of an altered aqua-ammonia based absorption refrigeration system utilizing heat recovery was done by the author with implementation of combined cooling and heating cogeneration system.

## Material and Methods

In the present work, incorporation of reheater is done to reheat the weak solution, utilizing heat recovery as primary source. An attempt has also been made to provide process heat by use of condenser as heater. The weak solution rejects heat to air and gets condensed to liquid state. Liquid weak solution, expanded in expansion valve, provides cooling effect at evaporator. Use of thermic fluid cycle has been employed to integrate both heat source and cogeneration cycle. Thermodynamic properties of aqua-ammonia mixture were obtained from the work by Xu and Goswami[8].

The schematic flow diagram of the cogeneration cycle is presented in figure-1. Compared to conventional vapor absorption refrigeration cycles, an additional heat exchanger has been employed to extract heat from return fluid. With addition of reflex condenser, efficiency of the cycle increases as it allows almost pure ammonia vapor to flow. With reduced percentage of water, possibilities of blockage in the evaporator at temperatures below 0°C are reduced. Assumptions considered for the analysis are enlisted below: i. The isentropic efficiency of pump and effectiveness of the heat exchanger are considered as 75 %. ii. The concentration difference between reflux condenser outlet and inlet is considered as 0.08. iii. Degree of reheat for reheater is 10°C. iv. Refrigerant temperature entering evaporator is -10°C. v. Absorber exit temperature is 5°C greater than atmospheric temperature. Vi. 20°C rise in air temperature from atmospheric condition is considered for heater, while air temperature at exit of evaporator is -10 °C.

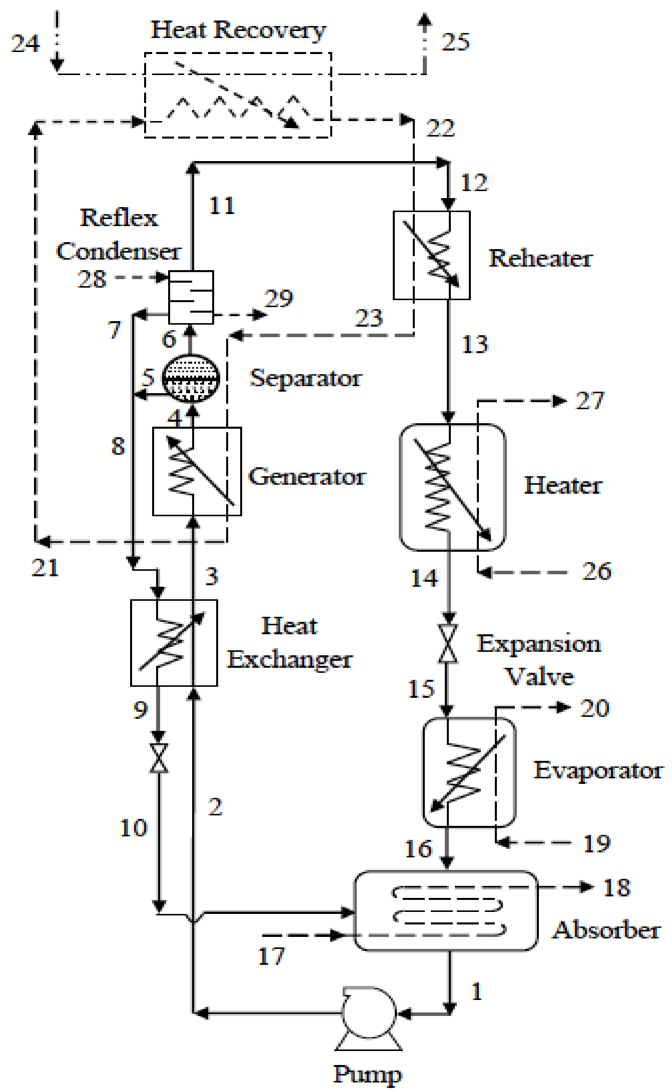


**Figure-1**
**Schematic flow diagram of proposed cogeneration cycle**

For performance analysis of the vapor absorption cogeneration system, equations (1) to (9) were used to determine the mass flow rate, concentration or enthalpy of mixture at specified point. Heat content of the mixture at pressurized state, after pump, is given by equation (1). Equation (2) gives the mass flow rate of reject fluid after separator, while (3) presents the mass of mixture entering reflex condenser. Weak solution implies mixture with very high concentration of ammonia. For varying concentration of weak solution from 0.96 to 0.99, mass flow after the reflex condenser is given by equation (4). Equation (5) gives the reject mass from reflex condenser, which mixes with separator reject. Equation (6) yields total mass of reject fluid and (7) gives the concentration. Equation (8) gives net heat content of the reject mixture.

Enthalpy of mixture after pump,

$$h_2 = h_1 - \frac{h_1 - h_2}{\eta_{pump}} \tag{1}$$

Mass of reject fluid from separator,

$$m_5 = \left(\frac{x_6 - x_4}{x_6 - x_5}\right) m_4 \tag{2}$$

Mass of mixture entering reflex condenser,

$$m_6 = \left(\frac{x_5 - x_4}{x_5 - x_6}\right) m_4 \tag{3}$$

Mass of weak solution after reflex condenser,

$$m_{11} = \left(\frac{x_7 - x_6}{x_7 - x_{11}}\right) m_6 \tag{4}$$

Reject mass from reflex condenser,

$$m_7 = \left(\frac{x_{11} - x_6}{x_{11} - x_7}\right) m_6 \tag{5}$$

Total mass of reject mixture,

$$m_8 = m_5 + m_7 \tag{6}$$

Concentration of reject mixture,

$$x_8 = \frac{m_5 x_5 + m_7 x_7}{m_8} \tag{7}$$

Enthalpy of reject mixture,

$$h_8 = \frac{m_5 h_5 + m_7 h_7}{m_8} \tag{8}$$

The heat gained by the generator is given by equation (9) and heat supplied by reheater is given by equation (10). Equation (11) provides the heat rejected by heater and (12) gives the heat absorbed by evaporator. Coefficient of performance for heater and evaporator are given by (13) and (14) respectively. Energy utilization factor of the cycle can be determined by equation (15).

Heat input to generator,

$$Q_{Gen} = (m_5 h_5 + m_6 h_6) - (m_3 h_3) \tag{9}$$

Heat supplied by reheater,

$$Q_{Rh} = m_{12}(h_{13} - h_{12}) \tag{10}$$

Heat rejected by condenser cum heater,

$$Q_H = m_{13}(h_{13} - h_{14}) \quad (11)$$

Heat absorbed by evaporator,

$$Q_E = m_{15}(h_{16} - h_{15}) \quad (12)$$

Coefficient of performance of heater,

$$COP_H = \frac{Q_H}{Q_{Gen}} \quad (13)$$

Coefficient of performance of evaporator,

$$COP_E = \frac{Q_E}{Q_{Gen}} \quad (14)$$

Energy utilization of cycle,

$$EUF = \frac{Q_H + Q_E}{Q_{Gen}} \quad (15)$$

## Results and Discussion

With alterations in the vapor absorption refrigeration cycle, improved results were obtained. Figure-2 presents variation of cooling output with thermic fluid temperature available from the heat recovery source. For increasing thermic fluid temperature, increase in cooling output was observed. Maximum output of 554.44 kW was attained for weak solution concentration of 0.96 at an ambient temperature of 20°C and thermic fluid temperature of 170°C. Although the output for varying weak solution concentration reduces with increase in concentration, the plot presents marginal difference in cooling output at increasing thermic fluid temperature. It should be noticed that ambient temperature influences the obtained plot a great extent. With increase in ambient temperature from 20°C to 35°C, cooling output for each concentration reduces nearly by 25 %. Also, higher temperature ranges are required to attain maximum cooling output.

The variation of heating output with varying atmospheric temperature, thermic fluid temperature and weak solution concentration is presented in figure-3. Following the same pattern and distribution as in figure-2, the process heat output increases with decrease in weak solution concentration. Also, the output reduces with increasing atmospheric temperature. For heat input temperature of 170°C, ambient condition of 20°C and weak solution concentration of 0.96, highest value of 732.05 kW was obtained. In figure-4, distribution of energy utilization factor has been exhibited.

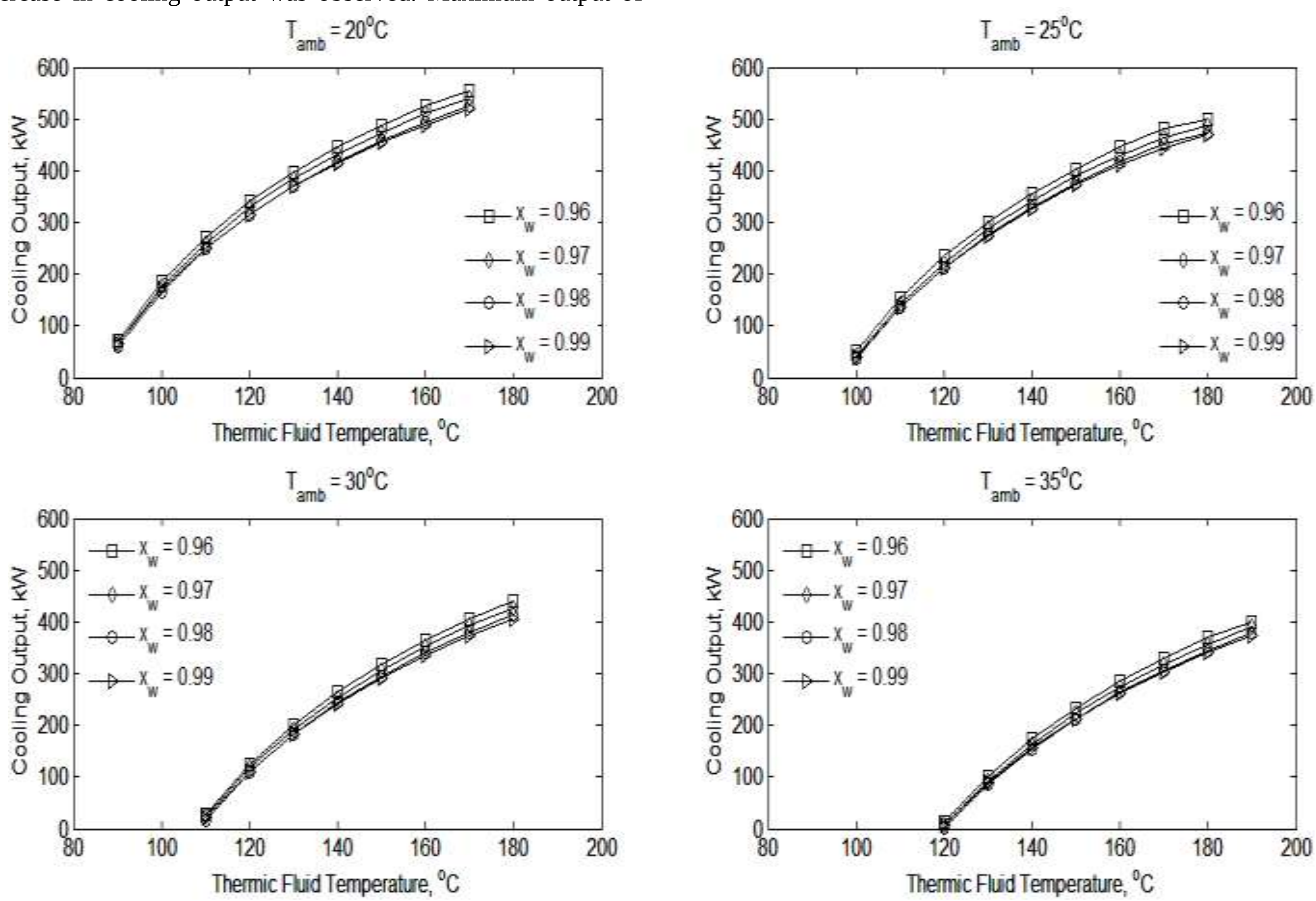


**Figure-2**
**Cooling output vs. Thermic fluid temperature ($T_{22}$)**

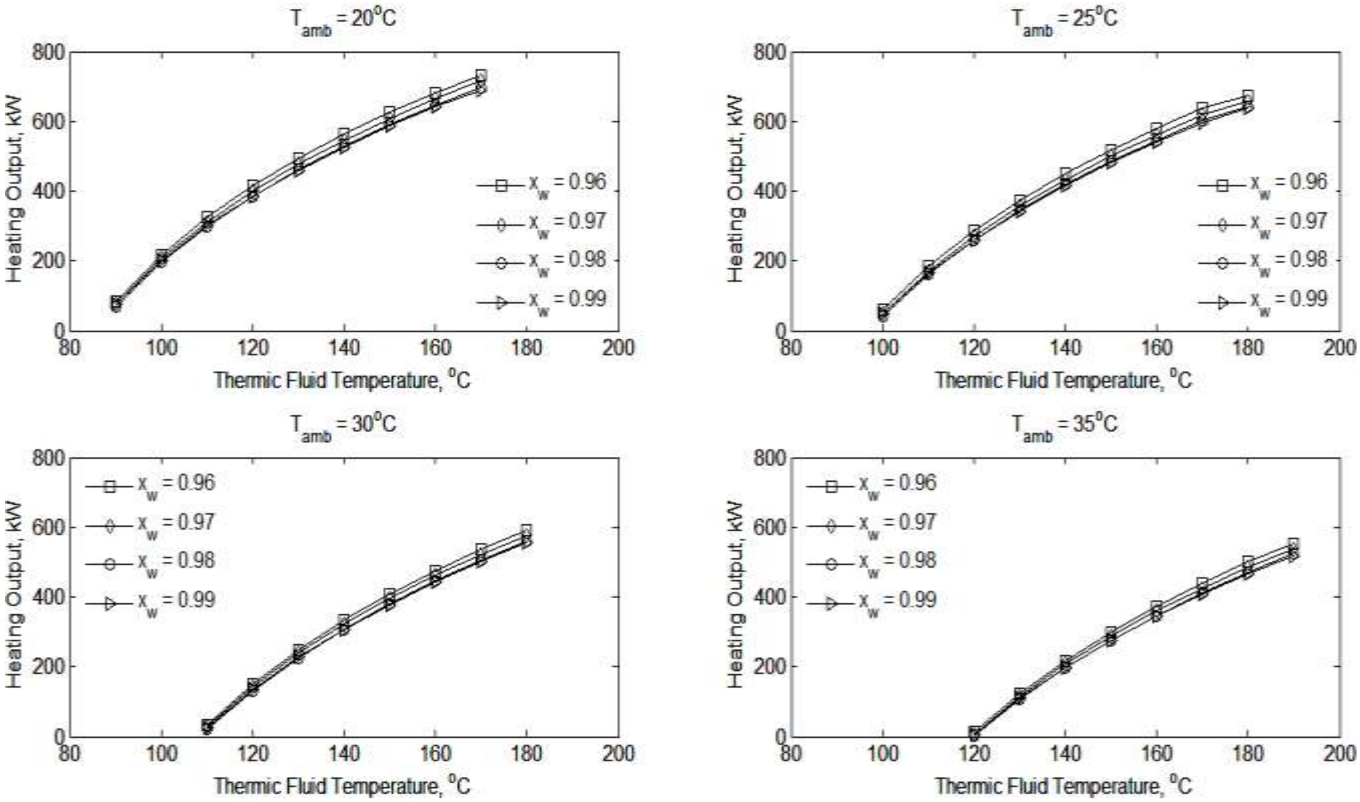


**Figure-3**
**Process heat output vs. Thermic fluid temperature ($T_{22}$)**

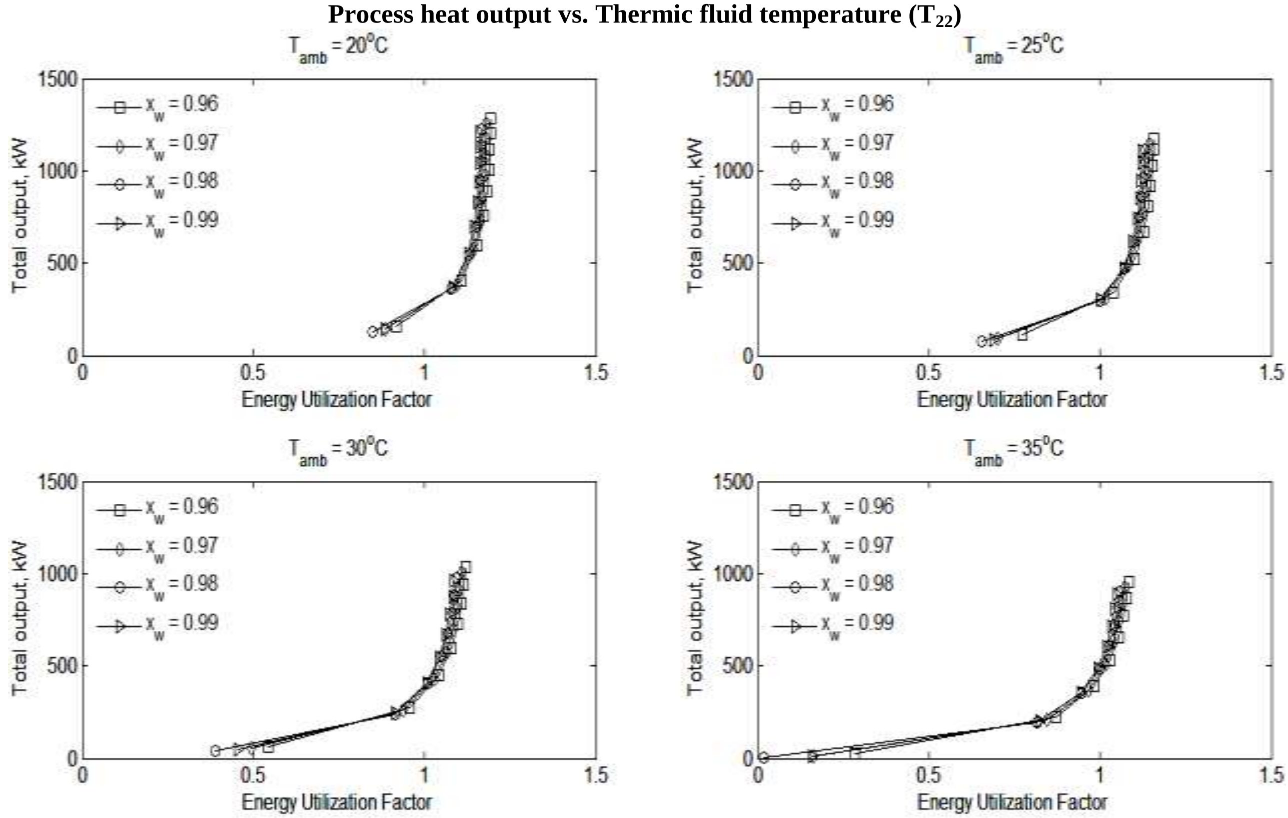


**Figure-4**
**Total output vs. Energy utilization factor**

Energy utilization factor gives the overall efficiency of the cycle, considering both cooling and heating outputs. As efficiency increases with increase in output, higher efficiencies were attained at higher values of heat input temperature. From figure-4, it can be inferred that ambient temperature of 20°C with thermic fluid temperature of 170°C and weak solution concentration of 0.96 proves to be the most optimum condition for functioning of proposed cogeneration cycle. Maximum output of 1284.49 kW with energy utilization factor of 1.193 was attained. Key performance parameters of the cycle at the optimum condition are presented in table-1.

**Table-1**
**Key performance parameters of the cycle at the optimum condition**

| Point | *P* (bar) | *T* (°C) | *x* | *m* (kg/s) | *h* (kJ/kg) |
|---|---|---|---|---|---|
| 1 | 2.9 | 25 | 0.496 | 1.00 | -133.91 |
| 2 | 9.7 | 25.11 | 0.496 | 1.00 | -132.81 |
| 3 | 9.7 | 73.45 | 0.496 | 1.00 | 90.50 |
| 4 | 9.7 | 150 | 0.496 | 1.00 | 475.48 |
| 5 | 9.7 | 150 | 0.100 | 0.49 | 578.08 |
| 6 | 9.7 | 150 | 0.880 | 0.51 | 1740.95 |
| 7 | 9.7 | 145 | 0.117 | 0.05 | 546.28 |
| 8 | 9.7 | 149.56 | 0.102 | 0.54 | 575.24 |
| 9 | 9.7 | 99.16 | 0.102 | 0.54 | 353.46 |
| 10 | 2.9 | 99.26 | 0.102 | 0.54 | 353.46 |
| 11 | 9.7 | 145 | 0.960 | 0.46 | 1640.58 |
| 12 | 9.7 | 145 | 0.960 | 0.46 | 1640.58 |
| 13 | 9.7 | 160 | 0.960 | 0.46 | 1677.69 |
| 14 | 9.7 | 25 | 0.960 | 0.46 | 86.16 |
| 15 | 2.9 | -10 | 0.960 | 0.46 | 86.16 |
| 16 | 2.9 | -10 | 0.960 | 0.46 | 1291.54 |

Comparing to the similar work on vapor absorption refrigeration system by Shankar and Srinivas, much higher cooling output is obtained in the present work[3]. But, the power generation overshadows the presented work as it involves pressure reduction. Vapor absorption refrigeration based cogeneration system presents itself highly efficient on the contrary to cogeneration systems based on vapor compression refrigeration[1]. Although there have been many modifications and optimization of vapor absorption refrigeration systems, the obtained results validate efficient performance of proposed cycle. Also, the proposed vapor absorption cogeneration cycle calls for further research and development to augment the technology.

## Conclusion

For the present work, optimum functioning delivered process heat of 732.05 kW with cooling effect of 554.44 kW at atmospheric temperature of 20°C, heat input temperature of 170 °C and weak solution concentration of 0.96. Simulation analysis of the proposed cycle also exhibited an energy utilization factor of 1.193 at best condition. The use of reheater for additional heat input and condenser as heat rejecter with incorporation of heat exchanger for pre-heating of working fluid at generator inlet, presents itself viable for application, and advance research and development involving exergy analysis as well.

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**Nomenclature:**

| | |
|---|---|
| *h* | Specific enthalpy, kJ/kg |
| *m* | mass flow rate, kg/s |
| *T* | Temperature, °C |
| *P* | Pressure, bar |
| *x* | Concentration |
| $\eta_{pump}$ | Pump efficiency |
| *Q* | Heat, kW |
| *COP* | Coefficient of performance |
| *EUF* | Energy utilization factor |