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THERMODYNAMICS ANALYSIS AND OPTIMIZATION FOR A COMBINED POWER AND REFRIGERATION CYCLE

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Abstract

A combined thermal power and cooling cycle using the combination of a Rankine Cycle and the Goswami Cycle has been analyzed in this study to assess its performance. It can provide power output as well as refrigeration with power generation as a primary goal. The Goswami Cycle uses very high concentration ammonia vapor in the turbine which can be expanded to a very low temperature in the turbine without condensation. This cycle uses an absorption condensation process instead of the conventional condensation process. In this study combined thermal power and cooling cycle (Goswami & Rankine Cycle combined) is first optimized for maximum thermal efficiency and then it is compared with conventional system. The combined cycle is also analyzed for different fraction of steam extracted from a pass out turbine of the topping cycle (Rankine Cycle) as heating source to the bottoming cycle (Goswami Cycle). The proposed heating sources are the waste heat at the exit of back pressure turbine and extracted steam from pass-out turbine. The main parameters that can be varied to influence the cycle are the heat source temperature, boiler pressure, basic solution ammonia mass fraction, ratio of working and heating fluid flow rates, and absorber pressure and temperature. However, the study focuses on the impact of change in the ratio of working and heating fluid flow rates. The combined power and cooling cycle is optimized for the maximum thermal efficiency.

***Keywords**:* Passout turbine; Goswami cycle; rectifier; superheater; combined cycle.

1. INTRODUCTION

Recently, alternative power cycles employing multicomponent working fluids have been studied intensively. The motivation for using mixtures is that heat transfer occurs at variable temperatures thus providing a better thermal match between a sensible heat source and the working fluid. A new combined power/refrigeration cycle uses ammonia/water mixture as a working fluid to produce both power and refrigeration in the same cycle. The cycle may be designed for various combinations of power and refrigeration. In an earlier paper by the authors, the cycle was optimized for efficiency, with power as the main intended output. This study puts an emphasis on the refrigeration part of the total output especially at low refrigeration temperatures. The objective was to find out what kind of outputs could be obtained at very low temperatures for a possible application in the Mars mission. The paper analyzes the performance of the cycle at low refrigeration temperatures [1]. At each refrigeration temperature, the cycle is optimized for maximum second law efficiency. The objective of this study was to analyze the output of the cycle while achieving very low refrigeration temperatures for a possible application in the Mars mission. Ammonia-water mixtures have been used in absorption refrigeration cycles for several decades. The properties of ammonia-water mixtures have been extended to a wider range in recent years in order to study their use in power cycles. The paper proposed a new combined power/ refrigeration cycle using ammonia-water mixtures as working fluids [2]. The cycle takes advantage of the varying boiling temperatures of the ammonia/water mixtures to get a better thermal match with a sensible heat source. It also takes advantage of the low boiling temperature of ammonia vapor to provide refrigeration even though power is the primary goal. A substantial improvement in the performance of power cycles can be achieved by reducing the mismatch in temperature between the working fluid and the heat source fluid during the heat addition process. One approach to reduce this mismatch and irreversibility is by using a multi-component working fluid [3]. A parametric analysis is conducted to evaluate the effects of thermodynamic parameters on the performance of the combined cycle [4]. In recent years, there are a great deal of waste heats being released into environment, such as exhaust gas from turbines and engines, and waste heat from industrial plant, which lead to serious environmental pollution. In addition, there are also abundant geothermal resources and solar energy available in the world. The ammonia–water mixture is a typical binary mixture, which not only has excellent thermo-physical properties, but also is an environmentally-friendly material. A parametric study of the cycle was conducted by Goswami and Xu [5]. The results revealed that the cycle has good potential for production of power and refrigeration at the same time and can be optimized for the best performance. The method presented which is used to calculate the properties of ammonia-water mixtures in this simulation [6]. This method uses Gibbs free energy equations for pure ammonia and water properties, and empirical bubble and dew point temperature equations for vapor-liquid equilibrium.

Nomenclature

COP		coefficient of performance
X		Dry-nessfraction
h		enthalpy (kJ/kg)
m		mass flow rate (kg/s)
P		pressure (kPa)
T		temperature (0C)
S		entropy (kJ/kgK
w		the amount of steam extracted per second to run goswami cycle
w_s		flow rate of steam (kg/s) entering the turbine
Q_{in}		total heat input
W_G		Work out from Goswami
Q_{cool}		Refrigeration output from Goswami
$W_{equivalent}$		Equivalent Work
η_T		Efficiency of Turbine
η_{th}		Combined Thermal Efficiency
$W_{equivalent}$	=	$W_R+W_G+Q_{cool}/COP$
Q_{in}	=	$w_s (h_1–h_7)$
Q_H	=	$w (h_2–h_5)$
$(w_s-w)h_4+wh_5$	=	w_sh_6
W_R	=	$w_s (h_1–h_2) + (w_s–w)(h_2–h_3)$
W_R	=	Work output from

2. System Description

A schematic of the combined power and cooling cycle (Goswami cycle) is shown in Fig.1 The relatively strong basic solution of ammonia-water leaves the absorber as saturated liquid at the cycle low pressure. It is pumped to the system high pressure and is preheated before entering the boiler by recovering heat from the weak solution returning to the absorber. As the boiler operates between the bubble and dew point temperatures of the mixture at the system high pressure, partial boiling produces a high concentration saturated vapor and relatively low concentration saturated liquid. The liquid weak solution gives up heat in the recovery unit and throttles into the absorber. The rectifier condenses out water to further purify the vapor, by rejecting heat to a secondary strong solution stream, before entering the boiler. The vapor is superheated and expanded through the turbine to produce work. Due to the low boiling point of ammonia the vapor expands to low temperatures yielding the potential for refrigeration. The vapor is finally absorbed back into the liquid, giving off heat that is rejected as the cycle heat output. The main parameters that can be varied to influence the cycle are the heat source temperature, system high pressure, basic solution ammonia mass fraction, ratio of working and heating fluid flow rates, and absorber pressure and temperature. Rectifier and superheater temperatures can also be modified, and the conditions of heat transfer from the source to the ammonia-water mixture as well. In this section to show how the analysis is done, a combined Cycle is presented in Fig.1 is the combination of Rankine Cycle and Goswami Cycle. Heat is supplied only in the boiler of Rankine Cycle by burning fossil fuel which gives power, and the exhaust steam from the back pressure turbine of Rankine Cycle is the heating source for the low temperature cycle (Goswami cycle) which gives out power as well as refrigeration output. In the Goswami Cycle the ammonia-water strong solution is pumped from the absorber to a high pressure at state 2. At this point, the solution is split into two streams. One stream goes through a heat exchanger (state 2') to recover heat from the weak solution exiting from the boiler. The second stream goes to the rectifier (state 2") to cool the ammonia vapor exiting the boiler to condense the water vapor in it. The two streams are combined again (state 3) before entering the boiler. In the boiler, the mixture is heated to boil off ammonia vapor (state 4). In order to get high concentration ammonia vapor (state 6), the vapor goes through the rectifier to condense some water in it. The condensate is rich in water and returns to the boiler (state 5). The enriched ammonia vapor is then superheated in a superheater (state 7). After expansion in the turbine, ammonia vapor drops to a very low temperature (state 8). The low temperature ammonia vapor provides cooling by passing through the refrigeration heat exchanger (state 9). Ammonia vapor is then absorbed into the weak solution in the absorber to regenerate the ammonia-water strong solution (state1). Weak solution leaving the boiler (state 10) goes through a heat recovery heat exchanger (state 11) to transfer heat to the strong solution. After passing through a pressure-reducing valve (state 12), the weak solution returns to the absorber.

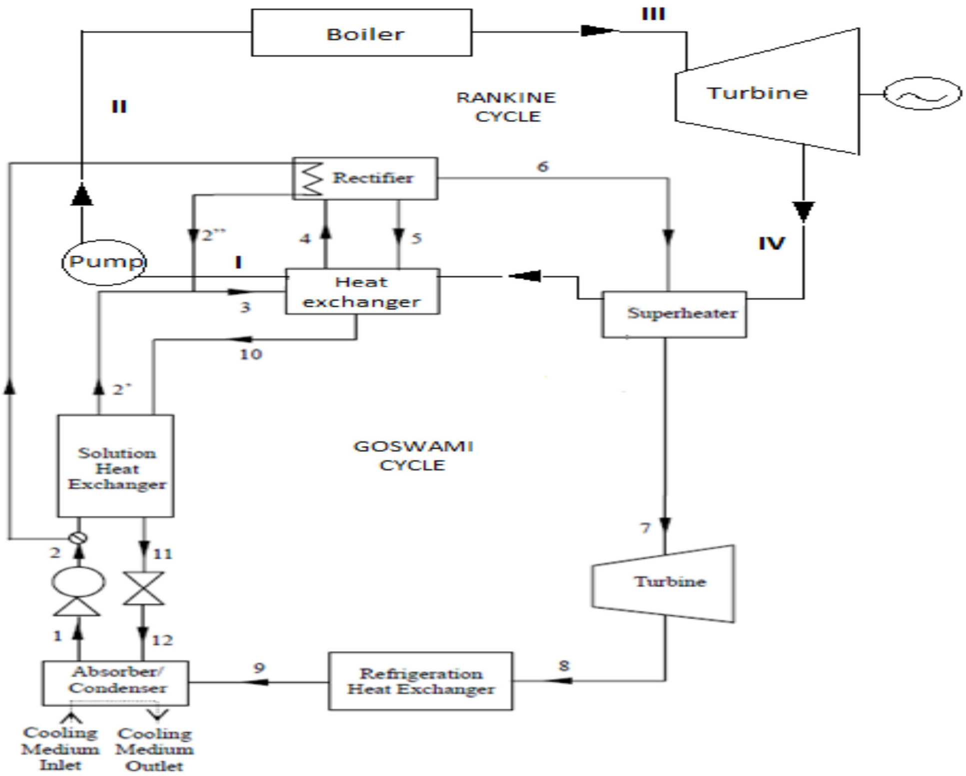

Figure: 1 Ammonia-Based Combined Power/Refrigeration Cycle.

The following equations are used for calculating the performance parameter for the combined cycle:

For Rankine Cycle-

Heat input:

$$Q_{in} = m_s(h_{III} - h_{II})$$

Steam turbine work output:

$$W_{ST} = m_s(h_{III} - h_{IV})$$

Process heat to Goswami Cycle:

$$Q_{out} = m_s(h_{IV} - h_I)$$

Thermal efficiency of Rankine Cycle:

$$\eta_{Rankine} = \frac{W_{ST}}{Q_{in}}$$

For Goswami Cycle-

Boiler heat transfer:

$$q_{boiler} = m_4h_4 + m_{10}h_{10} - m_3h_3 - m_5h_5$$

Condenser heat transfer:

$$q_{cond} = m_5h_5 + m_6h_6 + m_{3'}h_{3'} - m_4h_4 - m_{3'}h_2$$

Superheat input:

$$q_{superheater} = m_6(h_7 - h_6)$$

Absorber heat rejection:

$$q_{absorber} = m_1h_1 - m_{12}h_{12} - m_9h_9$$

Cooling capacity:

$$q_{cool} = m_8(h_9 - h_8)$$

Net work output:

$$W_{net} = m_7(h_7 - h_8) - m1(h_2 - h_1)$$

Thermal efficiency:

$$\eta = \frac{W_{net} + q_{cool}}{q_{superheater} + q_{boiler}}$$

3. Calculations and Results

Optimum condition of exhaust steam from Rankine cycle to run Goswami cycle for maximum combined thermal efficiency. Performance of Goswami cycle in combination of Rankine cycle is analyzed at different temperature and pressure condition at the exhaust of Rankine cycle. The exhaust heat from the Rankine cycle is a heat source for Goswami cycle. When the combined system is analyzed with passout turbine in the Rankine cycle, a part of steam is extracted from Rankine cycle turbine to run Goswami cycle, net work output from the system decreases but on the other hand we get refrigeration effect and the overall thermal efficiency increases. There is about 3% improvement in the efficiency of the combined system when whole mass of steam from the pass out turbine is extracted (i.e. back pressure) at 1.5 bar to run combined power/refrigeration cycle. A novel combined power/refrigeration cycle can effectively utilize low temperature steam from the exhaust of conventional power plant. For the same heat input overall efficiency of the combined system is improved in comparison to the conventional power plant because of the utilization of waste heat .In Table 1 shows the performance of the combined cycle (Rankine + Goswami) at different intermediate temperature and pressure condition.

Table 1 performance of the combined cycle (Rankine + Goswami) at different intermediate temperature and pressure condition.

SN	Pmax(Rankine) (bar)	Tmax(Rankine) K	Texhaust(Rankine) K	Tboiler(Goswami) K	ηth(R) %	ηth(G) %	ηII(G) %	ηth(combined) %
1	45	673	354	350	25.44	13.80	62.00	35.70
2	45	673	363	360	24.42	15.20	63.80	35.82
3	45	673	373	370	22.91	16.80	64.80	35.86
4	45	673	384	380	21.95	18.40	65.80	36.31
5	45	673	393	390	20.50	19.80	65.20	36.24
6	45	673	403	400	19.23	21.00	65.40	36.18
7	45	673	413	410	18.20	22.00	64.80	36.12
8	45	673	425	420	16.27	23.00	64.00	35.53
9	45	673	432	430	15.8	23.80	63.60	35.35
10	45	673	443	440	13.71	23.60	63.00	34.07
11	45	673	453	450	12.20	23.00	62.00	32.40
12	45	673	463	460	11.72	22.60	60.00	31.67

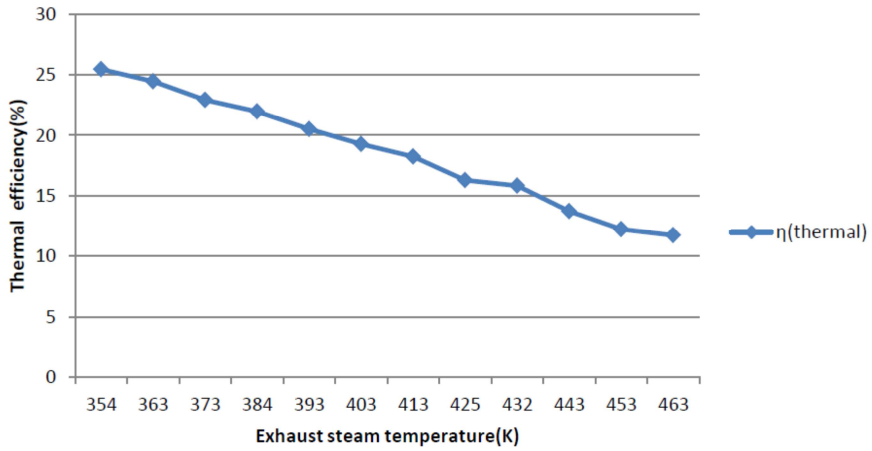

Figure: 2 Variation of thermal efficiency of Rankine Cycle with exhaust steam temperature

Thermal efficiency of Rankine Cycle as shown in fig. 2 decreases as the temperature at the exit of the turbine increases because the steam in the turbine is not fully expand to give the maximum work output.

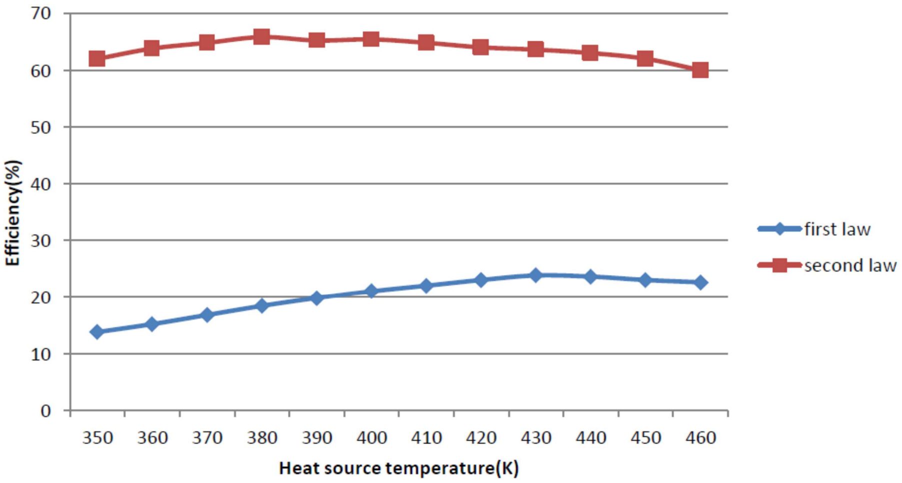

Figure: 3 Efficiencies of Goswami Cycle at various heat source temperatures

But at the same time as the exhaust steam temperature increases first law efficiency of bottoming cycle i.e. Goswami cycle increases as shown in fig.3, gives the maximum first law efficiency of 23.80% at temperature of 430K and maximum second law efficiency of 65.80% at 380K.

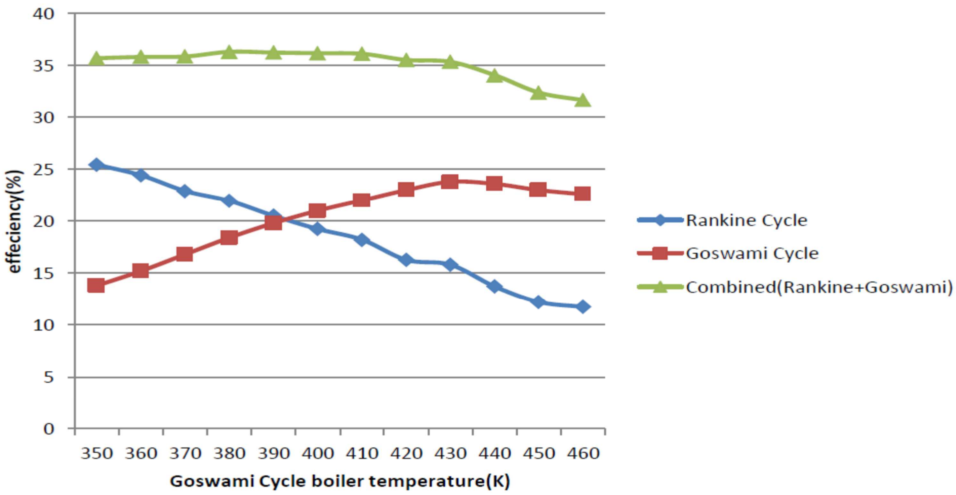

Figure: 4 Efficiency of Rankine, Goswami and Combined Cycle (Rankine + Goswami) at various Goswami Cycle boiler temperatures.

Fig.4 Shows that the first law efficiency of combined cycle (Rankine + Goswami cycle) increases as the temperature of the exhaust steam from Rankine Cycle (heating source for Goswami Cycle) increases. The combined cycle gives the maximum thermal efficiency of 36.31% at 380K. And at 380K the second law efficiency of the bottoming cycle is maximum which shows the best utilization of exhaust steam from Rankine cycle.

4. Conclusion

The thermodynamic analysis of the combined Rankine and Goswami Cycle has been done. The Goswami Cycle can effectively utilize low temperature steam from the exhaust of conventional power plant. For the same heat input overall efficiency of the combined system is improved in comparison to the conventional power plant because of the utilization of waste heat. The combined Rankine and Goswami Cycle is analyzed for optimum pressure and temperature of the extracted steam from the topping cycle (Rankine Cycle) which is heating source for bottoming cycle (Goswami Cycle) for its maximum thermal efficiency at a fixed maximum

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pressure and temperature condition of the system. For system maximum pressure and temperature of 45 bar and 673K respectively, the exhaust seam of temperature 380K gives the maximum thermal efficiency of combined cycle is 36.31%.

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