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Energy Analysis of Supercritical Water and Ammonia (Kalina) Power Cycle

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Abstract: The application of supercritical Rankine cycle is common in order to improve the energetic efficiency of thermal power plants, but due to the low temperature of the gas turbine exhaust outlet, the utilization of supercritical steam cycle as a bottoming cycle in combined cycles is not possible. Therefore, to achieve a higher efficiency, water as working fluid of the cycle, should be replaced with another fluid with a lower critical temperature. For this purpose, water and ammonia mixture (Kalina cycle) has been selected as the bottoming cycle in this manuscript. Unlike the pure water, the mixture of water and ammonia does not evaporate in a constant temperature, which reduces the evaporator's exergy lost in the heat transfer process. The energetic efficiency of a supercritical Kalina cycle equipped with an over atmospheric condenser, under thermodynamic conditions of 515 ^{o}C and 165 Bar for the gas turbine, ammonia mass fraction are 30% and 70% for condenser and boiler which is 12% more than Rankine cycle efficiency in the same conditions. This article is dedicated to modeling and thermodynamic analysis of a Kalina cycle and introduction of thermo-physical properties of the water and ammonia mixture in process of evaporation and condensation. In addition, the performance comparison of the

Kalina cycle and Rankine cycle in terms of different thermodynamic conditions is issued in this paper.

Keywords: Kalina Cycle; Rankine Cycle; Supercritical Pressure; Thermodynamic Modeling; Water and Ammonia Mixture.

1. Introduction

Rankine cycle plays a key role in conventional steam power plants burning coal and heavy oil, nuclear power plants, bottoming cycle of combined cycles and so on[1-8]. Turbine inlet temperature and outlet pressure of the vapor are known as the most important factors affecting the Rankine cycle performance. In other words, in order to increase Rankine cycle efficiency, regarding metallurgical constraints, the temperature and pressure of steam turbine inlet should be increased and the quality and output pressure should be reduced [4-7]. More recently, worldwide concerns about the cost and efficient use of energy has provided persistent opportunities for supercritical cycles. In supercritical Rankine cycles, steam temperature is about 560 ˚C and pressure is 240 Bar, therefore, in many cases, it is impractical to use supercritical Rankine cycle as the bottoming cycle because of low temperature of gas turbine exhaust gases [7-15]. Utilization of duct burner and changing the working fluid are two possible modifications in order to utilize the supercritical bottoming cycle. Although employing duct burner is not recommended because of an efficiency drop, replacing the working fluid by other fluids such as a water-ammonia mixture can be a suitable option.

Kalina cycle can be installed as a bottoming cycle in a combined cycle power plant to gas turbines or diesel engines exhaust waste heat recovery. In addition investment and operation and maintenance cost of Kalina cycle is same as Rankine cycle, however, it has a higher performance. Recently, due to demerits of new power plants based on Kalina cycle, it can be an innovative approach to focus on supercritical Kalina cycle in order to achieve higher efficiency [15-18]. In this composition thermodynamic simulation of supercritical Kalina cycle in different conditions has been addressed. And introducing the mixture of water and ammonia in the process of evaporation and condensation, the performance of thermodynamic cycles in different situations and will be compared with the Rankine cycle.

2. Super Critical Kalina cycle Properties

2.1. *The Thermodynamically Properties of Ammonia – Water Mixture*

Specific features of Kalina cycle's working fluid, water-ammonia mixtures are introduced in this section. First of all, molecular mass of ammonia is same as H2O; hence, the design of cycle components is similar to Rankine cycle. Secondly, in contrast to the pure fluids, water- ammonia mixture does not have constant boiling point in evaporation process, thus, the heat transfer process is more reversible in evaporator because of closer temperature profiles of gas flue and water-ammonia mixture. Therefore, exergetic efficiency of heat recovery boiler of Kalina cycle is more than Rankine cycle. As can be seen in "Figure 1", boiling temperature range of water-ammonia mixture depends on the pressure and concentration of ammonia in the mixture. Obviously, increasing the ammonia concentration will reduce the boiling point of mixture. For instance, in 10 Bar, evaporation begins at 63.99 ˚C (liquid phase) and it finishes at 153.6 ˚C (gas phase). The similar behavior is expected in the condenser of Kalina cycle where condensation temperature of water-ammonia mixture has a specific range regarding the condenser pressure. Thus, depending on the concentration of ammonia in the mixture, condensation temperature range should be between -32 ˚C, condensation temperature of ammonia and 100 ˚C condensation temperature of water in an atmospheric condenser. It is difficult to supply cold source for condensation of water-ammonia mixture with a high concentration of ammonia, therefore, the percentage of ammonia should decrease. For this purpose, before condenser, concentration of ammonia is reduced by adding water into the working fluid, so, the condensation temperature is increased. Finally, the concentration of ammonia should be set again before boiler feed water pump. Separation tank is employed to set the percentage of ammonia in the mixture.

2.2. Cycle Components

Condenser of this cycle is totally different from Rankine cycle, but, other components are same. As mentioned, water mass friction should increase in the condenser of Kalina cycle to set condensation temperature, however, it returns to previous level again at the end of condensation.

It seems the capital cost of Rankine and Kalina power plants are equal in the same capacities, however, Rankine cycle is much more known. On the other hand, turbine output of Kalina cycle has less specific volume, so, its size is smaller rather than Rankine cycle condenser. The cost of Kalina cycle cooling system is estimated approximately two third of Rankine cycle. Cost other components are similar. “Figure. 2” is a schematic plan of the simple Kalina cycle. It can be clearly seen that output fluid from the first condenser (low pressure condenser) is compressed by a pump to reach the average pressure (point 2) and is divided into two distinct categories (points 3 and 4). The first divergence (point 3) after crossing form recovery (point 5) it goes into a flash tank which does the task of separating water from ammonia. The Flash tank has two outputs, one with a high concentration of ammonia in the two-phase state (point 6) and the other one is low concentration of ammonia in the liquid phase (point 15). The first outlet (point 6) for a split second working fluid ammonia concentration (point 3) and the combined mass of the mixture is supplied (point 7). The second output (point 15) after passing through a Pressure control valve (point 17), with the output of the converter fluid recovery (point 14) is mixed. Cycle working fluid at point 7 in the two-phase mode through the second condenser (high pressure condenser), has been Condensed (point 8) and then the main pump working pressure of the cycle to be compressed (Point 9) and directing towards the boiler. In Kalina cycle of the boiler, the ammonia-water mixture to evaporate in the economizer heat-sees the frontier (point 10). Then the fluid enters into the evaporator and in the non-constant temperature converts from liquid to gas (point 11). Then in the highest level of the heater (super heater), the temperature of the cycle working fluid increases to reach the turbine temperature inlet (point 12) and in the end mixture of water and ammonia gets into the turbine and starts the production. The output fluid from turbine (point 13) in the gas phase is transformed into heat recovery. As a result, the output fluid (point 14) because of loss of heat remains in the second-phase mode position. At this point in a mixing tank with the equal pressure, liquid water mixed with ammonia which has low ammonia concentration (point 20) is added to the working fluid cycle (point 14) to reduce the concentration of ammonia mixture (point 17), to cover the condenser needs. The provided mixture in second-phase position gets into the low pressured condenser and condensed (point 1) and finally is ultimately directs towards the middle pump. Condensation in a condenser has been done with the help of a cool fluid within the situation of point 18 entering into the condenser and after heat exchange it goes out of the condenser (point 19). The temperature heat-recovery boiler to produce steam for the turbines, which can be supplied by the hot gas outlet of the gas turbine Or by any other heat source can be created, in point 22 enters into the boiler and after the boiler heating surfaces and heat transfer with the working fluid from the boiler it exits from the point 25. The heat transfer occurs in three stages in the entry of hot gas (point 22) it absorbs by super heater and enters into evaporator (point 23) and then under the new conditions (point 24) enters into the economizer And finally goes out of the boiler (point 25) meanwhile the boiler with absorption of steam's heat and under supercritical conditions produces. Specification of a 198MW Kalina cycle and its Thermodynamic properties are given in “Table 1” and “Table2” according to the numbering at “Figure. 2”.

Figure 1. Evaporating curve of water-ammonia mixture with mass friction 50%-50% in different pressures

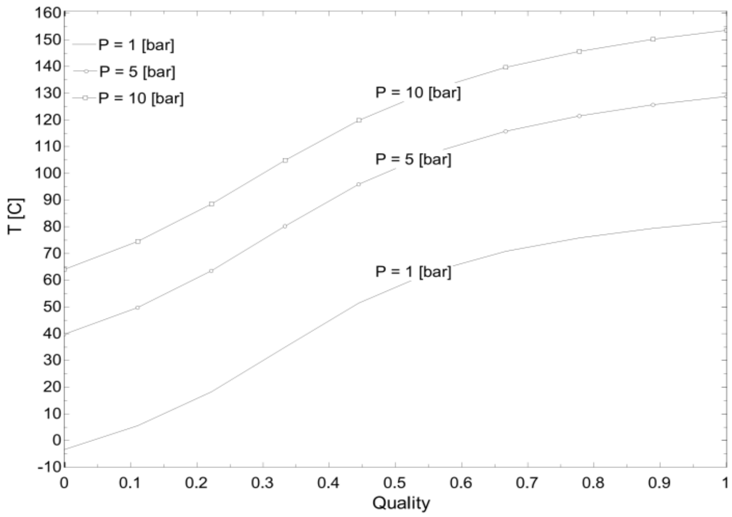


Figure 2. Super Critical Kalina Cycle

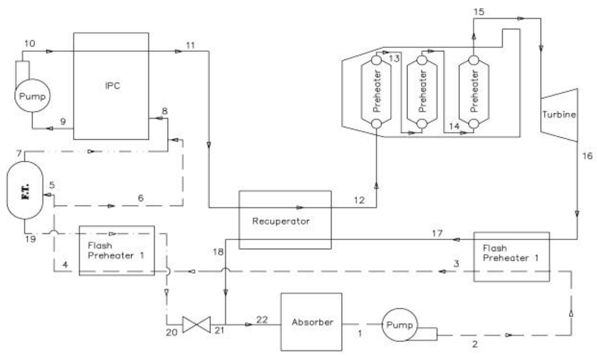


Table1. Thermodynamic properties

Node	Temp.[K]	Pres. [bar]	Enthalpy [kJ/kg]	Entropy [kJ/kg·K]	Fluid Ratio	Mass friction
1	304.6	10	-8.09	0.53	4.814	0.3
2	304.6	10	-8.97	0.53	4.469	0.3
3	304.6	10	-8.97	0.53	0.3449	0.3
4	319.6	10	332.7	1.62	1	0.7
5	330.3	10	108.7	0.89	4.469	0.3
6	302.2	10	324.7	1.64	0.6551	0.916
7	302.2	10	30.25	0.498	4.814	0.195
8	312	10	-94.48	0.21	1	0.7
9	320	165	-44.8	0.304	1	0.7
10	477.1	165	936.6	2.801	1	0.7
11	534.9	165	1906	4.68	1	0.7
12	793.2	165	3120	6.04	1	0.7
13	343.6	1.01	2950	6.34	1	0.7
14	330.3	1.01	2825	6.1	1	0.7
15	321.1	1.01	1817	6.44	4.814	0.3
16	302.4	1.01	1362	5.14	4.814	0.195
17	302.6	1.01	371	1.7	4.814	0.3

Table 2. Kalina Cycle Specification

Parameter	Amount	Unit
ISENTROPIC EFFICIENCY	0.89	%
MECHANICAL EFFICIENCY	0.98	%
PUMP EFFICIENCY	0.88	%
ENERGETIC EFFICIENCY	0.32	%
MASS FLOWRATE IN THE CONDENSER [i]	869	[kg/s]
HIGH CONSENTRATED AMMONIA FLUID[ii]	216	[kg/s]
POUR CONSENTRATED AMMONIA FLUID [iii]	646	[kg/s]
CIRCULATION OF FLUID IN BOILER[iv]	223	[kg/s]
GAINED HEAT IN ECONOMIZER	218836	[kW]
GAINED HEAT IN EVAPORATOR	215463	[kW]
GAINED HEAT IN SUPERHEATER	205631	[kW]
SPECIFIC POWER IN MAIN PUMP	49.66	[kW/kg]
SPECIFIC POWER IN INTERMITENT PUMP	10.26	[kW/kg]
SPECIFIC POWER IN TURBIN	1008	[kW/kg]

3. Comparison of Kalina cycle performance with the Rankine cycle

Knowing the behavior of the mixtures of water and ammonia in Kalina cycle operation, in this part the performance of Kalina cycle and Rankine cycle in supercritical conditions has been compared. For this purpose a simple model cycle Rankine and Kalina cycle with ammonia concentration from 70 to 30 in the same turbine inlet temperature of the fluid studied and the results are shown in “Table 3”. In these two examples can be seen that the Kalina cycle efficiency is 4.4% higher than of the Rankine cycle with temperature of 515 ^{0}C and pressure of 160 Bar. All cycles considered in this study are equipped with an atmospheric condenser, but if there is a source of atmospheric temperature cools down, for increasing productivity, there is the possibility of using vacuum condensers. For example, many of geothermal energy resources are located in areas where access to a cooling source temperature below cold land because of access to the source of the low temperature cooling (air-cooling system) due to sub-zero air is possible, so, In this condition the condensers in the mentioned areas can be used in bellow atmospheric pressure to increases the cycle efficiency.

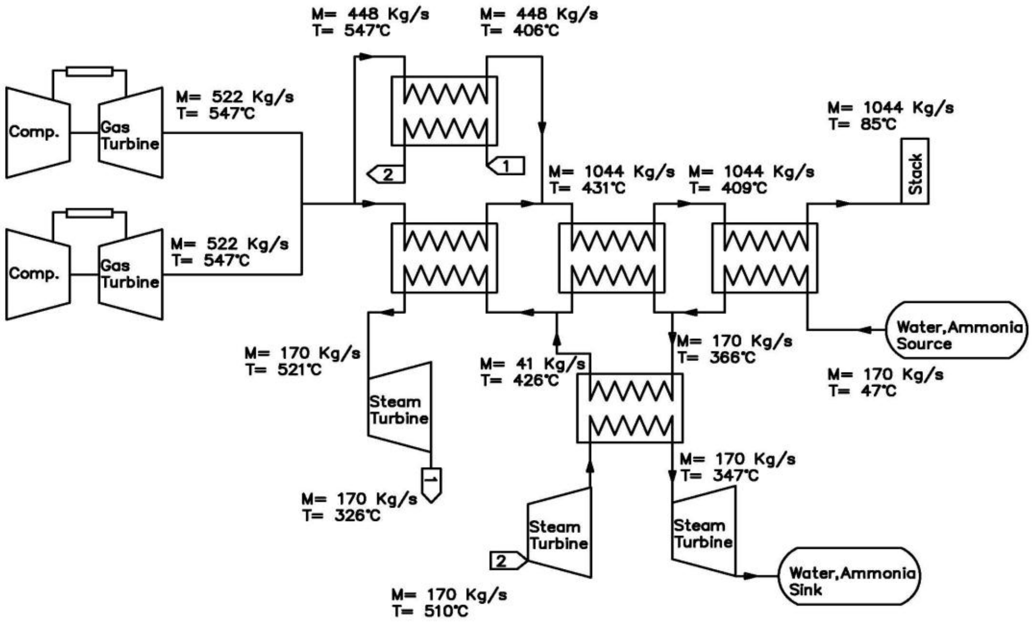
Table 3. Performance Comparison

PARAMITER	UNIT	Kalina cycle	Rankine cycle
Inlet temperature to the turbine	˚C	515	515
Inlet pressure to the turbine	bar	165	225
Energetic efficiency	%	34.8	30.4
Capacity of circulation fluid	kg/s	210.8	219.8
Turbine Capacity	kW	198	198

4. Kalina cycle performance of sensitivity analysis to changes in ammonia mass friction and environmental condition

The analysis cycle efficiency due to the effect of changing in operating parameters and fluid inlet temperature and pressure to the turbine. The mass friction of ammonia and water mixture flow 90% and 10% is selected. Under these conditions it is possible to absorb more heat from turbine flue gas and will increase the power generated capacity. Due to higher temperature (197 C) of water and ammonia mixture in turbine outlet and also the thermodynamic properties of concentrated mixture so lower temperature source for condensation is needed. So in this case, the power consumption for cooling will increase sharply and this will increase the losses exergy of cycle. Now days, to optimize the production capacity and cycle power consumption, most designs in the boiler and condenser respectively 70 and 30 are selected as a mass friction of ammonia and water, especially in the condenser in optimum point. The effect of environmental conditions including high temperature sites have been evaluated in “Figure. 3”. In analysis of site conditions from ISO to a new height of 1,000 m above sea level, temperature 5 ^{0}C and 60% humidity has changed. The site of new production capacity of 198 MW to 187 MW in Kalina cycle has been reduced. Also mixed in with constant flow rate, fluid inlet temperature of the steam turbine is also reduced to 505 degrees, this change reduces the temperature of the steam turbine output and the power required for condenser will be decreased. The major changes in this mode are to reduce the hot gas outlet flow and temperature of the gas turbine.

Figure 3. Kalina Cycle Arrangement for Combined Power Plant Cycle



5. Conclusion

This paper introduces, Kalina cycle modeling and analysis of the supercritical conditions for the utilization of high temperature heat sources such as combined cycle power plants bottom cycle Rankine replacement. Kalina cycle is considered as a practical solution to preserve environment. Water-ammonia mixture in the process of evaporation and condensation in supercritical conditions, such as water or ammonia with pure fluid is different and apposite those, these processes do not occur at a constant temperature. After boiling with variable temperature, exhaust temperature profiles to the profiles closer to evaporation and increase the evaporator exergetic efficiency. On the other hand, Kalina cycle to improve performance in the condenser vapor condensation in two phases with different pressures and water injection into the fluid. Kalina cycle energetic efficiency with an atmospheric condenser and the concentration of ammonia mixed with 70%, and thermodynamic conditions of fluid with 515 C and 166 bar in turbine inlet, is equal to 34.8% while it is equal to 30.4% for a Rankine cycle with the thermodynamic conditions. Changing environmental conditions on cycling performance, reduced production capacity from 198 MW to 187 MW, but on the other hand the power consumption in the condenser will be reduced.

Conflict of Interest

The authors declare no conflict of interest.

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