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DESIGN OF KALINA CYCLE FOR WASTE HEAT RECOVERY FROM 1196 CC MULTI-CYLINDER PETROL ENGINE

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ABSTRACT

The increasingly worldwide problem regarding rapid economy development and a relative shortage of energy, the internal combustion engine exhaust waste heat and environmental pollution has been more emphasized heavily recently. The total amount of energy supplied to engine out of which only 30% to 40% is convert into useful work. While rest of energy is expelled to the environment which causes serious environment damage. Therefore it is required to utilize this waste energy to improve thermal efficiency of engine and reduced greenhouse effect. This work is focus on waste heat recovery of 1196cc multi-cylinder petrol engine. Small car engine waste heat does not always find use due to its minimum quantity of heat availability. The Kalina Cycle is suitable for waste heat recovery from 1196cc petrol engine due to its high thermal efficiency. In the present work Kalina Cycle is design for waste heat recovery from 1196cc multi-cylinder petrol engine.

Keywords: Ammonia-Water Mixture, Exhaust Heat Recovery, Separator, Waste Heat

1. INTRODUCTION

With the increasingly prominent problem regarding rapid economy development and the graduallyserious environmental pollution, the waste heat recovery and waste gas pollution processing have receivedsignificant attention.Waste heat recovery is the system in which waste heat of different application such as internal combustion engines, turbines, industries, small power plants etc. are convert into useful mechanical or electrical energy. There are different direct and indirect technologies by using which this heat can be recover.Out of different technologies, the organic Rankine cycle and Kalina cycle are the good choices for electricity generation, because they are the feasible ways of utilizing low-temperature heat sources.

With automobile industrial revolution the manufacturing and sales of small vehicle increases drastically. Each small vehicle engine loses a large part of the fuel energy to the environment, most importantly with the exhaust gasses which can contain about 25% of the input energy [1].Hence it is required to reduce this wastage in small vehicle. Main problem in heat recovery from such system is its small amount of heat availability.

Dr. Alexander Kalian proposed waste heat recovery cycle which give high thermal efficiency than Organic Rankine Cycle. This cycle is known as Kalina Cycle or Ammonia-Water bottoming cycle. The mixture of Ammonia-water of different concentrations are used as working fluid. Because of non-isothermal phase change behaver of Ammonia-Water mixture, Kalina Cycle can extract low temperature heat effectively. Thus Kalina Cycle is suitable for waste heat recovery from light duty engine.

Nomenclature

T	Heat Rejection Temperature	T_b	Heat Absorption Temperature
m	Mass Flow Rate	m_a	Mass Flow Rate of Air
m_f	Mass Flow Rate of Fuel	m_W	Mass Flow Rate of Water
P_{Total}	Total Pressure of Ammonia-Water Solution	P_W	Pressure of Water
P_A	Pressure of Ammonia	n_a	Number of Moles of Ammonia
n_w	Number of Moles of Water	ρ_L	Liquid Density
ρ_G	Gas Density	ρ_w	Density of Water
	Density of Air	C_W	Specific Heat of water
C_A	Specific Heat of Ammonia	C_{Tota}	Total Specific Heat of Ammonia-Water Solution
η_v	Volumetric Efficiency	η_{carnot}	Carnot Efficiency
h_W	Specific Enthalpies of Water	h_A	Specific Enthalpies of Ammonia
h_T	Total Enthalpy		Mole Fraction
	Mass Fraction	C_d	Drag Coefficient
U_T	Terminal Velocity	V	Stork Volume
g	Acceleration Due to gravity		Heat Flow Rate
SFC	Specific Fuel Consumption	ΔT	Tempreture difference
D	Droplet Diametar		

Research on the Kalina cycle is currently ongoing. In a recent study by Ulrik Larsen et al. [2] studied experimentally, Kalina split-cycle for waste heat recovery on large marine diesel engines. This study investigated a unique type of Kalina process called the split-cycle, applied to the exhaust heat recovery from large marine engines. In the split-cycle, the working fluid concentration can be changed during the evaporation process in order to improve the match between the heat source and working fluid temperatures. Results show that the Split-cycle process can obtain maximum thermal efficiency when using reheat compared to a conventional reference Kalina cycle. Wencheng Fu et al. [3] studied experimentally, actual geothermal power plant in the oilfield was analysed with an aim to improve the efficiency. The performance of organic Rankine cycle (ORC) and Kalina cycle (KC) subsystems where evaluated numerically for different working fluids. Results show that the performance of the ORC subsystem using R236fa was better than other working fluids. The performance of the KC subsystem with the ammonia mass fraction of 0.8 was good. The net power output of the KC subsystem was higher than that of the ORC subsystem and the difference in power output increases with the increase of heat source temperature. Norio Yanagisawa et al. [4] carried out a development project of a 50 kW class Kalina cycle geothermal power generation system. In several areas in Japan, the temperature of hot spring shows about 90ºC to 100 ºC, at such low temperature conventional Rankine cycle shows low efficiency. Therefore Kalina cycle was used instead of ORC, at Matsunoyama hot spring field in Niigata Prefecture at middle of Japan. From 2011 this small power plant starts power generation. Paola Bombarda et al .[5] experimentally compared, the thermodynamic performances of Kalina cycle and an ORC cycle, using hexamethyldisiloxane as working fluid, was conducted for the case of heat recovery from two Diesel engines. Supposing reasonable design parameters and a logarithmic mean temperature difference in the heat recovery exchanger of 50ºC, it was found that Kalina cycle produce more power than that of the ORC with hexamethyldisiloxane as working fluid. Maria Jonsson et al. [6] experimentally studied, ammonia–water bottoming cycle configurations for spark-ignition gas engines and compression-ignition gas diesel engines had been compared. Single-pressure Rankine cycles had been used as a basis for the comparison.Low heat source temperatures should increase the difference in power output between the ammonia–water cycle and the Rankine cycle. However, in this study, the results of the simulations show different trends.In most cases, the ammonia–water bottoming cycles with gas engines as prime movers generate morepower compared to a Rankinecycle than when gas diesel engines are the prime movers.

II KALINA CYCLE

The Kalina cycle was first developed by Dr. Aleksandr Kalina in the late 1970s and early 1980s [7]. After Dr. Kalian many other Kalina cycle have been proposed for different applications. The systematic diagram of Kalina cycle is as shown in fig.1

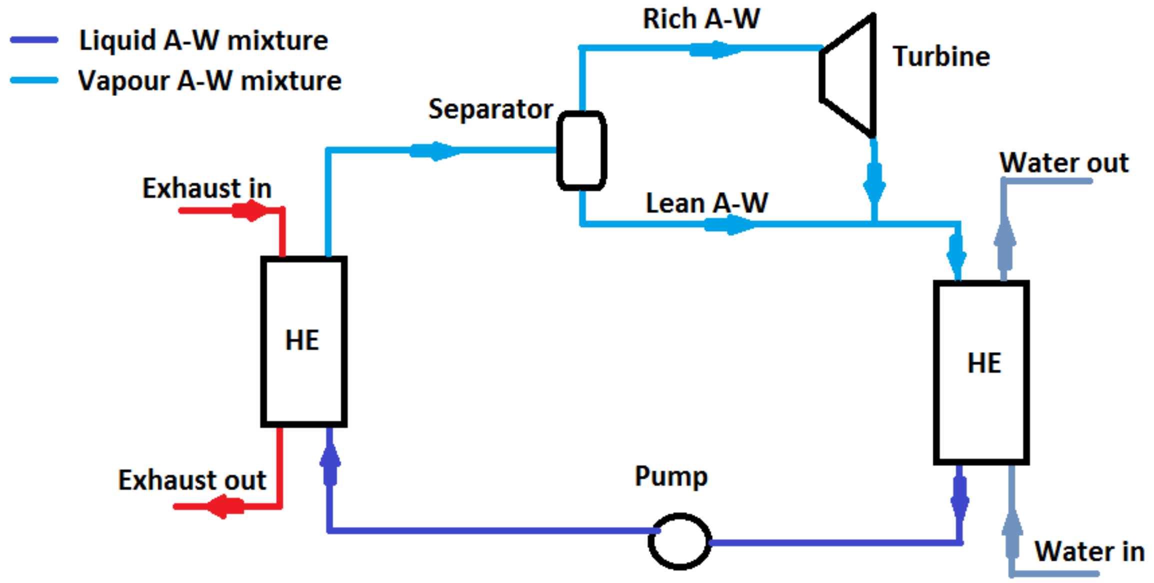
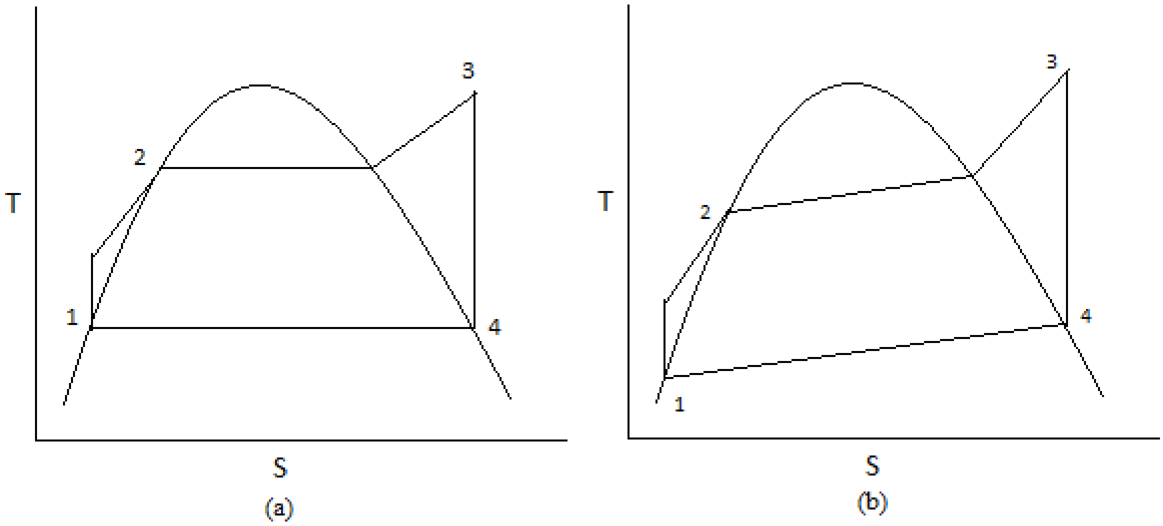


Figure. 1 Basic configuration of the Kalina cycle

Kalian cycle used binary working fluid, which contends Ammonia and water. The heat extraction efficiency can be improve by simply increasing the percentage of Ammonia in working fluid. The Kalina cycle is a new concept in heat recovery and power generation, which uses a mixture of 70% ammonia-30% water as the working fluid with the potential of significant efficiency gains over the conventional Rankine cycle. The Kalina cycle is suitable for medium and low gas temperature (450K to 800K) heat recovery system.The thermal efficiency of Kalina cycle is 40% to 60%.The main reason for the relatively high thermal efficiency of the Kalina cycle is the non-isothermal evaporation and condensation processes which occur because the working fluid is a zeotropic mixture of two fluids [8].

What makes Kalina cycle different from conventional Rankine cycle of power production is its choice of working fluid. Kalina cycle uses mixture of two fluids as working fluid, most commonly used is ammonia and water mixture. To get answer why Kalina uses a mixture as its working fluid, have a look at T-s diagrams of ordinary Rankine cycle (Fig.2.a) and Kalina cycle (Fig.2.b).



(a) (b)

Figure. 2 Comparison of Rankine and Kalina cycles

The major difference of Kalina cycle from Rankine cycle is that in Kalina heat addition and heat rejection happen at varying temperature even during phase change, since the fluid is a mixture. But in Rankine heat addition and heat rejection happen at uniform temperature during phase change. This is the one thing which makes all the difference in performance of Kalina cycle.

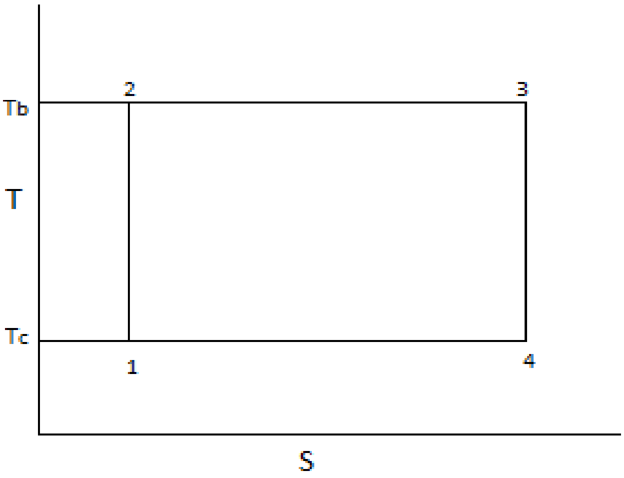


Figure.3 Carnot engine heat addition and rejection happen at uniform temperature

In a Carnot engine heat addition and rejection happen at uniform temperature. Efficiency of such an engine can easily be proved as,

$$\eta_{carnot} = 1 - \frac{T_c}{T_b}1$$

So it is clear that if heat rejection temperature (Tc) decreases or heat absorption temperature (Tb) increases thermal efficiency of Carnot engine will increase. Same analysis can be done for Rankine (Fig.4.a) and Kalina cycles (Fig.4.b), using average temperature of heat addition and rejection as reference temperatures. This is marked in dotted lines in following figures.

So it is clear from the diagrams that Kalina cycle has got lower average heat rejection temperature (Tc) and higher average heat addition temperature (Tb) compared to Rankine cycle. It will obviously lead to high thermal efficiency. This forms theoretical background of Kalina cycle, but in order to implement it we have to overcome some practical hurdles.

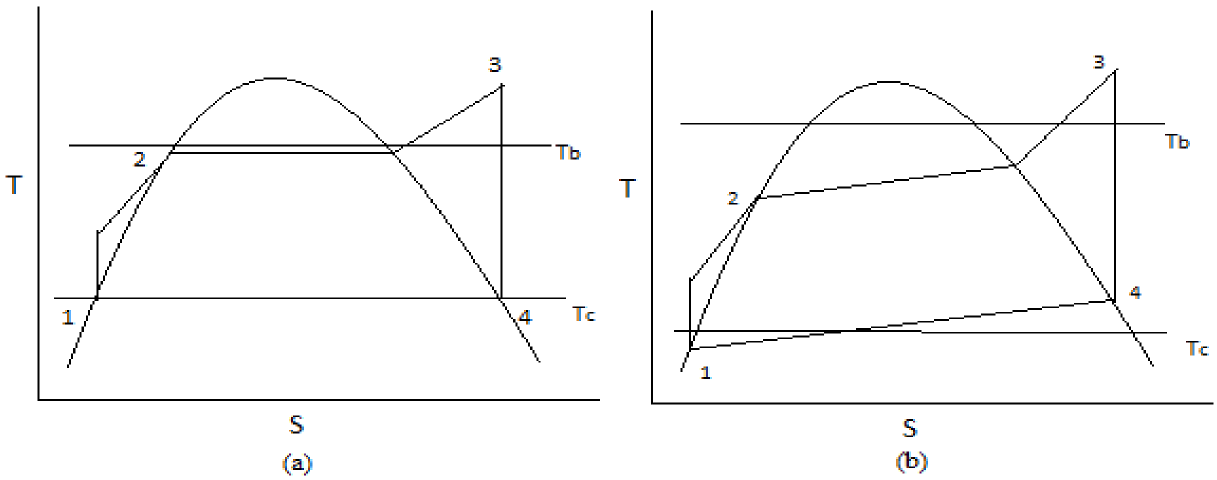


Figure.4 Average heat addition and rejection temperatures of Kalina cycle is much wider than a Rankine cycle

Kalina cycle uses high concentration ammonia mixture (around 70% ammonia) at steam turbine part, but such a mixture has got very low condensing temperature. Means you have to supply very low temperature cooling water at condenser for this purpose. Production of such low temperature cooling water is not economical. You can observe from Figure.5 that condensing temperature of ammonia-water mixture increases drastically with decrease in ammonia concentration. So in a Kalina cycle power plant, we will decrease ammonia concentration at condenser side. Equipment called separator will produce 2 streams of fluid from condenser outlet, one with high concentration and other with low concentration (30% ammonia). Low concentration ammonia mixture will get mixed with exist fluid at turbine and will produce a medium concentration (40% ammonia) ammonia mixture. This mixture will have fairly high condensing temperature and can be condensed with supply of ordinary cooling water. This is shown in following figure. Original state by mixing high Concentration of fluid is brought back to concentration ammonia stream from separator with fluid exit at condenser.

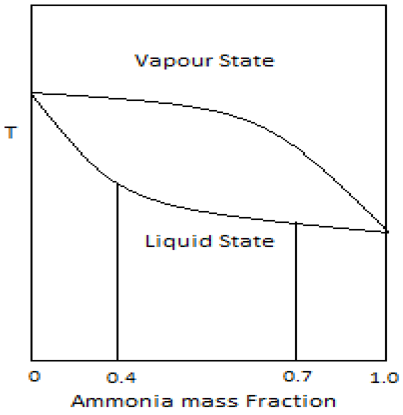


Figure.5 Temperature vs Ammonia-Water Phase Diagram

III CALCULATIONS

This work include waste heat recovery from 1196cc multi cylinder petrol engine. So, calculation is carryout in two parts IC-Engine and Kalina Cycle.

3.1 Heat Loss through the Exhaust in Internal Combustion Engine

Engine and dynamometer specification is given in table I and II. Heat loss through the exhaust gas from internal combustion is calculated as follows. Assuming,

Volumetric efficiency is 0.8 to 0.9
Specific gravity of fuel is 0.85 kg/lit
Calorific value of petrol is 44 MJ/kg Density of air fuel is 1.167 kg/m3 Specific heat of exhaust gas is 1.1-1.25 KJ/kg°K

Table I. Specification of Engine

Manufacture	Maruti Suzuki (Eco)
Engine	4 Cylinder, 4-Stroke, S.I. Engine
Bore	0.071m
Stroke	0.075m
Sp. Fuel Combustion	270gm/kw.hr
Capacity	1196CC
Maximum Power	73BHP @ 6000rpm
Maximum Torque	101Nm @ 3000rpm
RPM	6000rpm
Cooling System	Water Cooled

Table II .Specification of Dynamometers

Type	Eddy Current Dynamometer
Diameter of Brake Drum	250mm
Cooling System	Water Cooled

Exhaust heat loss through multi-cylinder petrol engine Mass flow rate of air in suction,

$$m_a = \eta_v \times \rho_a \times n \times V \qquad 2$$

$$m_a = 0.9 \times 1.16 \times \frac{3000}{2} \times 1196 \times 10^{-6}$$

$$m_a = 31.2 \text{ gm/sec}$$

Mass flow rate of petrol fuel,

$$m_f = (SFC \times POWER) \qquad 3$$

$$m_f = 270 \times 36$$

$$m_f = 2.7 \text{ gm/sec}$$

Heat avalable at exhaust gas

$$Q = (m_a + m_f) \times C_p \times \Delta T \qquad 4$$

$$Q = 33.9 \times 1.2 \times (400 - 40)$$

$$Q = 14.6 \text{ KW}$$

Therefore the total energy loss by Multi-Cylinder SI-Engine is 27.12%. Hence the loss of heat energy through the exhaust gas exhausted from I.C. engine into the environment 27.12% energy.

3.2 Kalina Cycle for Engine Heat Recovery

The calculation are based on Maruti Suzuki Eco engine. The model number of engine is HMT07. The data for petrol engine is supplied by the engine manufacturer as shown in table. The main components of Kalina cycle are Evaporator, Condenser, Separator, Mixture, Pump and Turbine. The design of each component is as shown as follows.

3.2.1 Working Fluid

Liquid ammonia and water are completely miscible in all proportions, hence can form solutions of all concentrations from 0 to 1, at normal temperatures. We are going to use 0.6% of Ammonia and Water solution. The effect of ammonia in water is to lower the vapour pressure of water, similarly the effect of water in ammonia is to lower ammonia's vapour pressure. Thus the total pressure over ammonia-water solutions is made up of partial pressure of ammonia and partial pressure of water vapour, and is always in between the saturation pressures of pure ammonia and water.

If Raoult's law is applied to ammonia-water mixtures, then the total pressure at any temperature, P_{total} is given by

$$P_{Total} = XP_A + (1 - X) \qquad 5$$

$$X = \frac{1}{n_a} \qquad 6$$

Specific enthalpy and enthalpy of Ammonia and Water solution can be calculated by using following formula

$$\xi = \frac{m_A}{m_A + m} \quad 7$$

$$C_{Tota} = \frac{(\xi.C_A.\rho_A)+((1-\xi).C_W.\rho_1}{(\xi.\rho_A)+((1-\xi).\rho_W)} \quad 8$$

$$h_{Total} = (\xi.h_A) + ((1-\xi). \quad 9$$

Where, x is the liquid phase mole fraction of ammonia which is equal to 0.6136, ξ is the mass fractionof ammonia which is equal to 0.6.

3.2.2 Pump

The condensing temperature of ammonia and water mixture is very low i.e. below atmospheric temperature at atmospheric pressure. So for proper condensation purpose we have to increase working fluid pressure inside system and for that we required pump with high pressure and low discharge. For given study we are going to use diaphragm pump (30W) with mass flow rate of 3 LPM and pressure 0.7 MP. According to design for a given system mass flow rate 8.67×10^{-3} kg/sec and pressure should be 6.5 bar.

3.2.3 Evaporator and Condenser

Evaporator is nothing but spiral tube heat exchanger. 0.60% Ammonia-Water solution is flowing through spiral tube with inlet and outlet temperature of 32°C and 100°C. Mass flow rate inside spiral tube is 8.67×10^{-33} kg/sec. The exhaust gas at 300°C is supply through shell and exits at 150°C with mass flow rate of 30×10^{-3}kg/sec. Heat available at exhaust is used to change phase of 0.60% Ammonia-Water solution from liquid to vapour.

Condenser is also spiral tube heat exchanger which contain Ammonia-Water solution vapour entering at 68°C and exits at 28°C with liquid phase. The water at 26°C is supplied through shell and exits at 70°C, with mass flow rate of 2.54×10^{-3} kg/sec. The heat calculation is done by

$$Q = m \times C \times \quad 10$$

3.2.4 Mixing System

The mixing system consist of separator and mixture. Separator is used to separator rich and lean mixture. The mixing chamber is used to mix this rich and lean solution. According to calculation the ξ_{Rich} is 0.7% and ξ_{Lean} is 0.358%, with mass flow rate of 6.12×10^{-3} kg/sec and 2.54×10^{-3} kg/sec. The maximum pressure available at the inlet of turbine is 16.3bar with 0.7% ammonia-water vapour solution. The calculation of mixing system is done by using design data book and following formulas,

$$m = m_1 + \,, \qquad 11$$

$$\xi.m = \xi_1.m_1 + \xi_2. \,, \qquad 12$$

$$U_T = \sqrt{\frac{4\times g\times D_P\times(\rho_L -}{3\times C_d\times\rho_G}} \quad 13$$

3.2.5 Turbine

The power produce in given study is found to be 1.02hp at turbine. The pressure and temperature at inlet of turbine is 16.3bar and 100˚C. The leak proof small turbine are not available in market. So it is required to manufacture small turbine according to our requirement. The manufacturing turbine is costly process. In present study centrifugal pump can be used as turbine with some adjustments.

IV CONCLUSION

Power cycles with ammonia-water mixtures as the working fluid are well suited for utilization of waste heat from multi-cylinder petrol engines. The 1196CC multi-cylinder petrol engine losses 27% of its energy in exhaust gas. This waste energy not only increases entropy but also causes other environmental damages. This waste energy can be utilize with the help of Kalina cycle. According to calculation the net power produce by Kalina cycle from 1196CC multi-cylinder petrol engine exhaust gas is 0.979 HP.

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