# DESIGN AND ANALYSIS OF KALINA CYCLE FOR WASTE HEAT RECOVERY FROM 4 STROKE MULTI-CYLINDERS

# PETROL ENGINE

**Arvind Kumar Chaudhary[1], Harsh Kandpal[2], Tushar Kapoor[3]**

[1,2,3]*Department of Automotive Design Engineering, University of Petroleum and Energy Studies, Dehradun, Uttarakhand, India*

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**Abstract -** *With the increasingly global issue regarding rapid economic development and a relative shortage of energy, the IC engine exhaust waste heat and its serious consequence related to environmental pollution have been highlighted recently. The total amount of energy supplied to engine out of which only 30% to 40% is converted into useful work. While rest of energy is expelled to the environment which causes serious environmental damage. Therefore it is required to utilize this waste energy to improve the thermal efficiency of the engine and the reduced greenhouse effect. In thermodynamics, the Carnot cycle has been described as the most efficient thermal cycle possible. The Kalina cycle is the most significant improvement in the steam power cycle since the advent of Rankine cycle in the mid-1800s. This work is focused on waste heat recovery of 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 petrol engine due to its high thermal efficiency. In the present work, Kalina Cycle is designed for waste heat recovery from multi-cylinder petrol engine*

***Key Words*: Kalina Cycle, Waste heat, Ammonia-Water mixture, Sepeartor, Petrol Engine**

## 1. INTRODUCTION

With the regular increasing problem regarding rapid economic development and serious consequences of environmental pollution, the waste heat recovery system has gained significant 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 converted 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 the small vehicle increase 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 a small vehicle. The main problem in heat recovery from such system is its small amount of heat availability. Ammonia-water of different concentrations is 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 the light-duty engine.

## 2. BRIEF ABOUT KALINA CYCLE

It is the most commonly used thermodynamic combined used in power plant. The cycle is operated at large temperature and act as a standalone cycle in power plant for waste heat recovery. KALINA Cycle is commercially used in a number of countries.

There is a large temperature gap at places, divergence between the thermal behavior of source/sink and working fluid is a potential cause of irreversibility in the cycle due to which we cannot recover a large amount of energy. Many times one tries to modify the RANKINE cycle i.e. instead of a single fluid, use a fluid mixture, because a single fluid condense at constant temperature but in case of mixture of fluid it boils and condenses over a range so during evaporation and condensation its temperature is not constant so, KALINA cycle instead of taking pure fluid as water as taken in RANKINE cycle, uses mixture of fluid (Ammonia-water solution) one of the most successful. This reduces the irreversibility also and it is also called REVERSED ABSORPTION CYCLE.

In Conventional RANKINE Cycle the condenser steam side we go at atmospheric pressure so that has got many problems of leakages. In KALINA cycle the pressure stays above atmospheric.

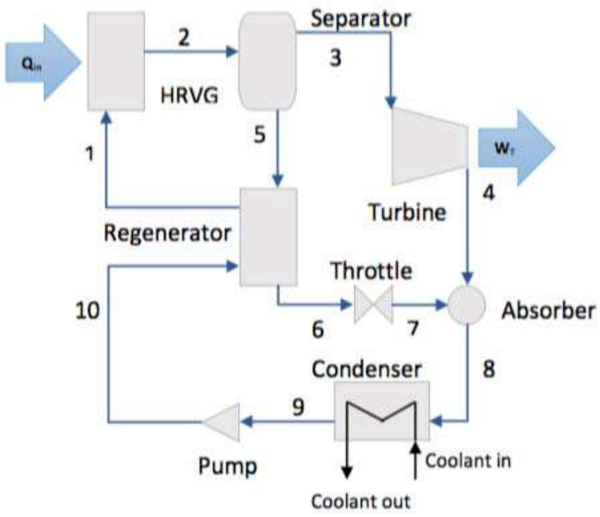


**Fig1: Kalina cycle system 1**

### 2.1 Basic Kalina Cycle

It has four basic operation Heat addition, Expansion, Heat rejection, pressure rise.

1) RECUPERATOR: heat transfer device

2) Vapor "TURBINE" Expander: Expansion

3) ABSORBER: condenser

4) PUMP: pressure rise

### 2.2. Working

In Distillation Condensation Subsystem mixture from the TURBINE is cooled first in the RECUPERATOR, then it is mixed with the lean solution of ammonia which comes fro SEPARATOR, then it produces the basic solution. Once the basic solution is made it goes into the ABSORBER, so after condensing, we raise its pressure and mostly it goes to RECUPERATOR. RECUPERATOR is internally exchanging heat.PUMP is raising the pressure and after that, the basic solution is partially heated but while it is coming to the RECUPERATOR in-between part of it is taken and part of it is mixed with the enriched vapor which is coming from the SEPARATOR and from the RECUPERATOR. The basic solution which is heated and the pressure has been increased goes to the SEPARATOR where it flashes when it flashes it produce vapors and also it produces the same amount of liquid that is a lean mixture and it comes here as previously described (a lean mixture of ammonia). The enriched vapors are mixing with the basic solution on the other side. Then the mixture goes to the condenser and in the condenser, it condenses then it is pumped by increasing the pressure to HEAT RECOVERY VAPOR GENERATOR (HRVG) to generate high-temperature vapor and in this manner, the cycle continues..

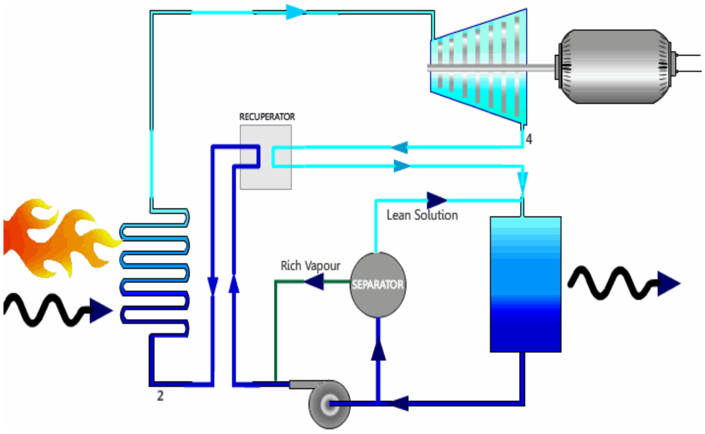


**Fig2: Process diagram**

### 2.3 Comparison Between Rankine& Kalina Cycle

1) In a typical Rankine cycle power plant a pure working fluid, water or in case organic Rankine cycle, lower molecular weight organic compounds are heated in a boiler and converted into high pressure, high-temperature vapor which is then expanded through a turbine which generates electricity in a closed loop system whereas
2) The Kalina cycle utilizes an ammonia-water mixture as a working fluid to improve system thermodynamic efficiency and provide more flexibility in various operating conditions.
3) As plant operating temperatures are lowered the relative gain of the Kalina cycle increases in comparison with the Rankine cycle.

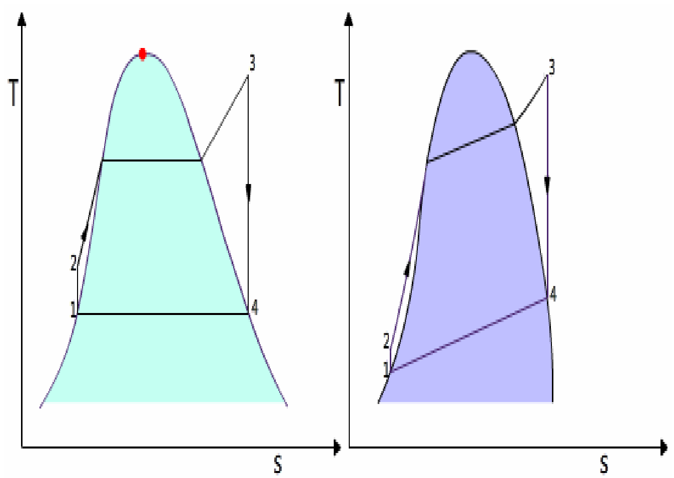


**Fig3: Graphically distinguishing Rankine cycle and Kalina cycle**

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 a uniform temperature during phase change. This is the one thing which makes all the difference in performance of Kalina cycle.

**2.4 Advantages Of Using Ammonia-Water Mixture in Kalina Cycle**

1) Ammonia and water have similar molecular weight.
2) The mixture is a new fluid.
3) Excellent heat transfer coefficient.
4) Fluid circulation is one-third or two-thirds of that in ORGANIC RANKINE CYCLE i.e. mass flow rate is comparatively smaller than the other cycles so equipment size can be made smaller.
5) Low freezing point.
6) Pressure stays above atmospheric pressure.
7) KALINA cycle is a family of cycle-variation.
8) An increase in efficiency of around 20 to 40% can be achieved for Waste Heat Recovery application.
9) Using this fluid mixture we can have different cycle design depending on the source temperature in this manner it gives a lot of flexibility including few economics aspect, payback period etc.
10) Global warming potential of ammonia is very less so emission point of view it is not bad.
11) Hazardous point of view it is not bad.
12) As it is lighter gas so in case of an accident removal of this gas is not a big issue.

**2.5 Disadvantages of Kalina Cycle**

1) Ammonia is more corrosive compound to water so we use ammonia water mixture.
2) In HVRG the vapor fractions is generally higher then the heat transfer is to vapor so heat transfer coefficient is low so that needs large heat exchangers.

**3. HEAT LOSS THROUGH THE EXHAUST IN INTERNAL COMBUSTION ENGINE**

**Fig4: System setup 1**

**3.1 Specification of Engine**

1) Make: Maruti (ZEN)
2) No. of Cylinders: 4
3) Stroke: 61Mm
4) Bore: 72Mm
5) Rated Speed: 1500 Rpm
6) B.P.=10hp
7) Compression Ratio:9.4:1
8) Fuel: Petrol
9) Cooling System: Water cooled
10) Type: Four stroke
11) Orifice Diameter: 20mm
12) Type of Loading: Water Loading
13) Type of ignition: Spark Ignition
14) Type of lubrication: modified splash lubrication
15) Type of starting: self-starting
16) Types of cylinder arrangement: inline

**3.2 Standard Data for Calculations**

1) $D_0$ : Diameter of orifice = 20 mm

2) $A_0$ : Cross section area of orifice = $314.159 \times 10^{-4} m^2$

3) $C_0$ : Coefficient of discharge = 0.62

4) $\rho_a$ : Density of air at 0 oC = 1.2 Kg/m3

5) $\rho_w$ : Density of manometer fluid (water) = 1000 Kg/m3

6) g: Acceleration due to gravity = 9.81 m/s2

7) 1 Hp: 746 Watts

8) CV: Calorific Value of petrol = 45800 KJ/kg

9) $C_p$ : Specific heat of water = 4.18 KJ/kg0C

10) Specific gravity of petrol = 0.72

11) Difference of Water Manometer Reading, $h_w$ = 0.070.m

12) Calorimeter Cooling Water Flow Rate, $m_{wc}$ = 0.0570 Kg/min

13) Engine Cooling Water Flow Rate, $m_{we}$ = 0.0580 Kg/min

14) Reading of dial of hydraulic dynamometer(S)=1.2kgf

15) Distance from center of dynamometer shaft to center of spring balance in m(R)= 0.32m

16) Room temperature, T = 35 0C

17) Engine Cooling water inlet temperature, $T_1$ = 38 $^0C$

18) Engine cooling water Outlet temperature, $T_2$ = 55 $^OC$

19) Engine Cooling water inlet temperature, $T_3$ = 38 $^OC$

20) Engine cooling water Outlet temperature, $T_4$ = 54 $^OC$

21) Engine Cooling water inlet temperature, $T_5$ = 440 $^OC$

22) Engine cooling water Outlet temperature, $T_6$ = 397 $^OC$

### 3.3 Calculations

Engine Performance Parameter

Torque=RS = 1.2*9.81*0..32=3.76Nm

1) Brake Power (BP) = $\frac{2\pi NT}{4500}$ horse power =7.889hp=5.882kW

2) Indicated Power Time for 10cc of fuel consumption, t = 6.78 Sec,

Total Fuel consumption, TFC = $\frac{(volume\ of\ fuel\ consumed\,(cm^3)\times specific\ gravity\ of\ fuel\times 10^3}{10^6\times t(\sec)}\times 3600$

TFC = $\frac{10\times 0.72\times 10^3}{10^6\times 6.78}\times 3600$ =3.823kg/hr

TFC = 3.823 kg / hr.

Indicated Power, I.P = B.P + F.P I.P = 5.882+ 3.823

I.P = 9.705 KW=13.01hp

Mass of air intake, $m_a = \rho_a C_d \times \frac{\pi}{4} d^2 \sqrt{2g\times\frac{h_w}{\rho_a}\times\rho_w}$

$m_a = 1.2\times 0.62\times\frac{\pi}{4}(0.02)^2\sqrt{2\times 9.81\times\frac{1000}{1.2}\times 0.070}$ =0.0079kg/sec=0.474kg/min

Density of air $\rho_a$ = 1.293 Kg/m3

### 3.4 Theoretical Air intake:

**Fig5.1: System setup**

Diameter of piston, D = 0.061 m

Stroke length, L = 0.072 m

Engine speed, N = 1500 rpm

Heat Balance Sheet on Minute Basis:

Heat input, HI = T.F.C ×CV KJ/min

HI= 3.823×45800

HI = 2918.2233KJ/min

Heat Equivalent of B.P, HB.P = B.P × 60..KJ/min

HB.P = 5.882× 60 ………..KJ/min

HB.P = 352.92 KJ/min

Heat gained by calorimeter cooling water, $H_{wc} = m_{wc}\times C_{pw}\times(T_4 - T_3)$

$H_{wc}$ = 0.0570 ×4.187 × (79 - 38) = 0.0570 ×4.187 × (79 - 38)=9.7850KJ/min

Heat gain away engine jacket water

$H_{we} = m_{we} \times C_{pg} \times (T_5 - T_6)$ =0.0580× Cpg× (440 - 397)=0.0580*14.563*43=36.32Kg/min

Specific heat of gas, Cpg = 14.563 kJ/kg.k

Heat carried away by exhaust gas $H_{eg} = m_g \times C_{pg} \times (T_5 - T_6)$ KJ/min

$H_{eg}$ = 0.5377 × 14.563 × (440-397) .....KJ/min $H_{eg}$ = 336.7 KJ/min

Heat unaccounted loss, Hu = HI – ( $H_{eg}$ + $H_{we}$ + $H_{wc}$ + $HBP$ ).....KJ/min Hu = 2918.2233 – (336.7+ 36.32+ 9.7850 + 352.92).....KJ/min

Hu = 2182.4983 KJ/min…………(i)uncounted heat

Power output = 36.37kW

**Kalina cycle efficiency calculation:**

Assumptions

i. Steady state operation of the cycle.

ii. All the devices are adiabatic.

iii. Throttling process is isenthalpic.

iv. The effectiveness of the Heat Exchanger is 80%.

v. Working fluid at the outlet of Condenser is saturated liquid.

vi. The isentropic efficiency of pump and turbine is 100%. Pressure losses and heat losses in pipes are neglected.

vii. Temperature of the working fluid at the outlet of Condenser is27˚C

viii. Separator completely separates the liquid and vapour.

ix. Working fluid at the inlet of the Turbine is saturated vapour.

x. The kinetic energy and potential energy changes in the devices are neglected.

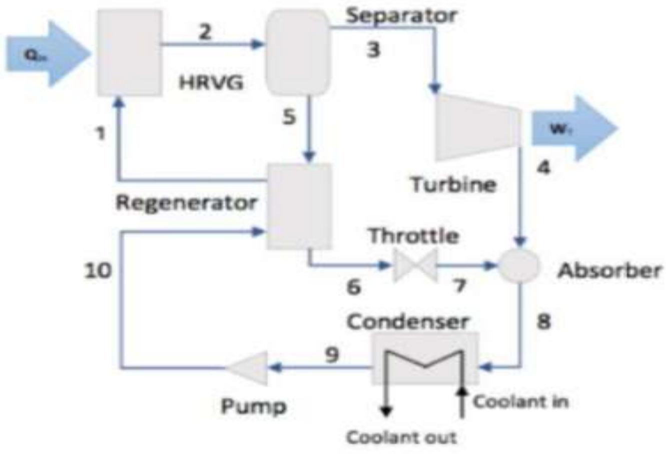


**Fig6: Kalina cycle system 2**

**Table 1: EnergyEquations**

| | |
|---|---|
| HRVG | $\dot{Q} = \dot{m}_1 \times (h_2 - h_1)$ |
| Separator | $\dot{m}_1 \times h_2 = \dot{m}_3 \times h_3 + \dot{m}_5 \times h_5$ |
| Turbine | $W_t = \dot{m}_3 \times (h_3 - h_4)$ |
| Regenerator | $\dot{m}_1 \times (h_1 - h_9) = \dot{m}_5 \times (h_5 - h_6)$ |
| Throttle valve | $\dot{m}_6 \times h_6 = \dot{m}_{10} \times h_{10}$ |
| Pump | $W_p = v_9 \times (p_9 - p_8)$ |
| Efficiency | $\eta = \frac{W_t - W_p}{\dot{Q}}$ |

**4. CONCLUSIONS**

Efficiency drawn from Kalina cycle is between 15% to 20% This leads to the obvious conclusion that the Kalina cycle is well positioned against an Organic Rankine cycle for applications with high utilization time, a base load application.

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