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Thermo-Economic analysis of Kalina cycle (using MATLAB and EES) for studying its scope in Indian Context and suggesting best locations for its application in India

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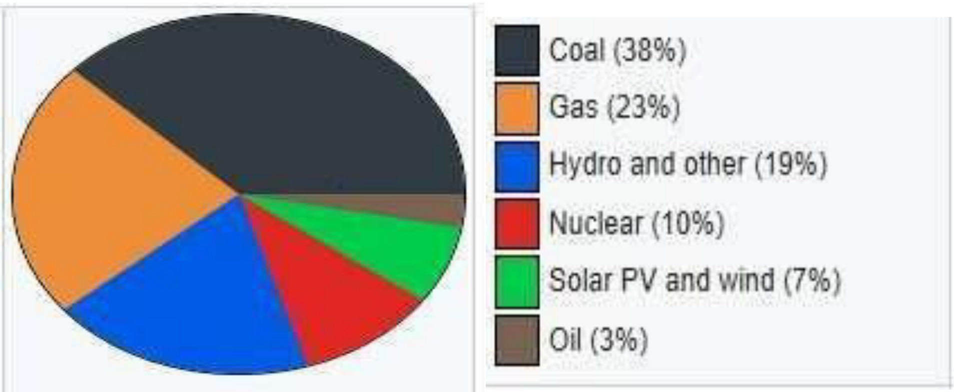
Abstract

Thermodynamic Analysis of Kalina Cycle for low temperature Energy Sources was done during this project using Engineering Equation Solver (EES) software and MATLAB (Matrix Laboratory). The Kalina Cycle system (KCS 11) was used for the study which basically comprises of HRVG Separator, Turbine, Condenser, Absorber, Throttle valve and Pump. The various input parameters such as pressure, temperature, heat input, mass fraction etc. were given based upon the theoretical values. The variation of Efficiency and Work output was studied by varying the pressure, temperature and ammonia fraction. It was found that the Efficiency and Work output both depend upon the temperature and pressure and for the range of the temperature taken into consideration, efficiency and work output increases with increase in temperature whereas for pressure after an optimum value both efficiency and work output starts to decrease. The optimum efficiency obtained was 21.88% for temperature and pressure 443 K and 30 bar. EES is also used in the given project to compute the overall Exergy of the Kalina cycle system. The following project also contemplates the comparison in economy of a Kalina cycle and a Rankine Cycle using MATLAB software . Using appropriate data (Marked in References) the project analyzes various types of waste energy sources viz Steel plants, Cement plants and Oil Refineries. Apart from the project also analyzes the Thermo-Economic Scopes of Kalina cycle in the field of Geothermal and Solar Energy.

1. Introduction

The total energy consumption of World can be broadly divided into four areas of sectors depending on various situations in which the energy being produced is to be utilized. These are Domestic Sector, Transportation Sector, Agriculture Sector and Industry Sector. Large amount of energy consumption in a country represent increased development and better comforts at home due to use of various appliances which can be used in agricultural, electrical and industrial production. The World Energy consumption is typically measured per year and is a measure of amount of energy produced from energy resources across various categories like conventional and non-conventional to support human activities across various sectors like industries, agriculture and day to day life activities.



2018 World energy generation (26,700 TWh) by source (IEA, 2019)

From the diagram, it can be clearly understood that the coal is the most utilised form of energy followed by oil and natural gas. Also the growth in utilisation of both these sources is also very appreciable and given the fact that these are non- renewable resources humanity have started to shift towards the cleaner and renewable sources such as Hydro, wind, solar which can also be inferred from the diagram. The growth in utilisation of renewable resources have been more than that of non renewable resources. Nuclear energy which also makes up a great portion of world energy consumption is not growing as rapidly because of the hazards and possibility of disasters associated with it such as Chernobyl accident.

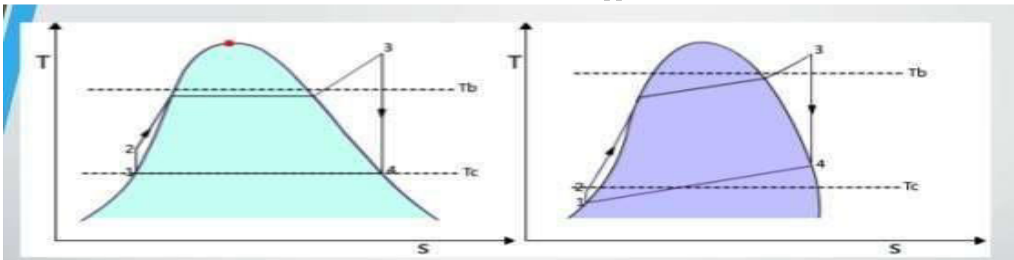
2. Literature Review

DR. Alexander Kalina proposed a new type of power system which uses multiple component, variable composition working fluid to extract work form low temperature heat resources as a replacement for various traditional cycles like Rankine cycle.

Since the introduction of Kalina Cycle various studies have been conducted to check the application of kalina cycle in various scenarios. Kalina A (1984) studied the application of cycle as the bottoming cycle in the combined cycle system and compared with traditional Rankine Cycle system. The efficiency of cycle was found to be 1.6 to 1.9 times higher than that of Rankine Cycle. Henry A. Mlcak [2] studied the Kalina power plant in terms of economic feasibility and found that this cycle can be 30% less capital-intensive than the Rankine cycle power plant for low temperature application and up to 10% for direct fired application, Seckin Candeniz (2018) [3] used EES to perform the thermodynamic analysis of a Combined power and refrigeration cycle for low temperature application. In his study selected the temperature range of 100 C to 135 C and found that the work output of turbine and efficiency increases with net increase in the temperature. Karimi Munawar (2014) (4) studied the application of KCS II and performed dynamic analysis for different temperatures and pressure ranging from 130^0 C to 19^0 C and pressures from 20 bar to 50 bar. In his study it was found that efficiency es with increase in temperature at a given pressure. Victar A R, Kim J, Smith R (2013) [5] developed an optimisation model for composition of mixed working fluid in Organic Rankine Cycle and Kalina Cycle for temperature range 100^0 C to 250^0 C from the heat source. In this study it was found that optimum water mole fraction in ammonia water mixture was 0.7549.
Knudsen T. Clausen DR Haglind F. Modi A (2013) (6) did the energy analysis of Kalina Cycle for the use in concentrated solar power plants with direct steam generation. The results obtained were that the cycle operating at a mole fraction of 0.7 gave the efficiency of 30.7% and it was also suggested that there would be no benefit of using Kalina Cycle over Rankine Cycle when taking heat directly from solar receiver. Madhwa H.D. Hettiarachchi, Worek W.M. Ikegami Y (2007) [7] studied the performance of KCS 11 with low temperature heat sources and compared it with the Organic Rankine cycle. It was found that KCS 11 was better in overall performance at moderate pressures than the Organic Rankine Cycle. Marston CH (1990) [8] performed the parametric analysis of Kalina Cycle and the cycle efficiencies was plotted against the temperature and mass flow rate of Seperator and the results showed close correlation between the mass flow rate and temperature. Oguz Arslan [9] used KCS 34 to carry out a case study to produce power from ten hot water springs of Simav Geothermal area. And demonstrated that 41.2 MW can be generated from these hot wells.Xin Zhang Maogang He, Ying Zhang (2012) [10] presented a review research on the Kalina Cycle and concluded that Kalina Cycle was developed in order to replace the conventional Rankine cycle and Organic Rankine Cycle and have a better thermodynamic performance in general when compared to them. Jianyong Wang (2014) [11] compared Organic Rankine and Kalina Cycle for waste recovery of heat of compressor intercooling Optimisation was performed for both ORC and Kalina Cycle. The results obtained by the study shows that Kalina Cycle show's the better performance than the ORC. Jiangfeng Wang (2102) [12] examined a solar driven Kalina Cycle efficiently utilising the ammonia water mixture and a parametric study was made. The results of this study showed that there exist and optimal turbine pressure corresponding to which the turbine net work is maximum corresponding to an optimum sale of ammonia water fraction El-Sayed and Tribus [13] made a theoretical comparison between the Kalina cycle and Rankine cycle. The configuration developed by them were very much complicated because several heat exchangers had more than two stems Goswami [141 proposed a new cycle after his name using binary fluid mixture for simultaneous production of power and refrigeration effect from a single cycle. He concluded several studies with other researchers to optimise the proposed cycle [15][16)

3. Kalina Cycle Description

This cycle is considered to be the competitor of Organic Rankine Cycle (ORC). The Kalina Cycle uses binary mixture which provides a better match with temperature than that with pure working fluids as in Rankine Cycle and due to this variable temperature capability of binary mixtures, the irreversibility that occurs in heat transfer process gets reduced along with a higher efficiency. For generation of power and refrigeration among the possible candidates of binary mixtures the ammonia water mixture is best suited. Kalina cycle as compared Rankine cycle is not as simple but the power plant running on Kalina cycle may have problem of complex arrangement of different devices and Models of Kalina cycle are designed depending upon the requirement for which it is meant to be utilized, hence for different applications the models differ.



T-S diagram of Rankine and Kalina Cycle

The graphs (T-S plots) shown above tells about the difference in working between a conventional Rankine Cycle and Kalina Cycle. The first graph represents the Rankine cycle and the boiling and cooling process of the working fluid which is mainly water takes place at constant temperature T_b and T_c.While in the Kalina Cycle the boiling and the condensation of working fluid takes at variable temperature and because of this a better temperature match for the heat transfer process takes place. Hence due to this property of Kalina Cycle it's efficiency increases.
The plant accounts for very low running cost, since the pressure and specific volume of the system can be varied to reduce the size of turbine ,condenser and heat exchangers. Average running cost of Rankine Cycle Plant = Rs 5 lakh/KW; Average running cost of Kalina Cycle Plant = Rs 3 lakh/KW; Average running cost of Solar Power Plant = Rs 15 lakh/KW. The cooling water

requirement for kalina is lower as compared to rankine cycle since a lean Ammonia - Water mixture enters the condenser which requires less cooling water . the System offers high level of flexibility to the operator and can be easily varied as per the ambient system parameters changes. The working fluid is a substance that is subjected to various thermodynamic processes during a thermodynamic cycle. In other words, working fluid is a pressurized gas or liquid that transmits or absorbs energy during a thermodynamic cycle. Different working fluids are used in different cycles and the efficiency of cycle may or may not be dependent on the properties of the working fluid being used. Based on their composition working fluids can be categorized into different categories: 1) Pure substance: These working fluids have constant or sate chemical composition throughout the fluid and have constant boiling and melting point for defining any state of a pure substance, any 2 properties such as pressure, Temperature, volume etc are required and if the state is saturated only one property is required to fix the state of the pure substance. Examples- air, water etc. 2) Mixtures: These types of working fluids may or may not have the same chemical composition throughout the volume and are basically composed of two or more different components. The mixture may be of two different liquids or one liquid and a salt. The mixtures have one component known as solvent and other known as solute. To fully obtain a state of a mixture 3 properties are required. Examples-ammonia water mixture, lithium bromide and water mixture etc.

With growing energy needs and the limited nature of non renewable sources of energy it has become imperative that a shift in the type of energy sources used is made with advent of Kalina Cycle low temperature heat sources which are mostly renewable sources of energy such as solar energy, geothermal energy ete can be efficiently utilized and a change in the type of energy sources used could be made. Thus more and more research and development has to be put into the Kalina Cycle so that it can fully replace the cycles using non renewable sources of energy as its heat sources.

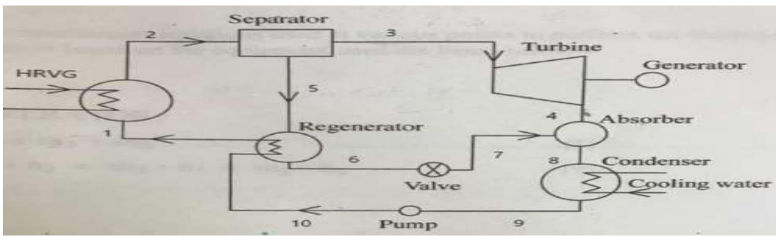
4. Mathematical Model Of Kalina Cycle

To perform the thermodynamic Analysis of Kalina Cycle several assumption were followed which are listed as below

- Steady State frictionless flow,
- One dimensional
- Only enthalpy and internal energy change are taken into consideration while the energy changes such as Kinetic and Potential energy are neglected.
- There is no leakage of the working fluid and it works in a closed circuit • Pressure losses in all the heat exchange processes like condenser, HRVG, recuperators etc. are neglected.
- Heat losses to the environment during the transportation of the fluid from one component to the other is neglected and the only heat release to the environment takes place during the absorption and condensation.
- The Isentropic efficiencies of Turbine are taken to be 100 percent.
- Throttling process is isenthalpic,
- The separator completely separates the liquid and vapor phases
- The fluid is completely converted into liquid phase at the end of condensation process • Effectiveness of regenerator is 80%

For the thermodynamic analysis Engineering Equation Solver (EES) was used in which the procedure for calculating the properties of ammonia water mixture in different conditions such as subcooled, saturated and superheated is already incorporated.

Kalina Cycle Modelling



The mass flow rate is represented by $\dot{m}$

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_8 = \dot{m}_9 = \dot{m}_{10}; \quad \dot{m}_3 = \dot{m}_4 ; \dot{m}_5 = \dot{m}_6 = \dot{m}_7$$

$$x = \dot{m}_{NH3}/\dot{m}_{total}$$

$$x_1 = x_2 = x_8 = x_9 = x_{10} ; x_5 = x_6 = x_7 ; \quad x_3 = x_4$$

$$P_{min} = P_7 = P_4 = P_8 = P_9 ; \quad P_{max} = P_1 = P_2 = P_3 = P_4 = P_5 = P_6 = P_{10}$$

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$$T_2 = T_3 = T_5$$

$$q = \dot{m}_{vapour}/\dot{m}_{total};\ q_3 = 1;\ q_5 = q_9 = 0$$

Seperator: $\dot{m}_1 = \dot{m}_2 + \dot{m}_8$; $\dot{m}_1 * h_1 = \dot{m}_3 * h_3 + \dot{m}_5 * h_5$

Turbine: $W_{turbine} = \dot{m}_3 * (h_3 - h_4)$

Absorber: $\dot{m}_8 * h_8 = \dot{m}_7 * h_7 + \dot{m}_4 * h_4$

Condenser: $Q_{condenser} = \dot{m}_8 * (h_8 - h_9)$

Pump: $W_{pump} = \dot{m}_9 * (h_8 - h_9)$

Regenerator: $\varepsilon = (T_5 - T_6)/(T_5 - T_{10})$

Throttle Valve: $h_7 = h_6$

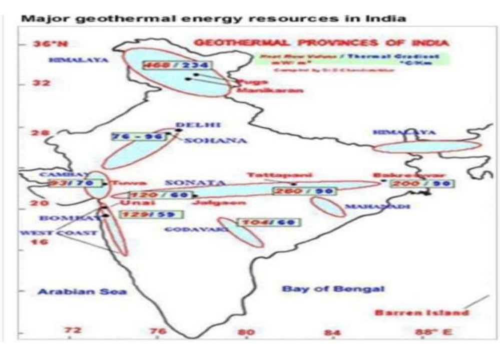
HRVG**:** $Q = \dot{m} * (h - h)$

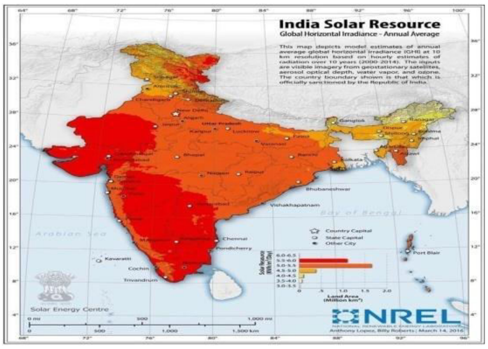
Efficiency $= (W_{turbine} - W_{pump})/Q_{in}$

5. Scope And Applications (In Indian Context)

Municipal Solid Waste : Delhi generates 10,500 MT (105*10^5 KG) . Average outlet of Organic Waste is around 500 MT which can generate 500*20 = 10,000 m^3 of biogas . the Calorific value of biogas is 20 MJ/m^3 , thus the net power output that can be obtained from biogas is 200 GJ on a daily basis . This low grade heat source can be best utilized with a Kalina cycle.

Geothermal Power Projects : The highest energy density is carried by Puga valley geothermal reservoir located in Jammu and Kashmir . It can provide a power load of 20 MW . this system can be used best wit Kalina Cycle .

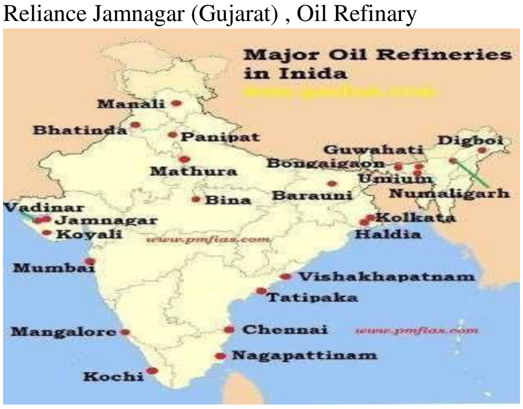


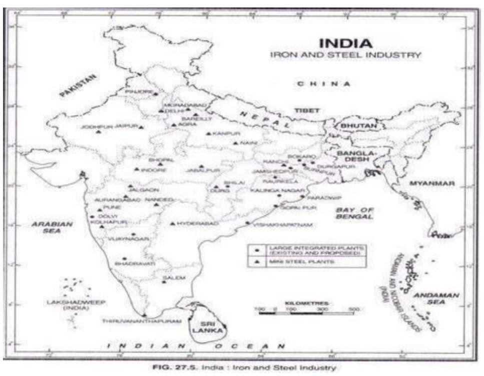


(Provinces And Geothermal Map Of India) (Solar Radiation Map of India)

Solar Energy : As India is classified as a hot tropical country which receives an average solar radiation flux of 200MW/KM square . Gujarat and Rajasthan receives maximum solar radiation flux of 250MW/KM square . Jaisalmer Solar power project is one of the largest in the world with an installed capacity of 500MW .

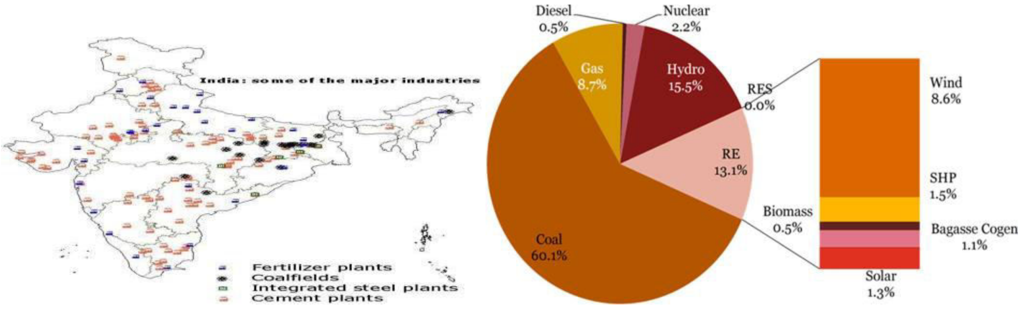
Oil Refineries And Steel Manufacturing Plants :Total Number of Oil Refineries in India - 24 and Largest Oil Refinery - Reliance Jamnagar (Gujarat) , Oil Refinary





Total Major Steel manufacturing Plants in India are 13 ; Largest Steel plant - Tata Steel Plant , Jamshedpur (Jharkhand)

Total Cement Manufacturing Plant – 210; Largest Cement Manufacturing Plant - Ultratech Cement Manufacturing Plant (Madhya pradesh)



(Indian Energy Scenario)

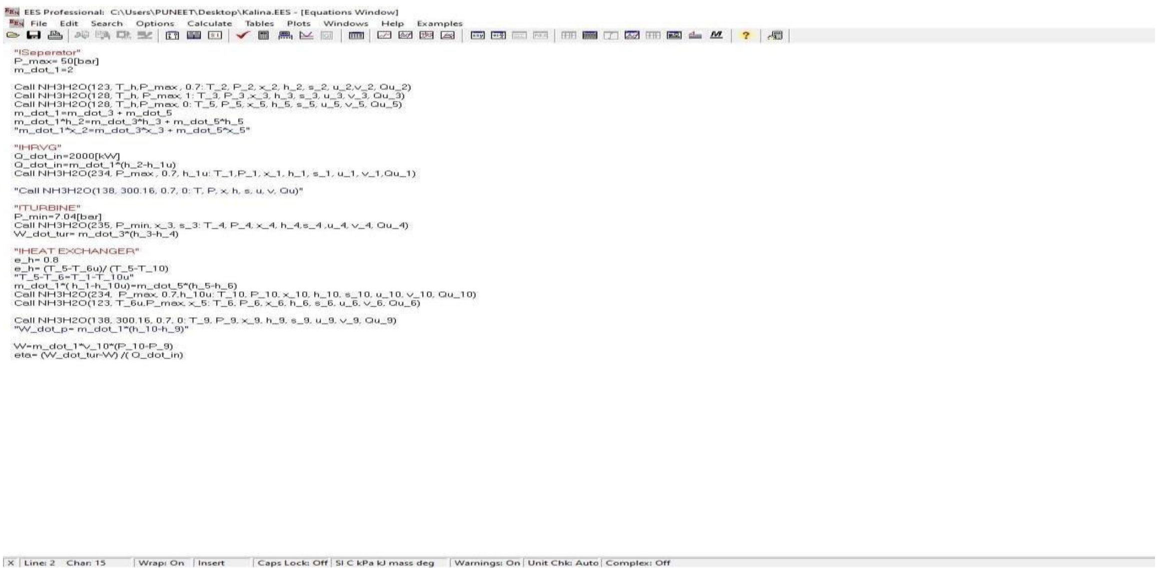
Average waste heat power released from these plants in the form of Flue gases , Exhaust gases ,Hot water , Solid residue from combustors accounts for a power wastage of around 5 MW .

EES Modelling Of Kalina Cycle

The ENGINEERING EQUATION SOLVER software was used for the thermodynamic analysis of Kalina Cycle. EES is a mathematical tool which uses numerical methods to solve simultaneous system of linear equations. For the thermodynamic analysis of Kalina Cycle, all the equilibrium equations were written down in the EQUATIONS window in a proper syntax so that solver is able to solve equations with least possible time. EES automatically identifies and groups equations that must be solved simultaneously. This feature simplifies the process for user and ensures that the solver will always operate at optimum efficiency. EES provides many built in mathematical and thermophysical property functions useful for engineering calculations. One of the functions incorporated in the EES library is the NH3H20 (AMMONIA - WATER) PROPERTIES function. The NH3H20 procedure provides the thermodynamic properties of ammonia water mixture in subcooled, saturated and superheated conditions. This procedure is called from EES by the statement: Call NH3H20 (CODE, In1.In2, In3: T, P, x, h, s, u, v, Qu)

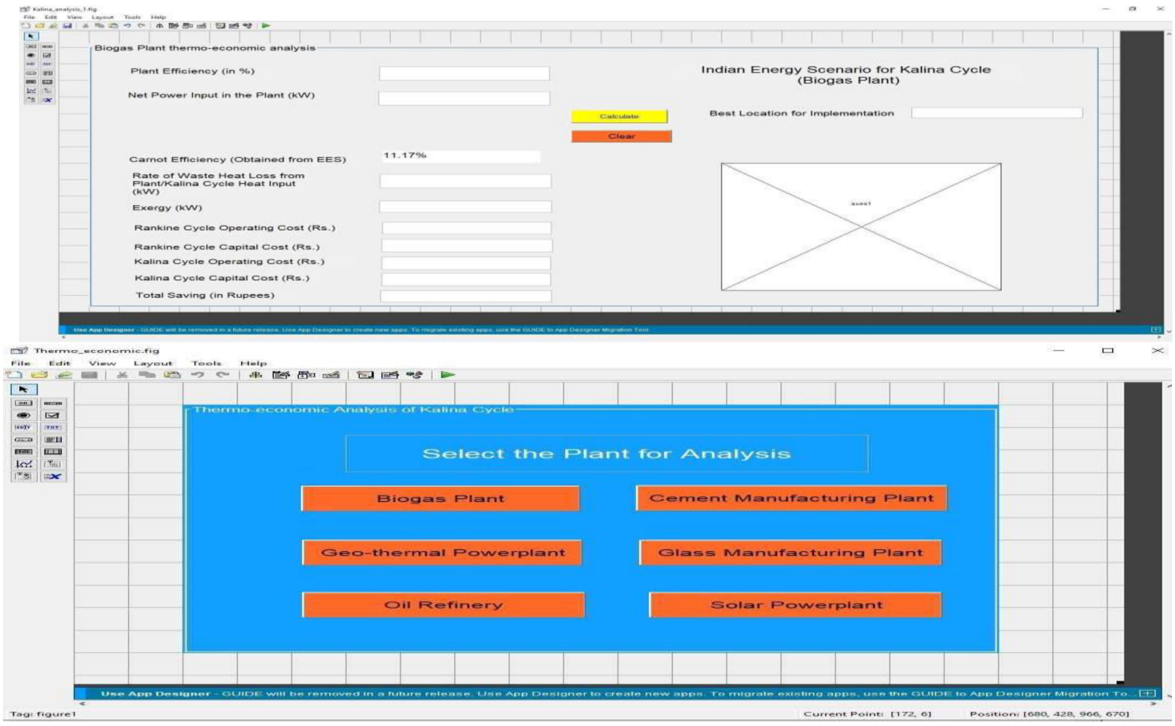
The 4 parameters to the left of the colon are inputs to the procedure: the eight values to the right are outputs whose values are set by the NH3H20 procedure. EXAMPLE: Call NH3H20 (123,403.16,P_max, 0.7: T_ 2,P _2,x_2,h _2,s_2,u_2,v_2,Qu_2). In this case, the input parameters are temperature, pressure and ammonia mass fraction and rest of the properties at the given point will be calculated by the function using correlations that are already built in. The parameters on right side of colon have a subscript signifying the particular point at which the function is being called. The complete code used for the thermodynamic analysis of kalina cycle is depicted in Section 6.2. The portion in red and blue signifies that it is a comment and is not considered by the compiler during execution of the program. To perform the parametric analysis of kalina cycle, the same code was used with a slight change that the parameter with which the variation was to be examined was kept an unassigned value and parametric analysis were performed separately.

Program On EES:



```
EES Professional: C:\Users\PUNEET\Desktop\Kalina.EES - [Equations Window]
File Edit Search Options Calculate Tables Plots Windows Help Examples

"!Seperator"
P_max= 50[bar]
m_dot_1=2

Call NH3H2O(123, T_h,P_max , 0.7: T_2, P_2, x_2, h_2, s_2, u_2,v_2, Qu_2)
Call NH3H2O(128, T_h, P_max, 1: T_3, P_3 ,x_3, h_3, s_3, u_3, v_3, Qu_3)
Call NH3H2O(128, T_h,P_max, 0: T_5, P_5, x_5, h_5, s_5, u_5, v_5, Qu_5)
m_dot_1=m_dot_3 + m_dot_5
m_dot_1*h_2=m_dot_3*h_3 + m_dot_5*h_5
"m_dot_1*x_2=m_dot_3*x_3 + m_dot_5*x_5"

"!HRVG"
Q_dot_in=2000[kW]
Q_dot_in=m_dot_1*(h_2-h_1u)
Call NH3H2O(234, P_max , 0.7, h_1u: T_1,P_1, x_1, h_1, s_1, u_1, v_1,Qu_1)

"Call NH3H2O(138, 300.16, 0.7, 0: T, P, x, h, s, u, v, Qu)"

"!TURBINE"
P_min=7.04[bar]
Call NH3H2O(235, P_min, x_3, s_3: T_4, P_4, x_4, h_4,s_4 ,u_4, v_4, Qu_4)
W_dot_tur= m_dot_3*(h_3-h_4)

"!HEAT EXCHANGER"
e_h= 0.8
e_h= (T_5-T_6u)/ (T_5-T_10)
"T_5-T_6=T_1-T_10u"
m_dot_1*( h_1-h_10u)=m_dot_5*(h_5-h_6)
Call NH3H2O(234, P_max, 0.7,h_10u: T_10, P_10, x_10, h_10, s_10, u_10, v_10, Qu_10)
Call NH3H2O(123, T_6u,P_max, x_5: T_6, P_6, x_6, h_6, s_6, u_6, v_6, Qu_6)

Call NH3H2O(138, 300.16, 0.7, 0: T_9, P_9, x_9, h_9, s_9, u_9, v_9, Qu_9)
"W_dot_p= m_dot_1*(h_10-h_9)"

W=m_dot_1*v_10*(P_10-P_9)
eta= (W_dot_tur-W) /( Q_dot_in)
```

7. Economic Analysis Of Kalina Cycle in Indian Context using MATLAB



Graphical UserInterface

8. Results and Analysis

In order to show the variation of parameters such as Efficiency of the cycle work done by the turbine (W_turbine) with the variables such as Pressure at HRVG (P_high). ammonia mass fraction (x). temperature at HRVG (T_h) graphs are drawn using the EES (Engineering Equation Solver) software. The basic composition of ammonia water solution for investigating the pressure and temperature variations was take as ammonia:water = 0.7:0.3,the primary mass flow rate of working fluid was taken as 2 kg/s. For the thermodynamic analysis the temperature range selected was 373k to 443k i.e. 100°C to 170°C. This temperature range is selected because the low temperature heat sources like geothermal, solar and waste heat from power plants provide heat bearing temperature ranges from 80°C to 180°C. The pressure range selected for the analysis is between 20 bar to 50 bar. The pressure is varied with steps of 5 bar and for each of these pressures the temperature is varied between 373 k to 443 k and the analysis is carried out to see the effect of variation of these two parameters on work output by turbine and efficiency both. In most of the cases the waste heat output is more or less the same throughout the operation of the plant and so the heat input at HRVG is taken to be constant value as 2000kW.

The table showing the parameters taken as input for the thermodynamic analysis is given below

INPUT PARAMETER	Value
Mass flowrate of primary solution	2Kg/sec
Pressure at HRVG	20 bar
Temperature at HRVG(T_High)	403.16 K
Heat Input from External Source	2000kW
Temprature at Output of Condenser	300.16K
Ammonia mass fraction of basic solution	0.7
Isentropic efficiency of turbine, Pump	100%
Effectiveness of Heat Exchanger	80%
Pressure at Exit of Turbine, Throttle	7.04bar
Vapour Mass Fraction at Outlet of condenser	0
Vapour Mass fraction at Turbine Inlet	1
Vapour Mass Fraction at Inlet from Separator to heat Exchanger	0

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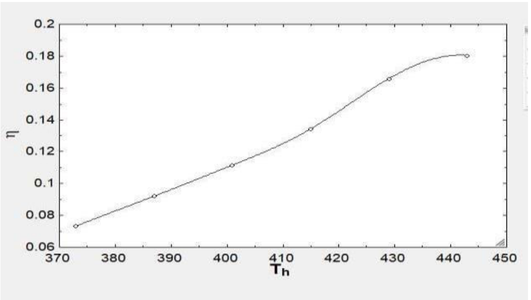
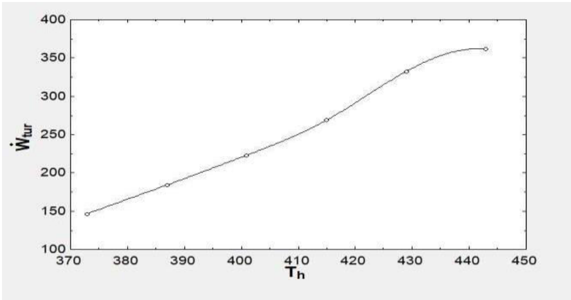
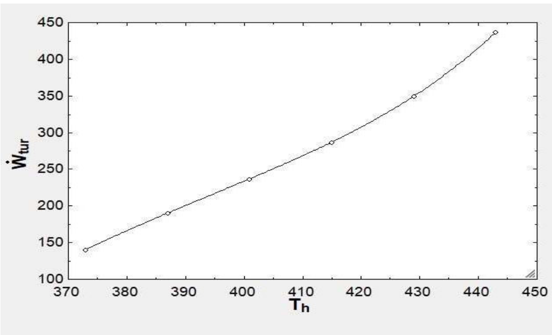
Variation Of Efficiency And Work Output With Temperapture At Different Pressures

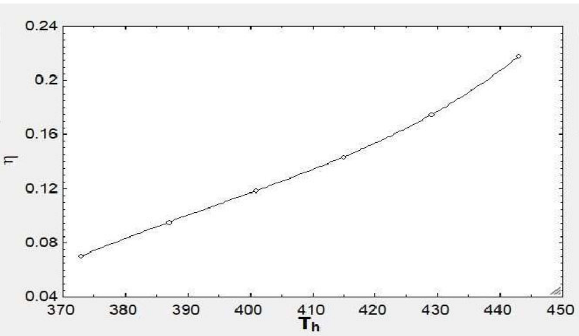
A parametric analysis was performed on the given set of conditions for the kalina cycle EES in which the effect of temperature of HRVG was investigated keeping the other parameters constant. Different iterations of the same parametric analysis were performed each time increasing the value of pressure by 5 bar from the previous value starting from 20 bar up to 50 bar. The results thus obtained were converted in the form of graphs for better representation in which temperature is plotted on the abscissa or the x-axis and on the ordinate or y-axis efficiency or work output by turbine is plotted.The general trend that can be inferred from the results is that both the work output and efficiency increase with increase in temperature at the selected pressure values.



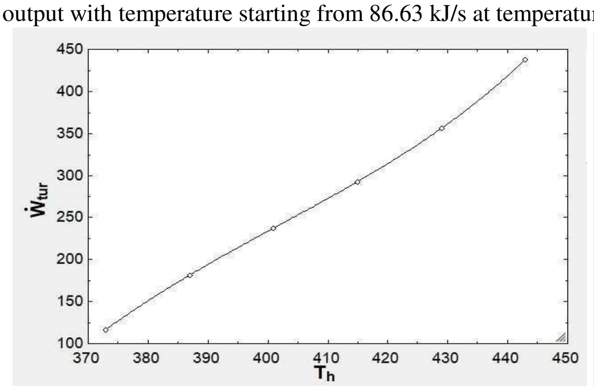


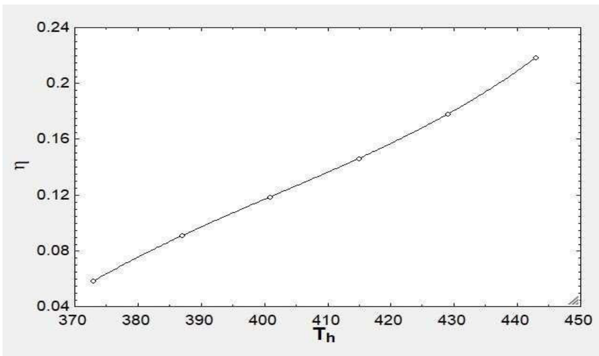
The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 1.343 % at temperature 383 K to 20.43 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 26.99 kJ/s at temperature 387K to 408.7 kJ/sec at temperature 443K



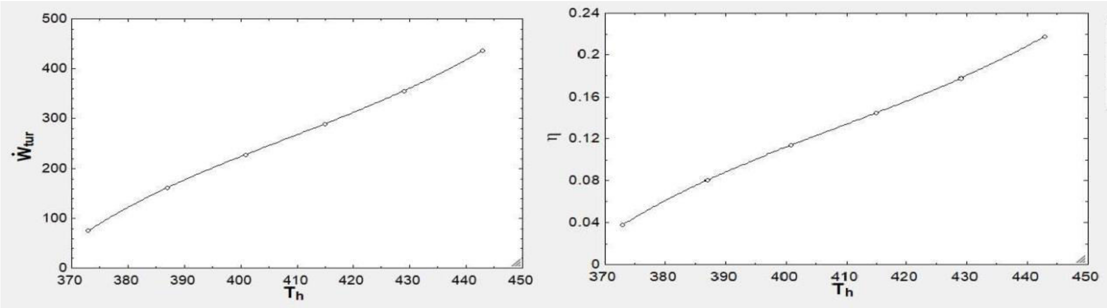


The efficiency vs temperature plots shows that efficiency keeps on increasing with temperature starting from 4.312 % at temperature 387 K to 21.05 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 86.63 kJ/s at temperature 387K to 421.2 kJ/sec at temperature 443K.

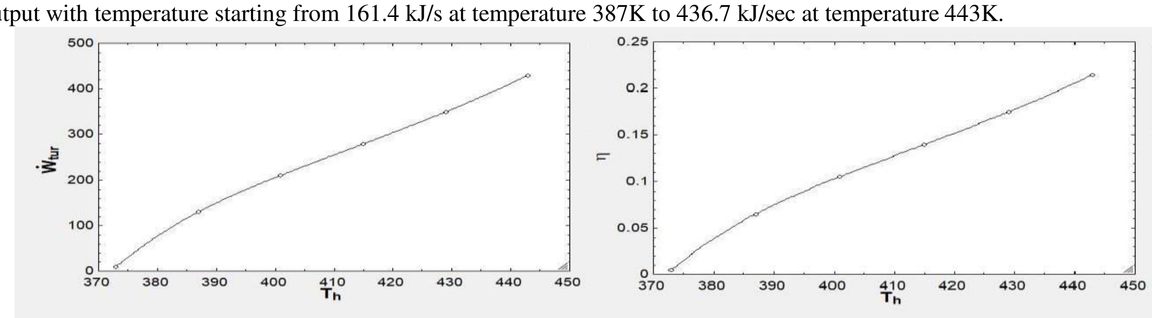




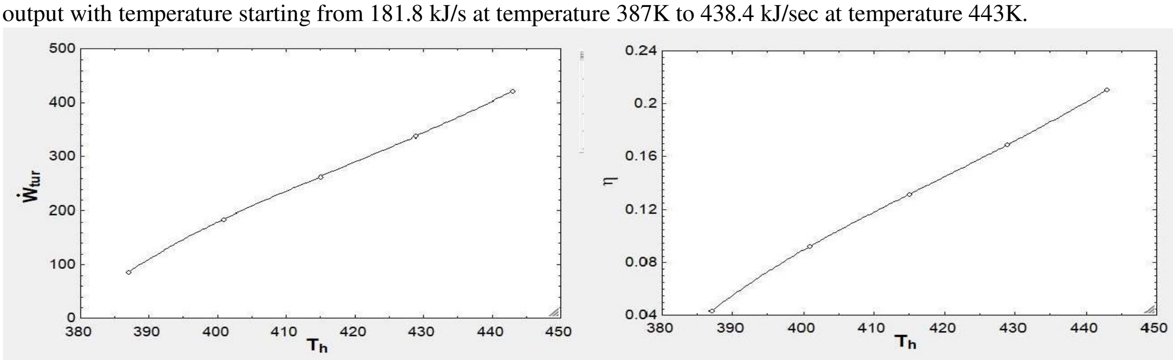
The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 6,48 % at temperature 387 K to 21.51% at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 9.7 kJ/s at temperature 387K to 430.4 kJ/sec at temperature 443K.



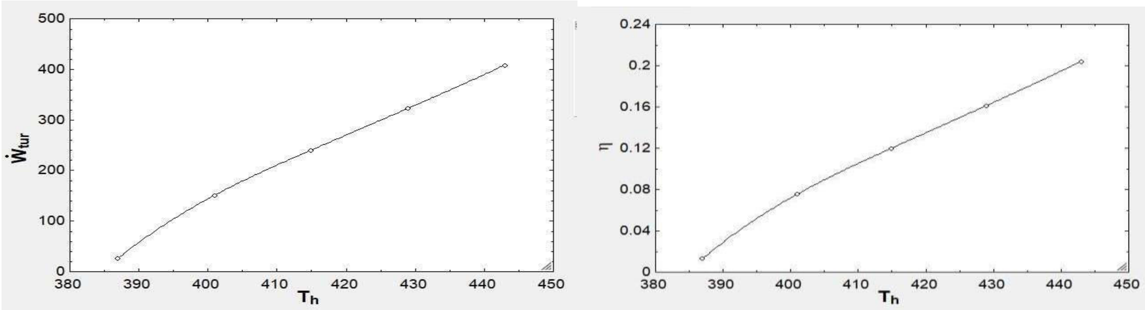
The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 8.06 % at temperature 387 K to 21.81 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 161.4 kJ/s at temperature 387K to 436.7 kJ/sec at temperature 443K.



The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 9.08 % at temperature 387 K to 21.88 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 181.8 kJ/s at temperature 387K to 438.4 kJ/sec at temperature 443K.



The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 9.5 % at temperature 387 K to 21.79 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 190.4 kJ/s at temperature 387K to 437.0 kJ/sec at temperature 443K.



The efficiency v/s temperature plots shows that efficiency keeps on increasing with temperature starting from 9.2 % at temperature 387 K to 18.05 % at temperature 443K. The work output v/s temperature plot shows an increasing trend of work output with temperature starting from 184.3 kJ/s at temperature 387K to 362.1 kJ/sec at temperature 443K.

7. Conclusion

In the thermodynamic analysis of Kalina cycle for low temperature ranges for application to geothermal energy source it was found that at a given pressure both the work output and efficiency of cycle would increase with increase in temperature irrespective of the given operating pressure. One would expect the same behavior with pressure variations but the results obtained show that the increasing trend of efficiency and work output is only up to a point at which these quantities are maximum after which they start to decrease. This value of pressure is called as optimum point. Moreover, the optimum point is not always the same for different values of temperature and increases with increase in temperature. The optimum efficiency obtained in this study was 21.88% at a temperature of 443k and 30 bar. This study shows that the efficiency is a function of both operating temperature and pressures at the exit of HRVG. Another conclusion is that the efficiency and work output are both function of ammonia mass fraction in basic solution also. This shows that after a point of minimum efficiency the quantity increases with increase in ammonia mass fraction

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