

## Kalina Cycle Thermal Analysis Using Heat Recovery Process

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### ABSTRACT

*It is not possible to measure very high temperature with help of physical temperature measuring probes, so in order to get temperature of flue gases, inverse heat transfer theory is applied. Measuring the temperature on outside wall of pipe from which flue gases are going out, it is possible to get calculated values of flue gases (which is not possible to get with physical probe) using inverse heat transfer analysis. From this, heat flux is calculated and that heat flux is suggested to be applied to run Kalina cycle. Furthermore, Kalina cycle thermal analysis is performed to understand the full working by applying first law of thermodynamics.*

**Keywords:** Kalina cycle, thermal analysis, gases, heat transfer

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### INTRODUCTION

There is always a rise in usage of energy and along with, the cost usage also increases. The waste heat which is released directly into the atmosphere, if recovered or used, then the thermal efficiency of any system or power plant increases and the cost of consumption of energy also reduces. Kalina and organic rankine cycle provides solution to recover low temperature waste heat which is actually being thrown away by industry into the atmosphere. Let us discuss something about organic rankine cycle. Organic Rankine Cycle (ORC) use organic substance like hydrocarbons or even refrigerants as a working fluid to our cycle. Orc's actually are rankine cycles but since the working fluids are organic, so the name is ORC. Kalina cycle was developed by Alexander Kalina in 1980 which was aqueous. Ammonia mixture as a working fluid.

### LITERATURE SURVEY

In STPP heat transfer fluid/working fluid like (oil synthetic, molten suit). First collect the energy from the solar radiation and operate at 400°C but not required us much

turbine. Inlet and pressure so Kalina cycle operates in bottoming cycle and increase the turbine inlet and pressure. In STPP by K.C. at 40 bar turbine inlet pressure & by 0.8 fraction of ammonia gives highest performance ratio. By varying temperature (of inlet turbine) 450°C solar and increase up to 550°C by K.C. by using 2 recuperate pump and 2 condensers in K.C [1]. Nowadays there is need in efficiency design reliable cost effective energy contusion system are concern so by using Kalina cycle fulfill this need. How grade heat recovered by system after ECP (Electro Static Prospector) and before chimney having temperature around 134.5°C and above main cycle having inlet turbine temperature 500°C (approx.) and pressure is 221/220 bar (below critical pressure). Around 500 mw plant having efficiency 29% and improved by Kalina up to 1 to 2% by using low grade heat with NH<sub>3</sub>H<sub>2</sub>O mixture cycle [2]. Vast amount of renewable energy sources such as solar thermal biomass, industrial waste heat used in Kalina cycle Kalina cycle is modified rankine cycle in which water ammonia used

as working fluid and being heated by low grade waste heat Kalina cycle restricted to 300–400°C in maximum and 100–120°C temperature in small power plant units. Kalina cycle used as bottoming cycle and increase the performance of power plant [3]. Kalina Cycle use ammonia and water as mixture and by considering the diesel engine plant and K.C. produce 1615 kW of power whereas ORC cycle produce 1603 kW also K.C. used required high pressure approx. 100 bar in K.C. and 10 bar in ORC, so for low and medium level plant K.C. is best at 0.89 fraction of ammonia by turbine exhaust is 346°C at 35 kg/sec mass flow rate [4]. Kalina cycle 11 mention above is used for low temperature heat source and by using water ammonia mixture at different fraction of ammonia at different evaporation pressure. And here they conclude at  $p=3$  mpa,  $\eta_{max}$  at  $y=0.89$  and for  $p=2.5$  mpa  $\eta_{max}$  at  $y=0.68$   $p=2$  mpa,  $\eta_{max}$  at  $y=0.6$  [5]. In the plant discussed in [6], heat is supplied by solar radiation and auxiliary heater supplied it into evaporator. Here for one condenser used and it also fin type by cooling air so we use two separators to separate lean and weak mixture of  $NH_3H_2O$ . Also, Kalina cycle is most preferable for low level as well as medium level of evaporation pressure and review state that by 10 degree tilting the solar radiation plates more power produce using this K.C. cycle.

## METHODOLOGY

The following governing equation for 1 dimensional transient heat conduction equation with boundary condition has been applied.

$$\frac{\partial y^2}{\partial x^2} = \frac{1}{\alpha} \frac{\partial t}{\partial \tau}; t > 0 \quad (1)$$

The span of the wall is having the length 'L'.

The boundary conditions are as under:

$$\text{Initial condition: } T(x,t) = T_0 \quad (2)$$

This means that the temperature is assumed to have some value that is constant. On the right face of the wall, the heat flux is assumed to be zero or insulated wall boundary condition.

$$\frac{\partial t}{\partial x} = 0; x=L; t>0 \quad (3)$$

On the left side of wall, heat flux is transferred to the wall.

$$K \frac{\partial t}{\partial x} = q; x=0, t>0 \quad (4)$$

Here, K is thermal conductivity.

Equation (1) can be discretized as under, One dimensional finite difference equation using implicit scheme can be given as under;

$$T_i^{n+1} - T_i^n / \alpha \Delta t = T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1} / (\Delta x)^2$$

$$\text{Let } \frac{\alpha \Delta t}{\Delta x^2} = s = \text{discretization factor} \\ T_i^{n+1} - T_i^n = (T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1}) \quad (3)$$

For the first node, we use the boundary condition as given by equation (4)

$$K \frac{\partial T}{\partial x} = q; \text{ discretizing this equation,} \\ K T_{i+1}^{n+1} - T_{i-1}^{n+1} / 2\Delta x = q \quad (5)$$

Putting  $i = 0$  for the first node,

$$T_1^{n+1} - T_{i-1}^{n+1} = 2\Delta x q \quad (6)$$

$$T_{i-1}^{n+1} = T_1^{n+1} - 2\Delta x q \quad (7)$$

Putting  $i=0$  in equation (5) and substituting the -1<sup>th</sup> node which is dummy node of equation (7) in (5),

$$T_0^{n+1} - T_0^n = (T_1^{n+1} - 2\Delta x q + T_1^{n+1} - \frac{2\Delta x q}{n}) \quad (8)$$

Hence, equation 8 is for first node calculation

Similarly, applying boundary condition (3) on the last node.

$$\frac{\partial t}{\partial x} = 0; T_{i+1}^{n+1} - T_{i-1}^{n+1} / 2\Delta x = 0 \\ T_{i+1}^{n+1} = T_{i-1}^{n+1} \quad (9)$$

Hence, putting equation (8) in (5)  
 $T_i^{n+1} - T_i^n = (T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1})$  (10)

Equation is for any node between first to last node, equation (8) is for first node and equation (10) is for last node,

The equations that are discussed up till now are for direct problem.

The next discussion is for the inverse analysis of the application considered.

These temperature measurements are done with respect to the time. So inverse heat transfer analysis is applied means knowing the temperature of outer wall, the inner wall temperature is calculated as well as the heat flux of flux gases which are passing through in contact with inner wall is calculated. This heat flux is our criterion to know quantitatively that we know that how much heat is available for preheating purpose.

Basically the inverse problem will assume some value of temperature and heat flux at inner wall and do further calculations following previous equations to get temperature at outermost wall. Now, the temperature at outermost wall we already know by [7] which are measured. Hence, our objective function is minimization of error which is given as under;

$$F(t) = \int_{t=0}^{t=tf} \{(mct) - T_{\text{calculated}}(t)\}^2 dt \quad (11)$$

$m(t)$  = measured temperature

$T_{\text{calculated}}$  = calculated temperature

Many iterations are done in order to minimize the function given in equation (11)

Now that we have the objective function, the requirement is to get the temperatures at each point on the slab or gas side such

that the objective function is fulfilled or the calculated temperature at right end becomes equal or near the range decided to the measured temperature. In order to get quick situation, conjugate gradient method has a sensitivity problem which has sensitivity function of  $\Delta T$ . In order to explain this, the heat flux is used to have some value  $q$  on gas side which is given some perturbation of  $\Delta q$  as a result the temperature in direct problem is changed by  $\Delta T$ , hence replacing the heat flux in direct problem equations (i.e.  $q$  by  $q + \Delta q$  and  $T$  by  $T + \Delta T$ ) and then if we subtract from direct equations, we get the sensitivity equations.

$$\partial^2 \Delta T / \partial x^2 = 1/\alpha (\partial \Delta T / \partial t) \quad (12)$$

Boundary conditions are as follows:-

$$\Delta T = 0; t = 0; \text{ at all points} \quad (13)$$

$$\partial \Delta T / \partial x = 0; \text{ at } x = L \text{ for all times considered} \quad (14)$$

$$\& \partial \Delta T / \partial x = \Delta q / k \quad (15)$$

For  $x = 0$  at all times

Sensitivity problem does not give the direction in which the equation needs to go say for example  $\Delta T$  needs to be positive or negative in order to satisfy the objective function. It requires a large computation time. In order to reduce the computation time, adjoint problem was introduced which had Lagrange multiplier [2] ' $\lambda$ ' which is used to quickly minimize the objective function. It has the following set of equations [2]:

$$\partial^2 \lambda / \partial x^2 = -1/\alpha \partial \lambda / \partial t; t > 0 \quad (16)$$

Boundary conditions:-

$$\lambda = 0; \text{ initial condition at all points} \quad (17)$$

$$\partial \lambda / \partial x = -2[T_{\text{calculated}} - M] / k \quad (18)$$

at  $x = L$  at all time

Where  $M$  is the measured temperature  
 $\partial \lambda / \partial x = 0; \text{ for } x = 0 \text{ at all times.}$

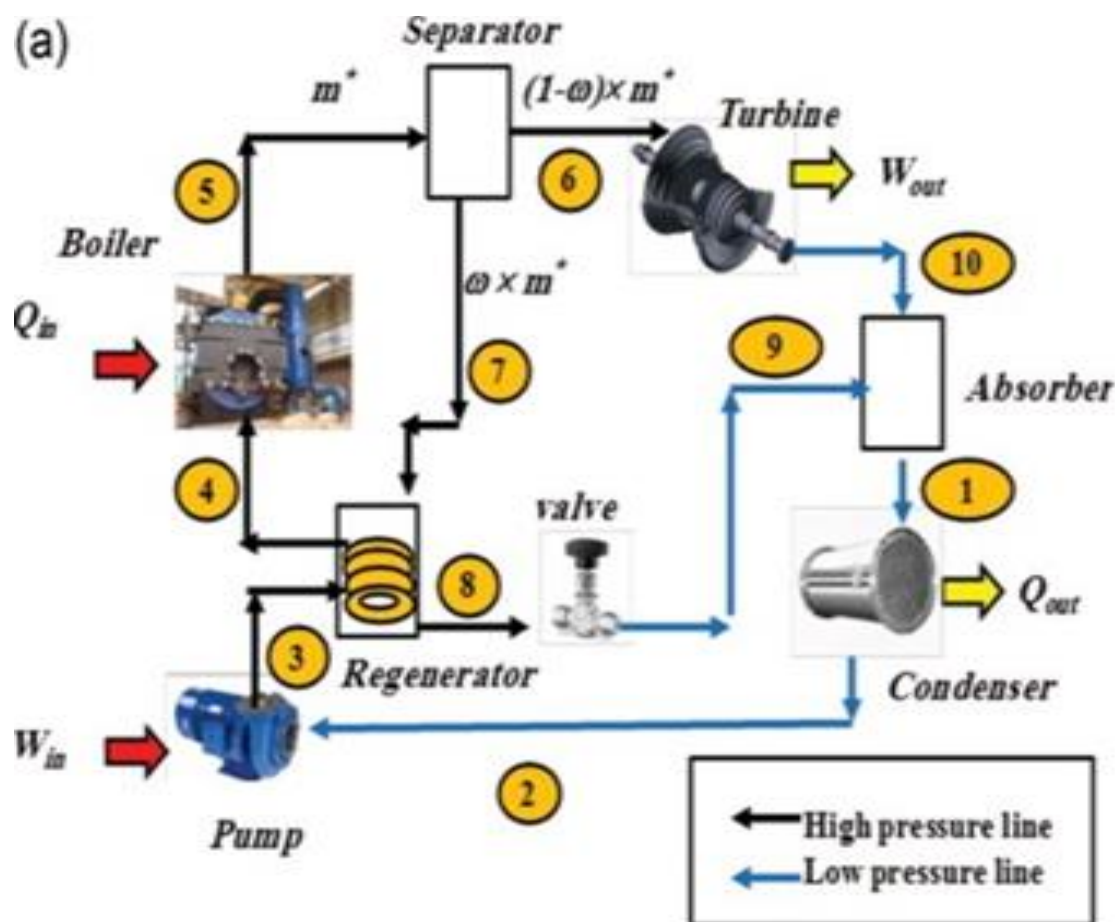


Fig. 1. Kalina cycle KCS11.

**Procedure To Solve The Equations**

Suppose that heat flux is assumed at a moment then it is required to

- By finite difference method solving the direct equations (since q is known which is assumed in the beginning)
- New value for the heat flux is calculated by following equation :-

$$q^{i+1} = q^i - L^j \quad (19)$$

L is calculated by:

$$L^j = \int [T_{\text{calculated}} - M] \Delta T \partial t / (\Delta T)^2 \partial t \quad (20)$$

j is the iteration, L is the step size to be taken [z]. it means how much maximum step size to be taken to reach the measured temperature or achieve objective function [z]. Now, the direction, .i.e., ΔT positive or negative to achieve the objective function is given by following equation:

$$j^i = \nabla f[t^i] + \gamma^j j^{i-1} \quad (21)$$

The conjugate gradient is now obtained by the following equation[z]:-

$$\gamma^i = \int [\nabla f(t^i)]^2 dt / [\nabla f[t^{i-1}]]^2 dt \quad (22)$$

Hence, direct problem is solved assuming arbitrary value of heat flux q, then the adjoint and conjugate equations are solved after that sensitivity equations are solved and then new q at i+1 step is obtained. These iterations are carried on and on until calculated temperature and measured temperatures are almost equal.

In order to calculate the heat flux and heat transfer for coefficient on the gas side, the following equation was proposed by R.C. Mehta.

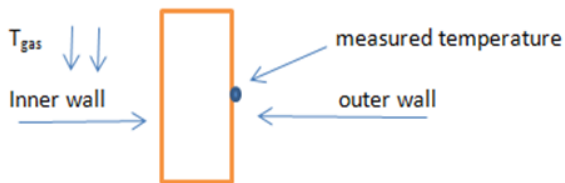
$$h = \left( \frac{41.8565}{(Dt)^{0.2}} \right) \cdot \left( \frac{\mu}{Pr} \right)^{0.2} \cdot \left( \frac{Pc \cdot g}{C} \right)^{0.8} \cdot \left( \frac{Dr}{r^{0.1}} \right) \cdot \left( \frac{At}{A} \right)^{0.9} \quad (\xi)$$

$$\xi = \frac{1}{\left[ \frac{T_w}{2T_s} \left( 1 + \frac{r-1}{2} M^2 \right) + 1/2 \right]^{0.68} \left( 1 + \frac{r-1}{2} M^2 \right)^{0.12}}$$

$$q = h (T_{\text{gas}} - T_{\text{wall}})$$

$T_{\text{wall}}$  = temperature of the wall adjacent to the gas flowing.

If the heat flux obtained by the calculation is used for the heat supplied for Kalina cycle, then useful work may be obtained.



The following analysis is the first law of thermodynamics applied to Kalina cycle (Figure 1).

### State 1

$P_1 = P_2$  (Isobaric process so at the inlet and the outlet of the condenser pressure difference remain constant)

$$h_1 = (w \times h_g) + (1 - w) \times h_{10}$$

Fluids of outlet of turbine + fluid comes from throttle valve,

Where,  $H_1$  = enthalpy of inlet of condenser

In this cause inlet fluid is addition of the fluid from the outlet of the turbine and fluid from the throttle valve.

$w$  = Fraction of mass  $h_g$  = Enthalpy at exit of turbine

$(1 - w)$  = Fraction mass after separator and after throttle valve which enters in condenser

### State 2

Temperature at the exit of the condenser is addition of sink temperature and pinch temperature

$$T_2 = T_{\text{sink}} + T_{\text{pinch}}$$

Pinch point it is a minimum allowable difference in heat exchanger unit

If pinch point is lower total heat received in heat exchanger is higher

Optimum value is at 8 to 10°C.

Also pinch point temperature is rate of exhaust of temperature between hot and cold fluid

### State 3

$$XX_2 = X_{12} = X_1$$

Because mass fraction from leaving of condenser is same from inlet of pump.

$$W_{\text{pump}} = \frac{V_2 (P_{\text{max}} - P_2) \times 100}{ETA_{\text{pump}}}$$

$V$  = Specific volume in

$P$  = Pressure

$ETA_{\text{pump}}$  = Isentropic efficiency of pump

### State 4

Since exit of pump pressure also increase so enthalpy also increases.

$$P_3 = P_{\text{max}}$$

$$X_3 = X_2 \text{ (Mass fraction does not change)}$$

$$h_3 = h_2 + w_{\text{pump}}$$

$$w_{\text{pump}} = v(P_{\text{max}} - P_2) \times 100$$

$Q_{\text{regen}}$  Is heat added in heat exchanger of liquid/fluid that is coming from separator.  $H_4$  Is found by change in enthalpy in cold fluid in regenerator is equal to change in enthalpy of heat fluid steam.

$$h_3 = h_{\text{reg}} \quad h_4 = q_{\text{regen}} + h_3$$

From 3 to 4 mass fraction and pressure remains same.

$$P_4 = P_3 \quad X_4 = X_3$$

### State 5 (exit of evaporator)

$$T_5 = T_{\text{source}} - T_{\text{pinch}} \quad X_5 = X_4$$

Mass fraction remains same from 4 to 5 and

$P_5 = P_4$  Also pressure from 4 to 5 remain same

**State 6**

$$T_6 = T_5 \quad P_6 = P_5$$

Temperature and pressure remains same to 5 to 6 and

Assume that heat capacity is equal to 1.

$$Q_{U_6} = 1$$

**State 7**

Entry of hot fluid into regenerator

Which preheat by pump?

$$T_7 = T_5 \quad P_7 = P_5 \quad Q_{U_7} = 0$$

The exit temperature for regenerator is set higher than condenser temperature due to pinch point.

**State 8** (before entry of throttle valve)

$T_8 = T_3 +$  (same valve which higher than condenser temperature)

$$P_8 = P_7 \quad X_8 = X_7$$

$$q_{reg} = w(h_7 - h_8)$$

Where, w = Mass of fraction

**State 9** (exit state of solution from heat exchanger regenerator)

$$h_9 = h_8$$

$$P_9 = P_1$$

$$X_9 = X_8$$

**State 10** (after turbine and work is produce)

$$P_{10} = P_1$$

$$X_{10} = X_6$$

$$S_{10} = S_6$$

Because expansion process is isentropic  
Where isentropic efficiency of turbine.

$$h_{10} = h_6 - ETA_{turbine} \times (h_6 - h_{10})$$

**Table 1.** Validation of present work in inverse heat transfer analysis.

Time (s)	Measured temperature (K)	Calculated temperature (K)
6	326	327.78
7	342	344.52
8	356	359.81
9	380	382.57
10	402	405.2
11	425	428.37
12	440	445.8

**Table 2.** Parameters considered in analysis of Kalina cycle are as listed below.

Parameter	Range
Source temperature	330 K to 500 K
Sink temperature	280 K to 315 K
Pinch point temperature	4 K to 10 K
Maximum pressure in cycle	11 bar to 30 bar
Pump efficiency	0.5 to 1
Turbine efficiency	0.5 to 1

**Table 3.** Heat flux at inner wall.

Time (s)	Heat flux calculated (kw/m <sup>2</sup> )
6	5258
7	3300
8	3311
9	3315
10	3290
11	3280
12	2385

**RESULTS**

Result obtained from the theory applied in Kalina cycle is as listed in Figures 2 and 3. The Figure 2 is for the maximum pressure of 1500 kPa and sink temperature of 280 K. It can be observed from the Figure 2 that maximum thermal efficiency increases with increase in evaporator temperature. Furthermore, at same evaporator temperature, there is a sudden drop in thermal efficiency at a certain value of mass fraction. This drop occurs at lower values of mass fractions at higher temperatures. Validation of present work in inverse heat transfer analysis is shown in table 1, Parameters considered in analysis of Kalina cycle are as listed in table 2 and table 3 shows Heat flux at inner wall.

The Figure 3 is for the maximum pressure of 2000 kPa and sink temperature of 280 K. As the source temperature rise, the thermal efficiency also rises. The maximum thermal efficiency in relation to the ammonia mass fraction is on a sudden spike. If the working fluid mixture is too lean in relation to the ammonia mass fraction, the thermal efficiency drops rapidly, but if the working fluid mixture is a little rich in relation to the ammonia mass fraction, the thermal efficiency drops gradually as the ammonia mass fraction is increased. This indicates that for a KCS11 in operation the ammonia mass fraction of the working fluid would need to

be rich to avoid a complete loss in the thermal efficiency of the cycle do to a mixing problem

or leak. Tables 3–5 explain performance of the cycle chosen in more detail.

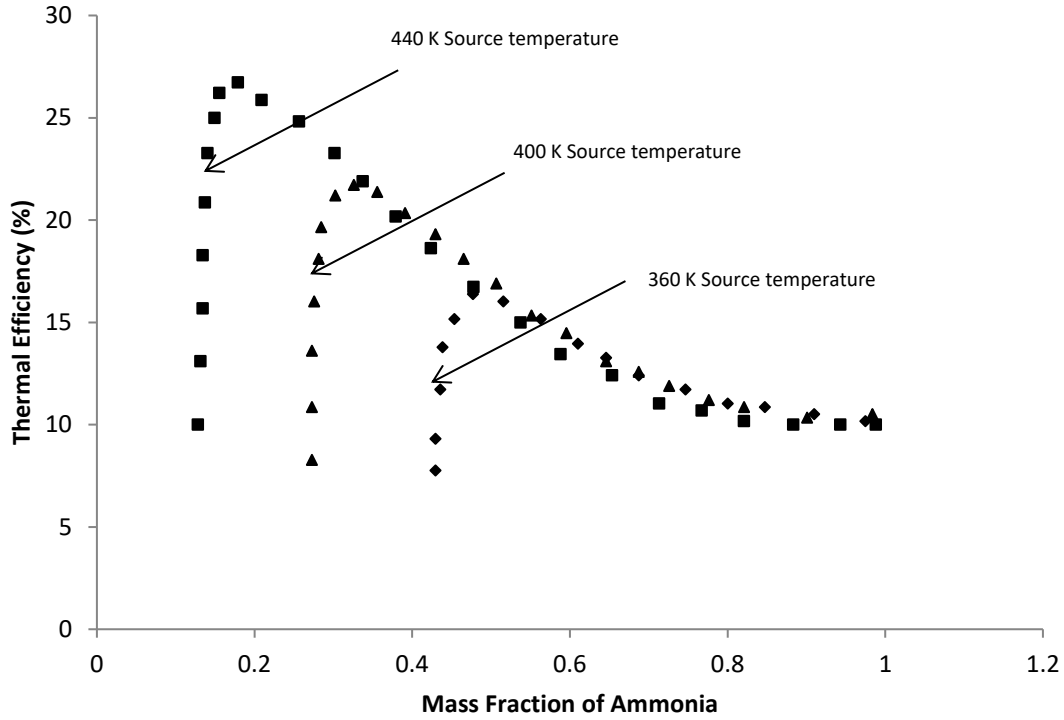


Fig. 2. Thermal efficiency versus mass fraction of ammonia (for the maximum pressure of 1500 kPa and sink temperature of 280 K).

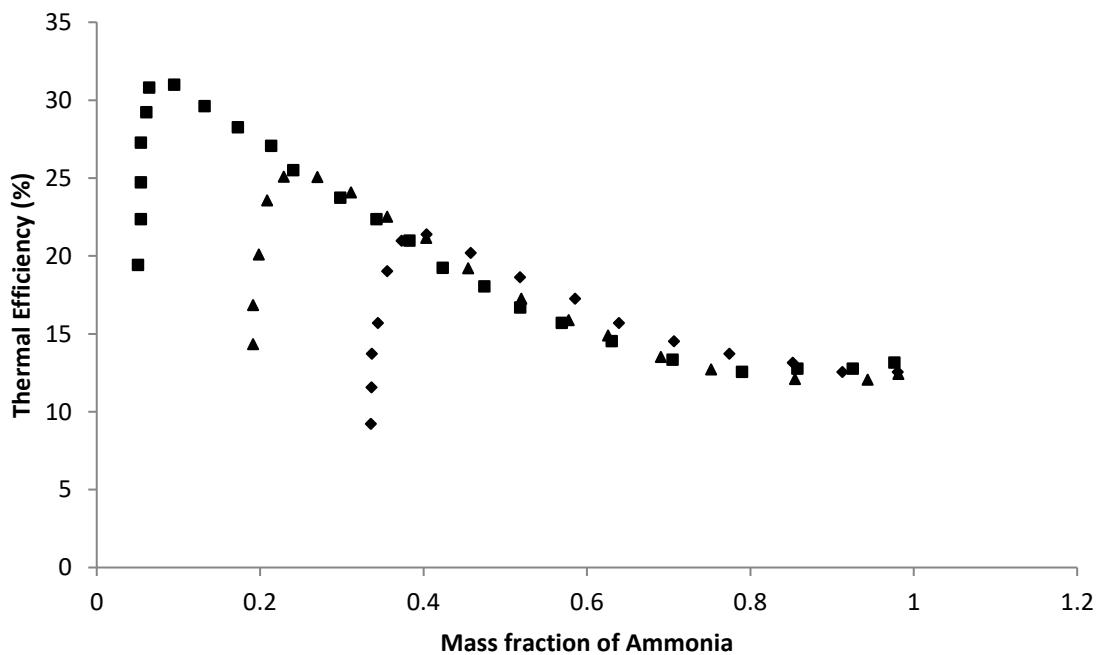


Fig. 3. Thermal efficiency versus mass fraction of ammonia (graph is for the maximum pressure of 2000 kPa and sink temperature of 280 K.)

**Table 3.** Performance of the cycle at sink temperature 10°C chosen in more detail.

Source Temp. (°C)	Sink Temperature = 10°C							
	15 bar		20 bar		25 bar		30 bar	
	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y
60	9.35	0.746	10.38	0.92	No Vapor			
80	12.25	0.589	12.56	0.687	13.11	0.799	13.78	0.911
100	15.46	0.481	15.34	0.558	15.37	0.63	15.56	0.71
120	18.64	0.385	18.34	0.457	18.13	0.517	18.01	0.576
140	21.58	0.303	21.19	0.366	20.88	0.423	20.63	0.475
160	24.39	0.218	23.86	0.285	23.16	0.315	23.15	0.384
180	27.29	0.129	26.62	0.195	26.05	0.251	25.65	0.296
200	32.01	0.021	29.62	0.101	28.79	0.159	28.26	0.207

**Table 4.** Performance of the cycle at sink temperature 17°C chosen in more detail.

Source Temp. (°C)	Sink Temperature = 17°C							
	15 bar		20 bar		25 bar		30 bar	
	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y
60	0.761	88	8.56	0.913	No Vapor			
80	10.71	0.585	10.98	0.683	11.47	0.789	12.12	0.903
100	13.98	0.478	13.87	0.554	13.9	0.632	14.07	0.702
120	17.19	0.386	16.91	0.454	16.72	0.515	16.6	0.572
140	20.18	0.297	19.79	0.366	19.47	0.415	19.25	0.473
160	23.04	0.218	22.53	0.283	22.11	0.337	21.8	0.383
180	26.06	0.128	25.35	0.195	24.81	0.249	24.36	0.296
200	30.87	0.021	28.43	0.101	27.61	0.158	27.09	0.205

**Table 5.** Performance of the cycle at sink temperature 25°C chosen in more detail.

Source Temp. (°C)	Sink Temperature = 25°C							
	15 bar		20 bar		25 bar		30 bar	
	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y	$\eta_{th}$	Y
60	5.645	0.73	6.478	0.904	No Vapor			
80	8.928	0.582	9.167	0.677	9.606	0.78	10.2	0.894
100	12.27	0.474	12.18	0.55	12.21	0.624	12.36	0.695
120	15.53	0.383	15.27	0.451	15.09	0.511	14.98	0.572
140	18.57	0.3	18.19	0.365	17.9	0.419	17.67	0.469
160	21.51	0.216	21.02	0.278	20.6	0.334	20.27	0.38
180	24.66	0.127	23.9	0.194	23.35	0.248	22.9	0.295
200	29.55	0.021	27.08	0.1	26.28	0.157	25.7	0.204

## CONCLUSION

A complete analysis for getting the flue gases temperature using inverse heat transfer analysis is done. This is accompanied by the analysis of Kalina cycle.

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