Thermodynamic Analysis of Air Refrigeration Cycle with Double Regeneration

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***Abstract:*-With the growing concern of researchers to achieve low temperature and high COP in conventional refrigeration cycles, lots of modifications has been suggested and successfully implemented in the existing refrigeration cycles except air refrigeration cycle where very few of it is available in literatures. So, in the present study for achieving the given objective a double regenerated air refrigeration cycle is considered .Its thermodynamic analysis is done from the point of view of achieving low temperature refrigeration. The exergy destruction of each of the components in the system is determined. In this arrangement the cold air leaving the refrigerated space is first used to cool the air leaving the compressor. Also some fraction of chilled air leaving the turbine is extracted for further cooling of air leaving the first heat exchanger. A simulation analysis is performed by varying the parameter such as mass extracted, the effectiveness of heat exchangers & pressure ratio to get low temperature refrigeration. The simulation is also carried out by varying above parameters to get exergy destruction of each component in the system using EES. It is investigated that by adding another heat exchanger as a regenerator the cabin temperature decreases considerably but there is a slight decrease in the COP of the cycle compared to the conventional regeneration cycle.**

The results of simulation are used to study the influence of various operating parameters such as effectiveness of heat exchangers, pressure ratio & percentage of mass extracted low temperature at the exit of turbine in order to get low temperature refrigeration. The results can be useful in the design of heat exchangers as well as control of other thermodynamic parameters to get optimum COP, as well as to get low temperature refrigeration.

I. INTRODUCTION

In this system we are using 2 regenerators. Air is first compressed in a compressor; the compressed air is then cooled in a heat exchanger (of 100% efficiency) to environment temperature. This air is then cooled simultaneously in 2 heat exchangers of effectiveness e_1 & e_2 respectively. The cooling air comes from 2 sources:-

a) Air after leaving the refrigerated space is very cold & this air is used as a cooling fluid in 1st heat exchanger.
b) Air after leaving the turbine is at very low temperature & a part of it is bled to the 2nd heat exchanger.

The air leaving the refrigerated space & the air leaving 2nd heat exchanger are mixed together in a mixing chamber , this air is then send to 1st heat exchanger. Due to multiple regeneration temperature at the entry of refrigerated space is very low, Thus Refrigerated space (cabin) can be maintained at very low temperature.

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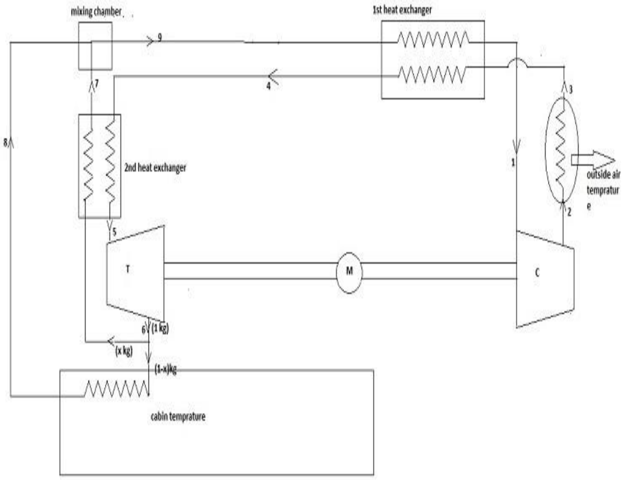

Fig 1 : Air refrigeration system with double regeneration

First law analysis of the system

Pressure ratio of both compressor & expander can be written as

$$\beta = \frac{P_H}{P_L}$$

$$\alpha = \frac{charecterstics\ gas\ constant}{specific\ heat\ at\ constant\ pressure}$$

$$\alpha = \frac{R}{C_P}$$

$$\eta_P = Polytropic\ efficiency$$

For compression process

$$\alpha_c = \frac{\alpha}{\eta_p}$$

$$\frac{T_2}{T_1} = \beta^{\alpha_c}$$

For heat transfer to atmosphere (assuming 100% efficiency)

$$T_3 = T_H$$

For expansion process

$$\frac{T_5}{T_6} = \beta^{\alpha_e}$$

Effectiveness of 1st heat exchanger

$$e_1 = \frac{T_3 - T_4}{T_3 - T_9}$$

Energy balance of 1st heat exchanger

$$T_3 - T_4 = T_1 - T_9$$

Effectiveness of 2nd heat exchanger

$$e_2 = \frac{T_7 - T_6}{T_4 - T_6}$$

Energy balance of 2nd heat exchanger

$$T_4 - T_5 = x * (T_7 - T_6)$$

Energy balance of mixing chamber

$$(1\text{-}x)*T_8 + x*T_7 = T_9$$

For refrigerated space i.e.Cabin

$$T_8 = T_L$$

Refrigeration effect can be written as

$$\text{R.E} = (1\text{-}x)*C_p * (T_8 - T_6)$$

Work done on compressor

$$W_c = C_p * (T_2 - T_1)$$

Work done by expander

$$W_T = C_p * (T_5 - T_6)$$

Net work input

$$W_{in} = C_p * (T_2 - T_1) - C_p * (T_5 - T_6)$$

Coefficient of performance can be written as

$$\text{COP} = \frac{(1-x)*C_p * (T_8 - T_6)}{C_p*(T_2 - T_1) - C_p*(T_5 - T_6)}$$

Second law analysis of the system

In the present work, a parametric study with various temperatures has been conducted to determine the performance evaluation of air refrigeration system with double regeneration.

The following assumptions are made to simplify exergy analysis.

1. All components are assumed to be a steady flow and steady-state process.
2. The changes in the kinetic energy and the potential energy of the components are negligible.
3. The pressure drops and heat loss in the piping connecting the components are negligible.
4. Heat exchangers are internally reversible

1) Exergy analysis of compressor

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$s_{g1} = c_p \cdot \ln\left[\frac{T_2}{T_1}\right] - R \cdot \ln(b)$$

$$X_{d1} = T_0 * S_{gen}$$

2) Exergy analysis of cooler

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$s_{g2} = c_p \cdot \ln\left[\frac{T_3}{T_2}\right] + \frac{c_p \cdot (T_2 - T_3)}{T_3}$$

$$X_{d2} = T_0 * S_{gen}$$

3) Exergy analysis of 1st Heat exchanger

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$\dot{s}_{g3} = c_p \cdot \ln\left[\frac{T_4}{T_3}\right] + c_p \cdot \ln\left[\frac{T_1}{T_9}\right]$$

$$X_{d3} = T_0 * S_{gen}$$

4) Exergy analysis of 2nd Heat exchanger

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$\dot{s}_{g4} = c_p \cdot \ln\left[\frac{T_5}{T_4}\right] + x \cdot c_p \cdot \ln\left[\frac{T_7}{T_6}\right]$$

$$X_{d4} = T_0 * S_{gen}$$

5) Exergy analysis of Turbine

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$\dot{s}_{g5} = c_p \cdot \ln\left[\frac{T_6}{T_5}\right] - R \cdot \ln\left[\frac{1}{b}\right]$$

$$X_{d5} = T_0 * S_{gen}$$

6) Exergy analysis of Refrigerator

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$\dot{s}_{g6} = (1 - x) \cdot c_p \cdot \ln\left[\frac{T_8}{T_6}\right] - \left[\frac{(1 - x) \cdot c_p \cdot (T_8 - T_6)}{T_8}\right]$$

$$X_{d6} = T_0 * S_{gen}$$

7) Exergy analysis of Mixing Chamber

$$S_{gen} = \Delta S_{sys} + \Delta S_{sur}$$

$$\dot{s}_{g7} = (1 - x) \cdot c_p \cdot \ln\left[\frac{T_9}{T_8}\right] + x \cdot c_p \cdot \ln\left[\frac{T_9}{T_7}\right]$$

$X_{des7}=T_0 * S_{gen}$

8) Total Exergy destroyed=Exergy destroyed in compressor + Exergy destroyed in cooler + Exergy destroyed in 1st heat exchanger + Exergy destroyed in 2nd heat exchanger + Exergy destroyed in turbine + Exergy destroyed in refrigerator(cabin) + Exergy destroyed in mixing chamber

$$E_{dt} = X_{d1} + X_{d2} + X_{d3} + X_{d4} + X_{d5} + X_{d6} + X_{d7}$$

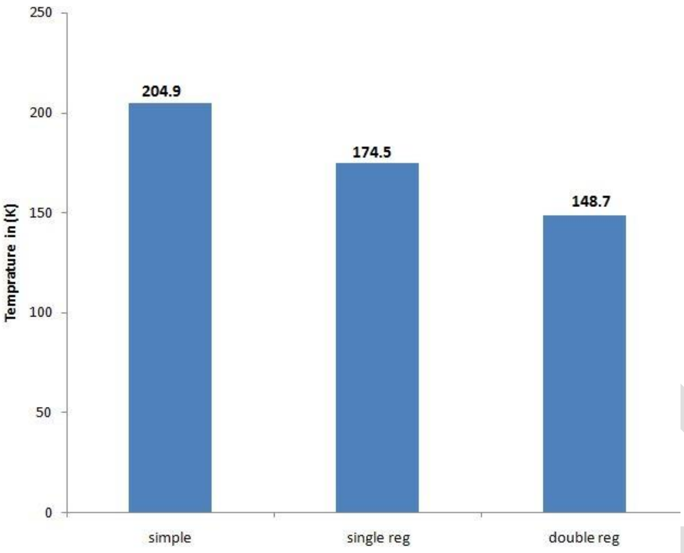

Fig 2 Temperature at exit of turbine (in K) in the three systems

It is clear from the above that to achieve deep freeze refrigeration system temperature at the exit of expander should be very low. In simple system (without using regeneration) this temperature is high so deep freeze is not possible. In double regeneration by controlling the mass fraction very low temperature can be produced. By extracting 40 % of mass for regeneration, temperature of (148.7 K) is produced at turbine exit, so deep freeze condition can be achieved inside the cabin.

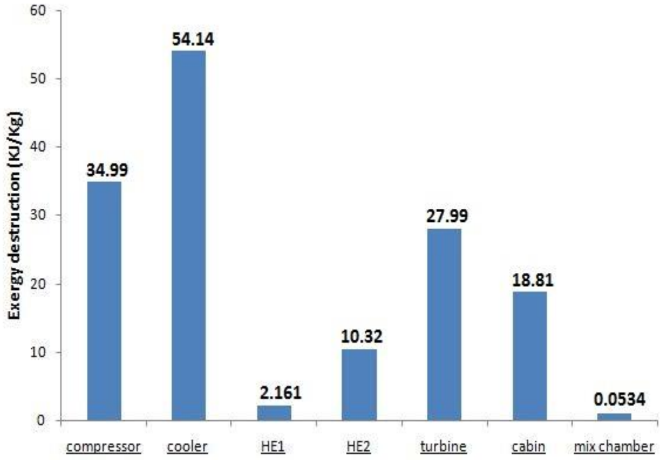

Fig 3 Exergy destruction (in KJ/Kg) of each component in system

It is clear from the above figure that almost 36% of total exergy is wasted in cooler .Exergy destructed in cooler is highest (54.14) after that it is high in compressor (34.99). These components should be thus designed properly in order to enhance its exergy utilization.

Variation of COP with effectiveness of regenerator

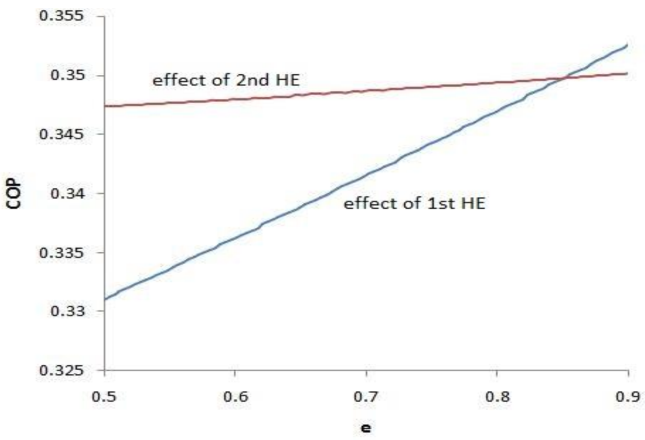

Fig 4 COP vs effectiveness of 1st & 2nd HE in double regeneration system

From the graph of COP vs effectiveness it can be seen that by increasing the effectiveness of either the 1st heat exchanger or the 2nd heat exchanger the COP increases. With increase of the effectiveness of first heat exchanger the COP increase at a high rate (linear increase). With increase of effectiveness of 2nd heat exchanger also the COP is increasing .However the rate of increase is negligible as compared the increase in first heat exchanger.

Variation of COP with percentage of mass extracted for 2nd regenerator

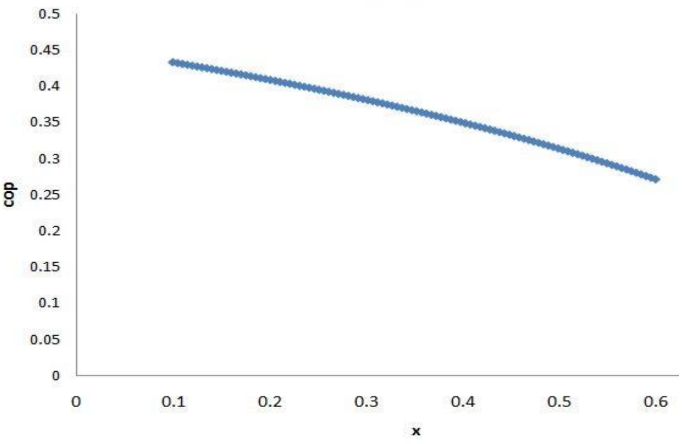

Fig 5 COP vs percentage of mass extracted for 2nd regenerator

From fig it is obvious that as the percentage of mass extracted in the 2nd regenerator goes on increasing the COP goes on reducing. However to obtain low temperature refrigeration more & more mass has to be extracted for the 2nd regeneration process. If 10 % of mass is extracted the COP is 0.4332 & If 60 % of mass is extracted the COP is 0.271.

Variation of Turbine exit temperature with effectiveness of regenerator

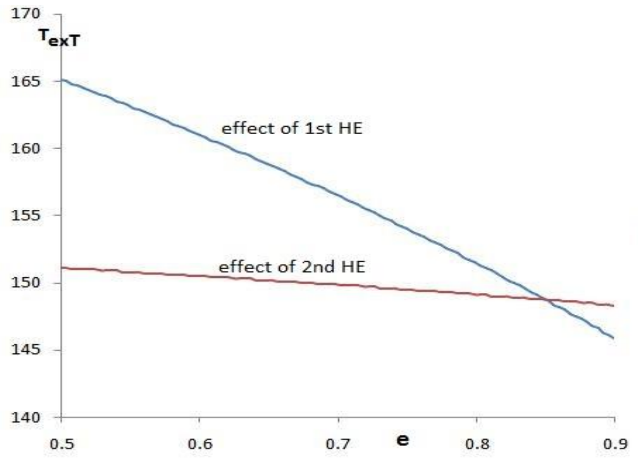

Fig 6 Turbine exit temperature vs effectiveness of heat exchanger

As the effectiveness of heat exchanger increases the turbine exit temperature decreases .With increase of effectiveness of 1st heat exchanger the rate of decrease in turbine exit temperature is much more as compared to that of 2nd heat exchanger(as the slope in 1st case is more steep).

Variation of Turbine exit temperature with percentage of mass extracted for second stage regeneration

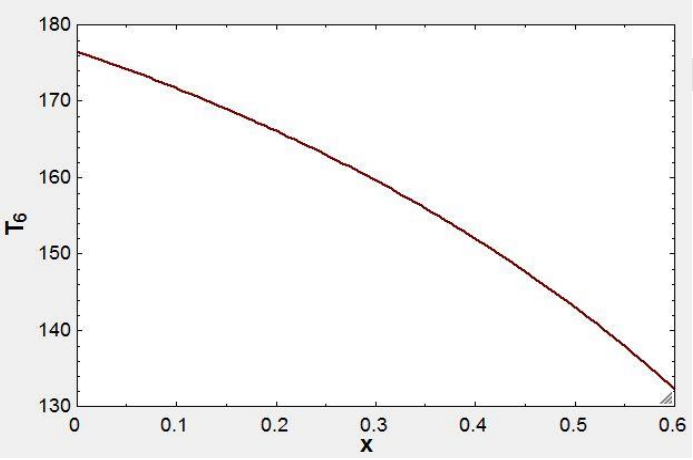

Fig 7 Turbine exit temperature vs percentage of mass extracted for 2ndheat exchanger

As the mass fraction extracted becomes more & more the turbine exit temperature decreases more & more rapidly. Although the numerical value of COP goes on decreasing but the decrease in turbine exit temperature will make deep freeze possible.

If 10 % of mass is extracted the turbine exit temperature is 170.1 k & If 60 % of mass is extracted the turbine exit temperature is 133.1 k.

Variation of Exergy destruction of all the components with effectiveness of HE 1

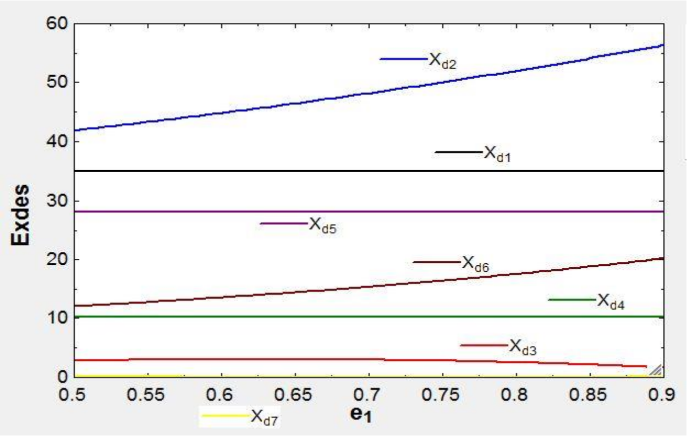

Fig 8 Exergy destruction of individual components vs effectiveness of first HE

From the above figure it is clear that as the effectiveness of 1st heat exchanger increases the exergy destruction in each component shows different trend.

In compressor, heat exchanger 2 & turbine exergy destruction remains constant with the change in effectiveness of 1st heat exchanger.

The rate of increase of exergy destruction is highest in cooler, after that it is in cabin & then heat exchanger 1 & mixing chamber respectively.

Although mixing chamber is highly irreversible but its exergy destruction value is coming low because we have neglected the pressure head loss in the connecting pipes.

Variation of Exergy destruction of all the components with effectiveness of HE 2

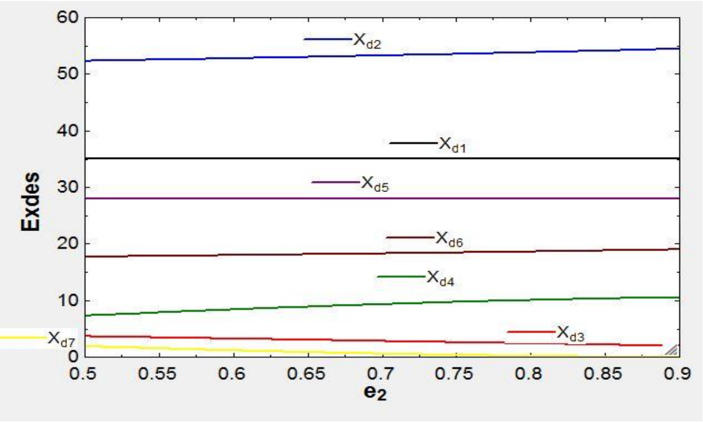

Fig 9 Exergy destruction of individual components vs effectiveness of second HE

From the above figure it is clear that as the effectiveness of 2nd heat exchanger increases the exergy destruction in 1st heat exchanger & mixing chamber goes on reducing & in remaining components it goes on increasing

The rate of increase of exergy destruction is highest in cooler, after that it is in compressor& then turbine , cabin & heat exchanger 2 respectively.

Although mixing chamber is highly irreversible but its exergy destruction value is coming low because we have neglected the pressure head loss in the connecting pipes.

Variation of Exergy destruction of all the components with percentage of mass extracted for 2nd state regeneration

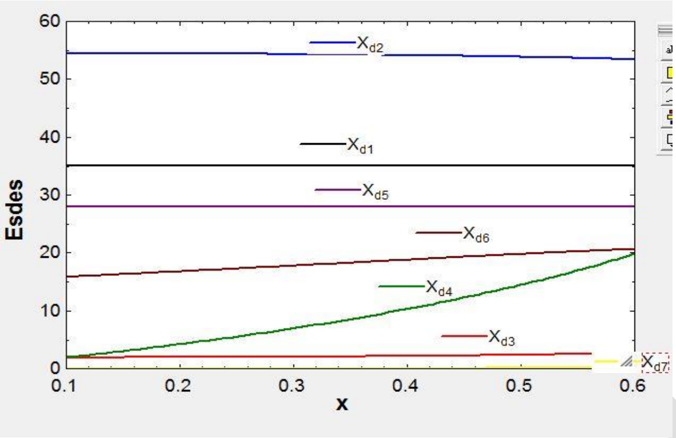

Fig 10 exergy destruction of individual components vs percentage of mass extracted

From the above figure it is clear that as the effectiveness of 1st heat exchanger increases the exergy destruction in each component shows different trend.

The exergy destruction in compressor & turbine remains constant.

The exergy destruction in HE 1 , HE 2, cabin & Mixing chamber increases. The rate of increase is highest in heat exchanger 2.

The exergy destruction in cooler decreases.

Variation of Exergy destruction of all the components with change in pressure ratio.

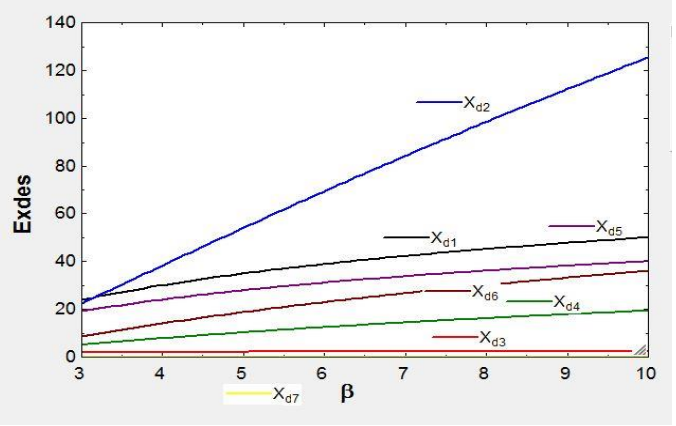

Fig 11. Exergy destruction of individual components vs pressure ratio

With increase in pressure ratio exergy destruction in each component goes on increasing.The increase is highest in cooler followed by compressor, turbine ,cabin , HE 2, HE 1 & mixing chamber respectively. Since in cooler heat is transferred to atmosphere so it is highly irreversible process & as the pressure ratio increases this irreversibility goes on increasing so highest exergy destruction is observed.

Although mixing chamber is highly irreversible but its exergy destruction value is coming low because we have neglected the pressure head loss in the connecting pipes.

Variation of Total Exergy destruction with effectiveness of HE 1

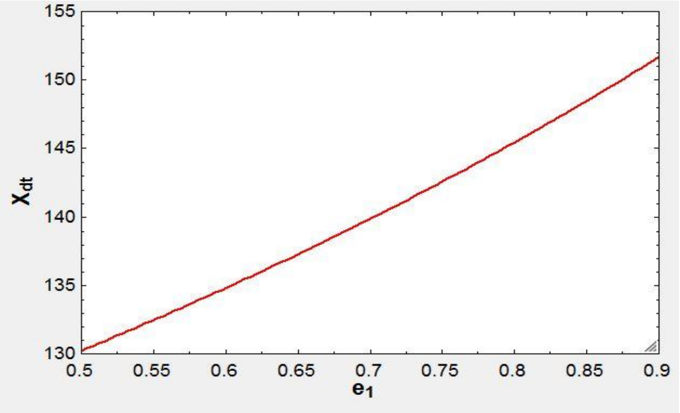

Fig 12 Total exergy destruction(X_{dt}) vs effectiveness of first HE

The graph shows us the values of change in total exergy destruction due to the change in effectiveness of first heat exchanger. From graph it is obvious that as the effectiveness of heat exchanger increases the total exergy destruction goes on increasing. It can be seen from graph that up to a certain value of effectiveness of heat exchanger (almost 0.62) there is linear increment in the value of total exergy destruction ,after that the rate of increase in exergy destruction value increases.When the effectiveness of heat exchanger is 0.5 the value of total exergy destruction is 130.4 (KJ/Kg) & when the effectiveness of heat exchanger is taken to be 0.9 total exergy destruction is 152.3 (KJ/Kg).

Variation of total Exergy destruction with effectiveness of HE2

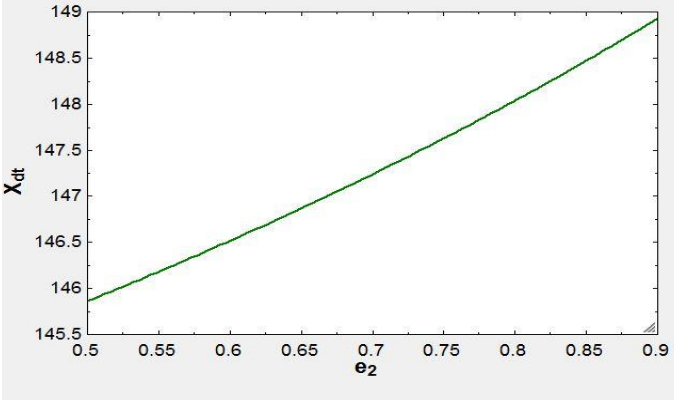

Fig 13 Total exergy destruction(X_{dt}) vs effectiveness of second HE

The graph shows us the values of change in total exergy destruction due to the change in effectiveness of second heat exchanger. From graph it is obvious that as the effectiveness of heat exchanger increases the total exergy destruction goes on increasing. When the effectiveness of heat exchanger is 0.5 the value of total exergy destruction is 145.8 (KJ/Kg) & when the effectiveness of heat exchanger is taken to be 0.9 total exergy destruction is 148.3 (KJ/Kg).

Thus due to the increase in effectiveness of second heat exchanger the total exergy destruction value increases by small amount only.

Variation of total Exergy destruction with mass fraction extracted for 2nd HE

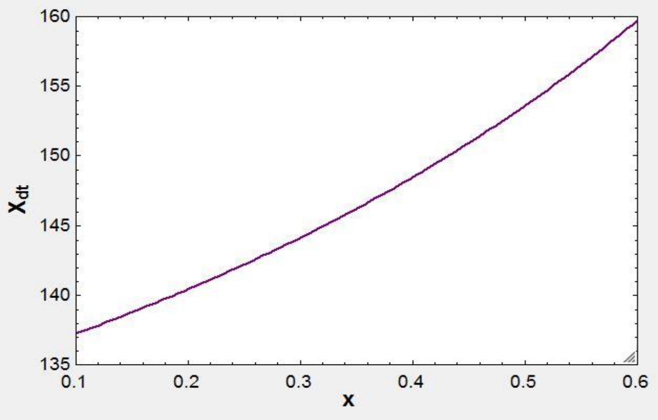

Fig 14 Total exergy destruction(X_{dt}) vs fraction of mass extracted

If the fraction of mass extracted for second state regeneration increases the total exergy destruction value increases. To maintain low temperature in the cabin the temperature at the exit of turbine should be very less therefore more mass has to be extracted & hence exergy destruction will be high.

If 10% of mass is extracted exergy detruction is 137.5 (KJ/Kg), the rate of exergy destruction goes on increasing with increase in percentage of mass extracted. At 60 % its value is 160(KJ/Kg).

Variation of total Exergy destruction with pressre ratio

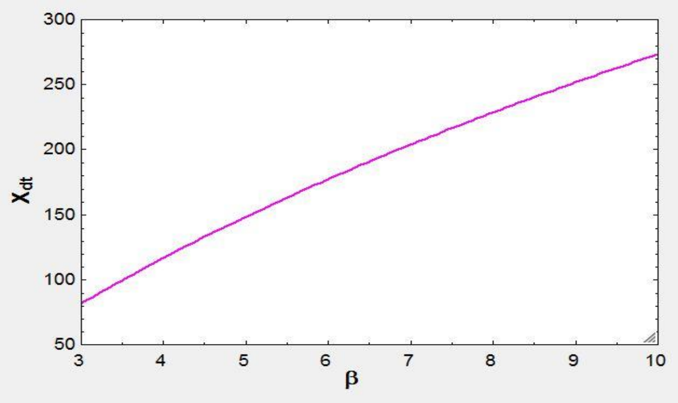

Fig 15 Total exergy destruction(X_{dt}) vs pressure ratio

The graph shows us the values of change in total exergy destruction due to the change in pressure ratio. From graph it is obvious that as the pressure ratio increases the total exergy destruction goes on increasing. It can be seen from graph that as the pressure ratio increases the rate of increase of exergy destruction goes on reducing.

When the pressure ratio is 3 the value of total exergy destruction is 81.3 (KJ/Kg) & when the effectiveness of heat exchanger is taken to be 0.9 total exergy destruction is 269.6 (KJ/Kg).

Thus it is observed that change in pressure ratio has huge impact on total exergy destruction as compared to other operating parameters.

II. CONCLUSION

It is observed that by using double regeneration the temperature at the exit of turbine (expander) reduces. As this temperature reduces the low temperature refrigeration is possible. It is observed that as the effectiveness of heat exchangers goes on increasing the temperature at the exit of turbine goes on reducing. Also as the mass extracted for second state regeneration increases the turbine exit temperature goes on reducing.

The COP of the system will decrease with increase in fraction of mass extracted & will increase with increase in effectiveness of either of the heat exchangers.

The exergy destruction in the compressor, Heat exchanger 2 & turbine remains constant on increasing the effectiveness of 1st Heat exchanger. The exergy destruction increases in cooler & cabin while it reduces in Heat exchanger 1 & mixing chamber.

The exergy destruction in the compressor & turbine remains constant on increasing the effectiveness of 2nd Heat exchanger. The exergy destruction increases in cooler, heat exchanger 2& cabin while it reduces in Heat exchanger 1 & mixing chamber.

The exergy destruction in the compressor & turbine remains constant on increasing the fraction of mass extracted for second state regeneration. The exergy destruction increases in Heat exchanger 1, heat exchanger 2 &cabin while it reduces in cooler & mixing chamber.

On increasing the pressure ratio the exergy destruction in each component goes on increasing. The results can be useful in the design of heat exchangers as well as control of other thermodynamic parameters to get optimum COP, as well as to get low temperature refrigeration.

With addition of second heat exchanger although we are getting very low temperature at the exit of turbine ,but COP value is decreasing by a small amount .In future we can use high efficient heat exchangers to get high COP.

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