Selection and Comparative Studies of Working Fluids for Organic Rankine Cycle (ORC)

Mr. Vipin K
M Tech (Scholar)
Dept of Mechanical Engineering
LBS College of Engineering
Kasaragod , India

Mr. Anil Kumar. B.C
Assistant professor
Dept of Mechanical Engineering
LBS College of Engineering
Kasaragod , India

Abstract- **Energy conservation within the world is becoming more important in recent years particularly the use of low grade temperature and small scale heat sources. Organic cycle has the ability to deal with low heat source to generate power. The conventional Rankine cycle which uses water as the working fluid needs much higher temperature heat source while Organic Rankine cycle can generate power at much lower temperature heat source. However the water becomes uneconomical as working fluid. This is because high boiling point of water compared with organic fluid and also water is a wet fluid so in the T-S diagram the expansion lies inside the curve that indicate the droplet formation at the exit. So to avoid that we need to go for new fluid. So here we introduce a new methodology for selecting the appropriate fluid. In this paper numerical program is developed based on COOLPROP and find out the Thermal efficiency, Second law efficiency and Volumetric flow rate. of 30 fluids. The Temperature profile in the evaporator and condenser plays an important role in energy utilization. The condenser and evaporator pressure limits the use of some working fluids. According to results obtained from the analysis of Thermal efficiency, Second law efficiency, Volumetric flow rate in the case of sub critical cycle with varying evaporator temperature, the fluid R125 is selected as the suitable fluid with 3-6% efficiency while varying the temperature from 313-363K.then while considering the subcritical cycle with varying pressure The fluid R22 is more suitable with 7-10% efficiency while varying the pressure 10-20bar. Third cycle that is Trans critical cycle with varying pressure in that R134a is more suitable with 16-17% efficiency while varying the pressure 70-90 bar. To generalize the fluid which is applicable to all the cycle is R125 not much efficient but can be used in all the cycle that will be discussed in detail.**

Keywords: - Organic Rankine cycle, Subcritical cycle, Trans critical cycle, Working fluid.

I. INTRODUCTION

The first Organic Rankine Cycle was implemented in 1883 when Naptha Engine was patented by Frank W Ofledt. The fuel used in the Engine was Naptha in order to replace steam engines on boats. The clear liquid Hydrocarbon Naptha can be produced during the fractional distillation of coal tar or crude oil. The heat of vaporization for Naptha is lower than Water and it's clear that a given amount of heat input will give more work output can be attained by this Engine. In 1960 Harry zvi Tabor developed an Organic Rankine Cycle to retrieve heat from low temperature sources like Solar Energy and convert them in to electricity. Tabor also developed a turbine for Organic Rankine Cycle and that turbine was capable of operating at relatively low temperature below 273 K .Lars J Brasz, William .M. Bilbow[7] they developed thermodynamic cycle program for predicting the performance of Organic Rankine Cycle systems. They have compared the thermodynamic cycle efficiency of those refrigerants with some of the new refrigerants. In order to cover number of applications in this study, they considered two types of cycles, simple organic cycle and the recuperated cycle. Different evaporation temperatures were selected based on the type of waste heat available. The condensation temperatures varied based on the choice of condenser. The differences in organic rankine cycle thermodynamic efficiency of various refrigerants were found to be substantially larger than the differences in thermodynamic efficiency of these same fluids for vapor compression cycle applications. Qidi Zhu, Zhiqiangsun, Jiemen Zhou[8] conducted experiments with 10 dry/isentropic organic fluids with critical temperature varying from 375.8 K to487.1 K and 9 wet organic fluid with critical temperature ranging from 339 K to 410.1 K and the objective was to study the dependence of performance parameters on the critical temperature of the working fluids under the saturated and super saturated expansion. He concluded tht under saturated expansions, the thermal efficiency, exergy efficiency and the outlet temperature of the hot fluid increase with the critical temperatures of the dry/isentropic fluids. The evaporation temperatures may affect the relative distribution of the performance parameters of the organic rankine cycle's using various wet fluids except the outlet temperature of the hot fluid. The evaporation and the condensing pressure. The Inlet temperature of the hot fluid has an impact on the elative distribution of the exergy efficiency for all types of

Organic fluids. And additionally says that to achieve a high net power, the organic fluids with small difference between its critical temperature and the inlet temperature of the hot fluid are recommended. Peter Collings and Zhibin Yu [[1] created MATLAB code based on REFPROP software for the design and analysis of organic rankine cycle systems. A small –scale organic rankine cycle with scroll expander was designed using the MATLAB and the effects of varying the expander pressure ratio, maximum cycle temperature and the presence of the recuperator were investigated. Working fluids for this are selected as R245fa from the screen test and the rest fluids were phased out under the montreal protocol, and is therefore considered to have lesser potential for future development than R245fa. The implications of the results generated by the computer model vary depending on the organic rankine cycle application. On the other hand the heat source is solar or geo-thermal collector, the primary working fluid is generally recirculated instead of releasing out. This means that any heat not used by the organic rankine cycle will simply result in higher inlet temperature at the collector. Haddad et al [5] has developed a general approach to select the working fluid that meet the sustainable development criterion. The various configurations of the rankine cycle based on the organic working fluids were considered. The approach gives direct assessment of the efficiency criteria for the rankine cycle via artificial neural networks (ANN). Artificial neural networks represent the mathematical tool which allows us for establishing dependences between entrance data and target characteristics of any degree of complexity.

II. THERMODYNAMIC MODELS OF DIFFERENT ORGANIC RANKINE CYCLE

In this some thermodynamic models have been developed in MATLAB and linked to the working fluids data base in COOLPROP. The thermodynamic models are developed in MATLAB in order to run numerical calculations and compare the working fluids from a thermo physical perspective. We have studied 30 fluids some fluids have very high or extremely boiling point (NBP). This kind of working fluids is not suitable for organic rankine cycle when the heat source temperature can vary between 283- 523 K. the high normal boiling point working fluids need very high condensation and evaporation temperature to keep the pressure in condenser and evaporator over atmospheric pressure. For the themodynamic properties the MATLAB is linked with COOLPROP software. The COOLPROP program is designed to provide the most accurate thermophysical properties currently available for pure fluids and their mixtures. The COOLPROP is limited to vapor-liquid equilibrium (VLE) only and does not address liquid-liquid equilibrium (LLE),vapor-liquid-liquid equilibrium (VLLE) or other complex forms of phase equilibrium. The program does not know the location of freezing line for mixtures.

CASE 1: SUBCRITICAL CYCLE WITH VARYING EVAPORATOR TEMPERATURE

In this case super heat effect on subcritical cycle is studied. The condenser and evaporator temperature are set to 298K and 313K respectively. After the woring fluid evaporates in the evaporater and reaches the saturated vapor line, it is subjected to extra thermal energy in order to be super heated. The working fluid leaves the evaporator as super heated and enters the expander to produce useful work. The numerical calculation consists of 40 calculation loops. In the first loop the working fluid leaves the evaporator at saturation vapor line and enters the expander as denoted in the figure 1. The result obtained from peter Collin model.

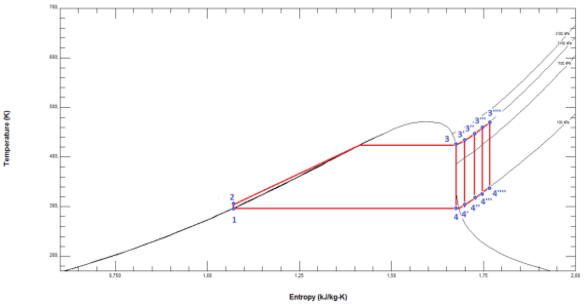

Fig. 1 T-S diagram Case1

CASE 2: SUBCRITICAL CYCLE WITH VARYING EVAPORATOR PRESSURE

Evaporator pressure is raised to different levels in this case in order to investigate its impact on thermal efficiency and the cycle performance. It is clear that a higher evaporator pressure needs a higher pumping work and requires a higher evaporation temperature. By varying the evaporator pressure, the organic rankine cycle can be adjusted to the deal with different heat source. That is shown in the figure 2. The higher the evaporators pressure higher the temperature at which the heat is added to the working fluid. Vapor quality varies significantly that depend upon the used working fluid. The vapor quality at the expander outlet for the dry and the isentropic fluids increases with increase in the evaporator pressure. While the expansion process starts directly from the T-S saturation curve. At the same time the vapor quality for the wet fluids may decrease depending on the slope of saturation vapor line and expander efficiency.

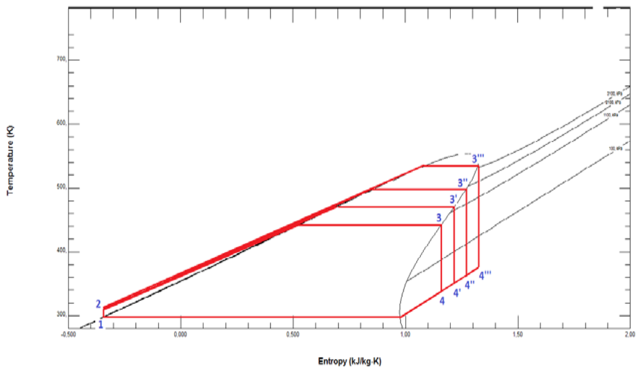

Fig. 2 T-S diagram Case2

For the wet fluids may leave the expander as unsaturated vapor. The dryness fraction may decrease by increasing the evaporator pressure as shown in the figure 3

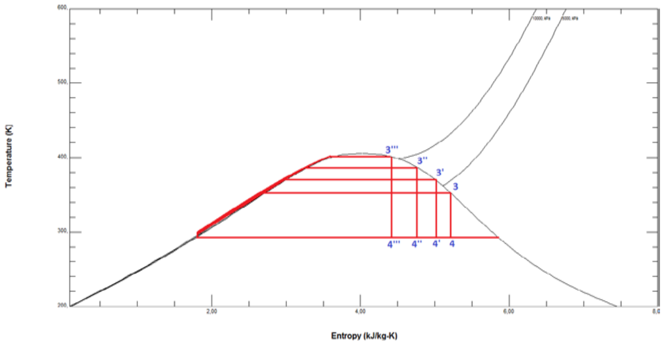

Fig. 3 T-S diagram Case1

The result obtained is validated with result obtained from peter Collin model.

CASE 3: TRANSCRITICAL CYCLE WITH VARYING EVAPORATOR PRESSURE.

A Transcritical is another solution to recover thermal heat from the low grade heat source and convert it to electrical energy. In these cycles working fluids with low normal boiling point (NBP) can be used. The system works with high evaporator and condenser pressures. High pressure means a stronger material should be used to withstand mechanical stresses in heat exchangers and the piping systems. In this cycle the working fluid is pressurized to a pressure higher than the critical pressure. The heat is supplied to the working fluid at the constant pressure. The heat supplied to the working fluid at the constant pressure in the evaporator. The expansion process is considered to start at an Entropy rate given by condenser pressure and Vapor quality equal to 0.9. Figure 4 shows the process in T-S diagram for wet fluid. The blue line in T-S diagram shows expansion process.

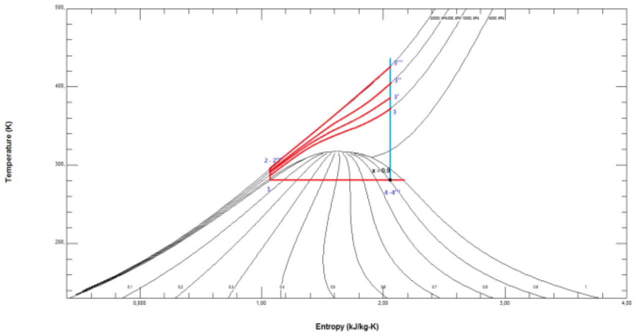

Fig 4 T-S Diagram of Case 3

III. SIMULATION RESULTS

CASE 1: SUBCRITICAL CYCLE WITH VARYING EVAPORATOR TEMPERATURE

Thermal Efficiency- According to the first law of thermodynamics, the thermal efficiency can never exceed 100% because energy output never exceeds energy input and there is always irreversibility in the cycle. Figure 5 illustrates the thermal efficiency for Ammonia, R125, R143a, R1270, Propyne and Toluene. From that we can see that R125 has efficiency 3-6% hike when increasing the temperature 360 K to 400 K. That is illustrated in the figure5. R125 is the best fluid by comparing the safety data.

$$Thermal\ efficiency = \frac{Energy_{out}}{Energy_{in}} = \frac{W_{net}}{Q_{evaporator}} = \frac{W_{expander} - W_{pump}}{Q_{evaporator}}$$

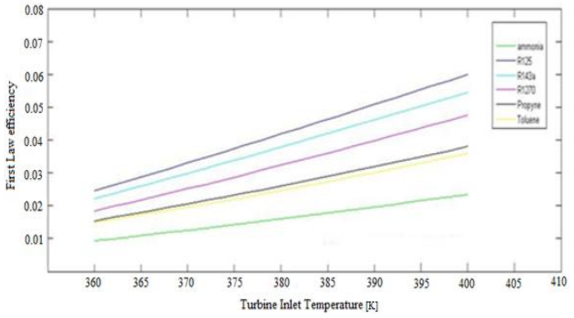

Fig. 5 Thermal efficiency of Case 1

Figure 5 shows that the fluid R125 has higher thermal efficiency in this case. We can infer that the increase in the molecular mass, specific volume also influence the boiling point and thereby effecting the thermal efficiency.

Second law Efficiency:-

$$Second\ law\ efficiency = \frac{Thermal\ \ efficiency}{carnot\ \ efficiency} = \frac{W_{net}}{Q_{evaporator}\ \ *(1-\frac{T_L}{T_h})}$$

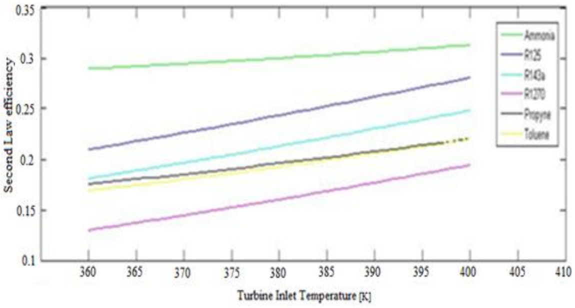

Fig.6 Second law efficiency Of Case 1

Figure 6 shows the second law efficiency for Ammonia, R125, R143a, R1270, propyne and Tolulene. It is clear that the second law efficiency gives us the details of the exergy destruction and if particular fluid is selected that fluid should also have maximum efficiency.

Volumetric flow rate And Expansion Ratio: - The volumetric flow rate is an important parameter in organic rankine cycle design and component sizing. The higher the volumetric flow rate the bigger the component size and the higher the work absorbed by the fluid circulation pump. Volumetric flow rate at the turbine inlet together with expansion ratio gives important information about expander design. Volumetric flow rate at the expander inlet can be calculated by dividing mass flow rate to the density at the expander inlet.

$$\dot{V}_{inlet} = \frac{\dot{m}}{\rho_{inlet}}$$

Expansion ratio can be calculated by the following formula:

$$expansion\ ratio = \frac{\rho_{inlet}}{\rho_{outlet}} = \frac{\dot{V}_{outlet}}{\dot{V}_{inlet}}$$

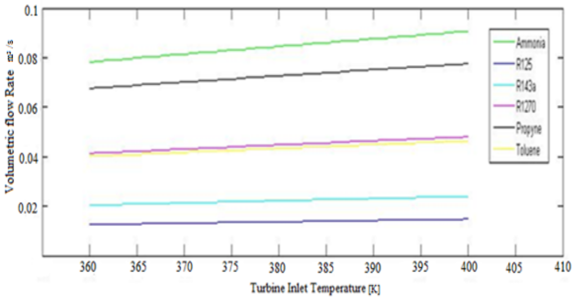

Fig. 7 Expansion Ratio of Simulation Case 1

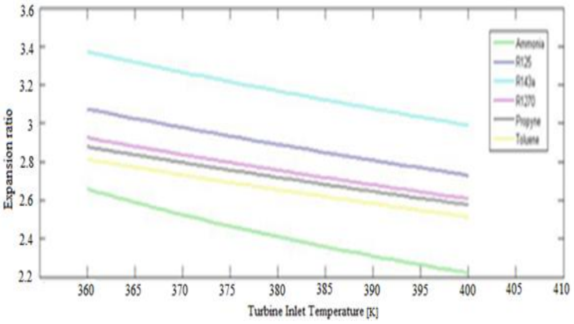

Figure 8 volumetric flow rate of Simulation Case 1

Figure 7 shows expansion decreases for all the working fluids with increasing superheat and Figure 8 shows that the volumetric flow rate increases. Which we have selected from the second law efficiency and the thermal law efficiency and also it should have low volumetric flow rate, high expansion ratio. That means work output obtained is maximum thereby we need only small size equipments. if the temperature is increased, it requires more than one expander but beyond a limit there is no change in the expansion or efficiency.

CASE 2: SUBCRITICAL CYCLE WITH VARYING EVAPORATOR PRESSURE

Thermal Efficiency: - The highest efficiency is achieved by propyne i.e.4-14% hike in the efficiency when the temperature is increased from 320-440 K. when its compared with the specific volume propane is the suitable one for this case. Then R1270 that has low specific volume and high critical pressure the reason that the propyne is above R1270is because of the critical pressure difference. When considering the safety propyne is difficult to handle and R1270 lies in the high flammability group. So coming to the conclusion we can't use these fluids because of these restrictions. So we go for the fluid R22 which is more efficient after these two fluids but the efficiency is

4-10% efficiency when the temperature is raised from 320-440 K.

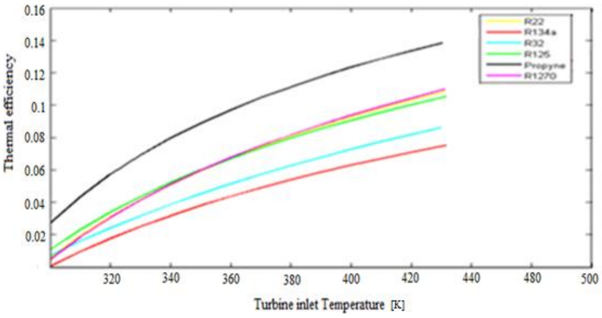

Figure 8 Thermal efficiency of Case 2

Second law Efficiency:-

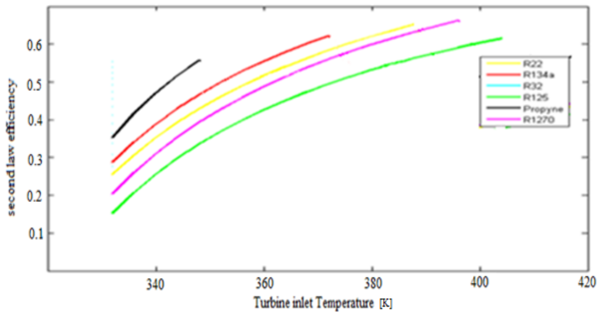

Figure 9 Second law efficiency of Case 2

In figure 9 shows the variation in second law efficiency. Second law reveals the largest irreversibility occurs. When it comes to our fluid selection it predict which fluid causes that propyne cannot be used in the cycle so R22 is selected that fluid has 3-6% efficiency hike when increasing the temperature from 340-400 K.

Volumetric flow: - In this case propyne has higher volumetric flow rate as expected the propyne is having higher specific volume so it's harder to handle they need more auxiliary plant to maintain the fluid so propyne is not used. R22 has lower so due to the lower value in the volumetric flow rate and thereby small equipment is required for the plant. The following figure10 illustrate the volumetric flow rate.

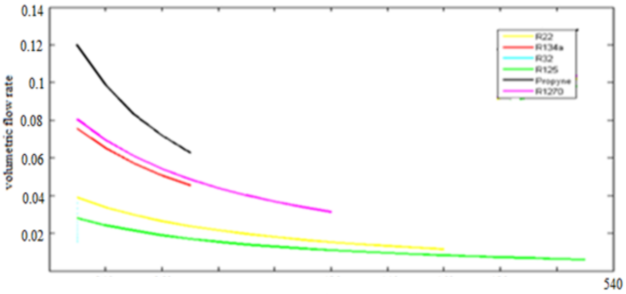

Figure 10 Volumetric flow rate of Case 2

CASE 3: TRANSCRITICAL CYCLE WITH VARYING EVAPORATOR PRESSURE

Thermal Efficiency: - The thermal efficiency is increasing steeply with increase in the temperature and if we further increases the temperature there will be a decrease in the efficiency is due to loss of fluid property

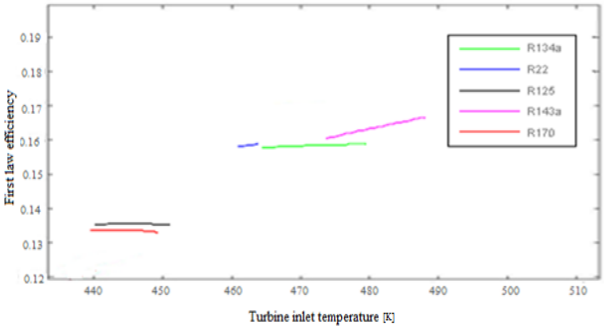

Fig. 11Thermal efficiency of Case 3

It dissociate after that temperature. Dry fluid disintegrates faster than wet fluid. In this wet fluid R134a has efficiency of 16-17 % efficiency when we raised the temperature from 440-490K. That is shown in the figure 11.

Second law Efficiency: - In the figure12 the second law efficiency is illustrated that there is a steep decrease in the second law efficiency. It is because as me move to higher temperature they start losing the property that is on the irreversibility. So that is clear from the below figure 12.

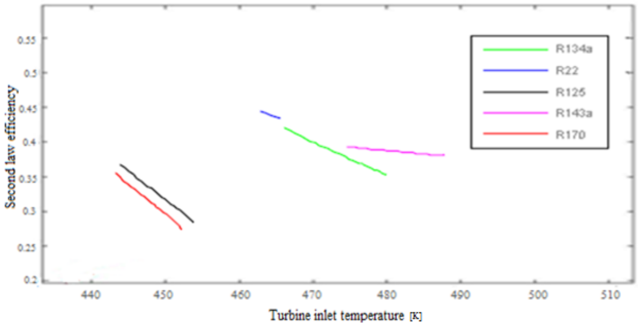

Fig. 12 Second law efficiency of Case 3

Expansion Ratio: - From Thermal efficiency and second law efficiency we have selected R134a. So while obtaining the expansion ratio R134a has higher value. So we can obtain more energy out of it. And require more than on expanders that is illustrated in figure 13.

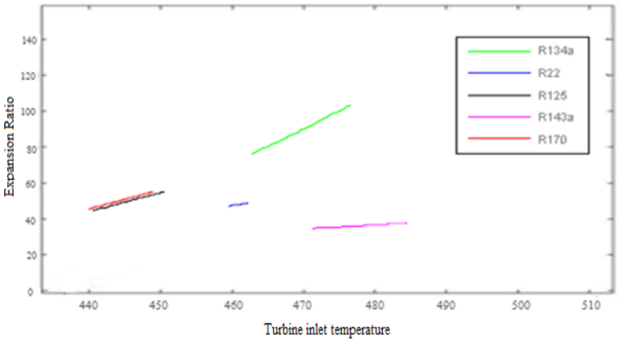

Fig. 13 Expansion ratio of Case 3

Volumetric Flow Rate: - from the figure 14 R134a has lower volume flow rate that means small equipment is needed for the construction of organic rankine cycle with R134a

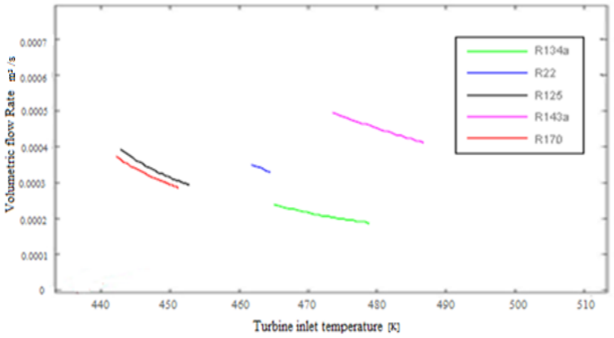

Fig. 14 Volumetric flow rate of Case 3

IV. CONCLUSION

From the analysis it observed that is no working fluid that satisfies all the desired condition. The trade off is between high thermodynamic performance, environmental and safety criteria. The selection of optimal working fluid for organic rankine cycle is so complicated because some working fluids have good thermodynamic properties but at the same time they don't have desirable environmental and safety data.on the other side if the fluid have good environmental and safety data, they won't be having good thermodynamic performance. So coming to the conclusion in the case 1 subcritical cycle with varying pressure the fluid selected for this cycle according to the temperature range is R125with 3-6% thermal efficiency when varying the temperature from 360-400 K and also the fluid is safe and environment friendly. In the case 2 subcritical cycle with varying th evaporator pressure it is observed that R22 is the suitable fluid for this cycle with 7-10 % efficiency hike during the temperature increase from 320-400 K. In the case 3 Trans critical cycle with varying the evaporator pressure, R134a is found to be the suitable fluid for the cycle with 16-17% Thermal efficiency hike during the temperature raised from 440-490 K. Regarding the environmental and safety criteria, the selected working fluid should have zero ozone depletion potential (ODP), non-flammable, non-toxic and global warming potential should be very low. Taking all these safety criteria in to consideration the following working fluids are not optimal: Ammonia (flammable and toxic), Toluene (toxic), and R21 (flammable, toxic and ODP=0.04), R1270 (flammable), R143a (flammable), R152a (toxic), and R22 (ODP=0.040 and GWP=1790). The environmental and safety data are not available for toluene and the safety group is also not available. The fluid should be selected according to the heat sink temperature and heat source temperature and the program can predict the efficiency of the cycle with that particular fluid.

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