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Performance Assessment of Three Eco-Friendly Hydro-Fluorocarbon and Hydrocarbon Refrigerant Mixtures as R22 Alternatives in Refrigeration Systems

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Abstract: In this study, performances of the ozone-friendly hydro-fluorocarbon and hydrocarbon refrigerant mixtures (R413A, R417A and R422A) were investigated theoretically as alternatives to ozone depleting R22 refrigerant. Thermodynamic properties of these refrigerants were analysed using the REFPROP software and the vapour compression refrigeration cycle. The results obtained showed that the vapour pressure and specific volume of the three refrigerant mixtures are very close to those of R22. All the investigated refrigerants have similar performance in terms of refrigerating effect, condenser duty and COP. The average COPs obtained for R413A, R417A and R422A were 4.2, 9.0 and 12.6% less than that of R22. All the three refrigerants exhibited better compressor work input and discharge temperature than R22. R422A performed better in terms of lower discharge temperature and compressor work input.

Key words: Thermodynamics · Performance · Hydro-fluorocarbon · Hydrocarbon · Alternative refrigerants · R22

INTRODUCTION

The most commonly used refrigerant and propellant in various air-conditioning and heat pump applications is Chlorodifluoromethane (R22). Also, among all refrigerants, R22 has the largest sales volume. However, the continuous depletion of the ozone layer, which safeguards the earth's surface from UV-B radiation, has resulted in a series of international agreements demanding a gradual phase out of CFC and HCFC refrigerants [1-3]. R22 belongs to the group of hydro-chlorofluorocarbons (HCFCs) which contained the ozone depleting chlorine atom and is considered as a damaging working fluid to the environment. Though due to its relatively low ozone depleting potential (ODP = 0.055), it is considered as transitional alternative refrigerant to the highly ozone-depleting chlorofluorocarbon (CFC) refrigerants. ODP of R22 is among the lowest for the chlorine-contained halogenated hydrocarbons. Nevertheless, refrigerants short of zero ODP are no more currently considered as suitable working fluids; hence R22 and other HCFC refrigerants will be phased out internationally by year 2020 and 2030 in developed and developing nations respectively [3-5].

The search for a perfect replacement for R22 is a key issue in research. R22 was so versatile that it will require many refrigerants as alternatives to cover all its applications [6-8]. Several studies have been conducted to search for substitutes to R22 [6-10]. Currently, replacement refrigerants available for R22 in air-conditioners and heat pumps are hydro-fluorocarbons (HFCs) and natural substances such as CO_2, R717 and hydrocarbons (HCs). However, the main disadvantage of CO_2 as a refrigerant is its extremely high working pressure which is much higher than other natural and synthetic refrigerants. Ammonia (R717) is slightly flammable and toxic, while hydrocarbons are highly flammable, which limits their use in the residential air-conditioners and heat pumps [11-13]. Refrigerant blends have been considered as the favourite candidates for R22 alternatives [14].

Researchers have renewed their interest in refrigerant blends, since by mixing two or more refrigerants a different working fluid with the preferred characteristics can be created. For example, by modifying the

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composition of a blend having high-pressure and low-pressure refrigerants, the vapour pressure of the resulting fluid can be tailored to match that of the chlorofluorocarbon (CFC) or HCFC being replaced. New blends that are non-flammable but still contain flammable refrigerants could be created through mixing of refrigerants. Moreover, blends of two or more refrigerants have made it possible to improve system characteristics such as compressor discharge temperature and lubricant circulation [15-17].

Through the Alternative Refrigerant Evaluation Program (AREP), various azeotropic and zeotropic refrigerant mixtures were investigated theoretically and experimentally as potential alternatives to R22 in vapour compression refrigeration systems and the comparisons among R410A, R404A and R407C as R22 alternatives were reported in literatures [8, 18-22]. R407C with the composition of R32/R125/R134a (23%/25%/52% by weight), is a zeotropic mixture that has a temperature glide of 5 - 6 °C. This causes its temperature to increase and decrease as it passes through the evaporator and the condenser, respectively. The cooling capacity and the coefficient of performance of R407C are lower than those of R22 by about 2-30% depending on operating conditions [18, 22]. R410A gives higher volumetric cooling capacity than both R22 and R407C [22, 23]. The assessment of alternative refrigerant mixtures (azeotropic and zeotropic mixtures) revealed a substantial increase in coefficient of performance of azeotropic blends and a slight decrease for the ternary blends in comparison to R22 [24, 25].

R413A, R417A and R422A are mixtures of hydro-fluorocarbon and hydrocarbon refrigerants. R413A is a zeotropic mixture of 88% of R134a, 9% of R218 and 3% of R600a by mass. R417A is the ternary mixture refrigerant composed of 46.6% of R125, 50.0% of R134a and 3.4% of R600 by mass, while R422A is a zeotropic mixture of 85.1% of R125, 11.5% of R134a and 3.4% of R600a by mass. Hydrocarbon is added to the composition of these refrigerants in order to ensure the return of the lubricant oil to the compressor and the compatibility with traditional mineral oils or new lubricants such as poly-ol-ester oil. Also the flammability of hydrocarbon is effectively counteracted. Therefore, in this study, the performance analysis of refrigerant mixtures (R413A, R417A and R422A) with the composition of both hydro-fluorocarbon and hydrocarbon refrigerants was investigated theoretically in vapour compression refrigeration system and compared with that of baseline refrigerant (R22).

MATERIALS AND METHODS

Vapour Compression Refrigeration System: Vapour compression refrigeration cycle is the most widely adopted refrigeration cycle. It is used in about 95% of the world's mechanical refrigerators and heat pumps [26]. Fig. 1 shows the simple vapour compression refrigeration cycle on p-h diagram. The refrigeration system consists of four main components: compressor, condenser, expansion device and evaporator. Compressor activates the refrigerant by compressing it to a higher pressure and temperature after it has produced its refrigeration effect through the evaporator. It drives and circulates refrigerant through the system and provides the necessary force to maintain the operation of the system. The compressed refrigerant is passed to the condenser where it condenses to liquid after transferring its heat to a medium which has lower temperature. The high pressure liquid refrigerant from the condenser is throttled through an expansion device to a low-pressure, low-temperature vapour existing in the evaporator. The expansion device regulates or controls the flow of liquid refrigerant to the evaporator. The low-pressure low-temperature liquid refrigerant vaporizes in the evaporator by absorbing latent heat from the material being refrigerated and the subsequent low pressure vapour refrigerant then passes to the compressor.

The following assumptions are made with reference to the vapour compression refrigeration cycle on p-h diagram (Fig. 1) [27]:

- Isentropic vapour compression process in the compressor, from point 1 to point 2. The compressor specific work input (W_{comp}, kJ/kg) is obtained as:

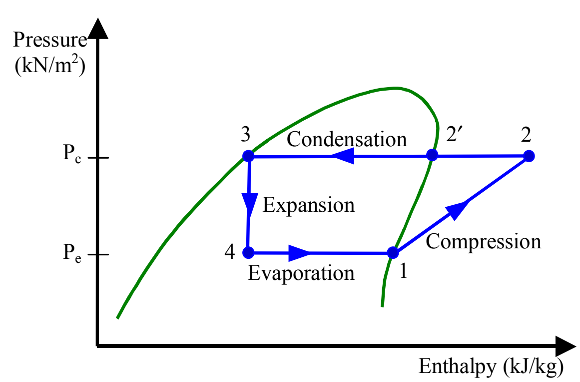

Fig. 1: Vapour compression refrigeration cycle on p-h diagram

$$W_{comp} = (h_2 - h_1) \quad (1)$$

where, h_1 = specific enthalpy of refrigerant at the outlet of evaporator (kJ/kg); and h_2 = specific enthalpy of refrigerant at the outlet of compressor (kJ/kg).

- Isobaric de-superheating at pressure (P_c) from compressor discharge temperature at point 2 to condenser temperature at point 2′, followed by an isothermal and isobaric condensation from point 2′ to point 3. The specific heat rejection (Q_c, kJ/kg) in the condenser is given as:

$$Q_c = (h_2 - h_3) \quad (2)$$

where, h_3 = specific enthalpy of refrigerant at the outlet of condenser (kJ/kg).

- Isenthalpy liquid expansion in the throttling valve from point 3 to point 4,

$$h_3 = h_4 \quad (3)$$

- Isothermal and isobaric evaporation in the evaporator from point 4 to point 1. The specific heat absorbed by the refrigerant in the evaporator (Q_{evap}, kJ/kg) is given as:

$$Q_{evap} = (h_1 - h_4) \quad (4)$$

where, h_4 = specific enthalpy of refrigerant at the inlet of evaporator (kJ/kg).

The coefficient of performance (COP) is the ratio of the heat absorbed by the refrigerant to the work input; therefore, COP is obtained as the ratio of Eq. (4) to Eq. (1):

$$COP_{ref} = \frac{Q_{evap}}{W_{comp}} \quad (5)$$

Determination of Thermodynamic Properties: The determination of thermophysical properties of refrigerants is essential for thermodynamic analysis of vapour compression refrigeration systems. Thermodynamic properties of the three hydro-fluorocarbon and hydrocarbon refrigerant mixtures (R413A, R417A and R422A) were obtained to study and compare their performance with that of R22. The pressure, volume and temperature (PvT) in an equilibrium state are most needed thermal properties that are necessary for the estimation of refrigerant performance in a refrigeration system. Other properties could be obtained from a PvT Correlation (equation-of-state), utilizing specific heat [13]. The REFPROP database software from the National Institute of Standards and Technology (NIST) is one of the most widely used tools designed to provide data on a wide variety of fluids. The program uses equations for the thermodynamic and transport properties to calculate the state points of the fluid (single substance or blends) [27]. REFPROP is useful for the performance studies of possible replacements for the CFC and HCFC refrigerants. This software was used in this study for the thermodynamic analysis and computation of the refrigerants' properties.

RESULTS AND DISCUSSION

The variation of saturated vapour pressure and temperature for R22 and its three alternative refrigerant mixtures (R413A, R417A and R422A) is shown in Fig. 2. As shown in this figure, the saturated vapour pressure curves for the three alternative refrigerants are very close to the vapour pressure curve of R22 refrigerant. This indicates that these refrigerants can exhibit similar properties and could be used as substitute for R22. Moreover, curve of R417A is closer to that of R22 with 5.9 % deviation, while R413A and R422A deviate by 14.8 % and 11.1 %, respectively.

Fig. 3 shows the variation of specific volume of vapour refrigerant for R22 and the three alternative refrigerant mixtures. Specific volume increases as saturated temperature reduces. The alternative refrigerants (R413A, R417A and R422A) exhibited very close specific volume and temperature characteristic with R22, which shows that these refrigerants can use the same compressor size with R22. Again, the curve of R417A is closer to that of R22 than the other two alternative refrigerants.

The refrigerating effects of R22 and the three alternative refrigerant mixtures at varying evaporator temperature for condensing temperature of 40 °C are shown in Fig. 4. As shown in the figure, refrigerating effect increases as the evaporator temperature increases for all the investigating refrigerants, which is due to the increase in latent heat value of the refrigerants. High latent heat value is desirable since the mass flow rate per unit of capacity is less. The efficiency and capacity of the compressor are enhanced at high latent value. This reduces the power consumption and the compressor displacement requirements that permit the use of smaller and more compact equipment.

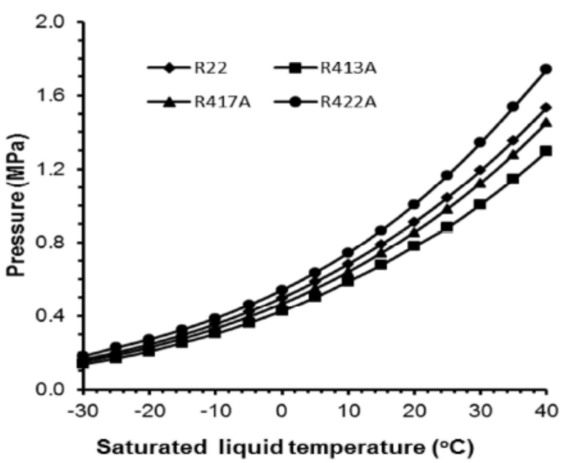

Fig. 2: Variation of pressure with saturated liquid temperature

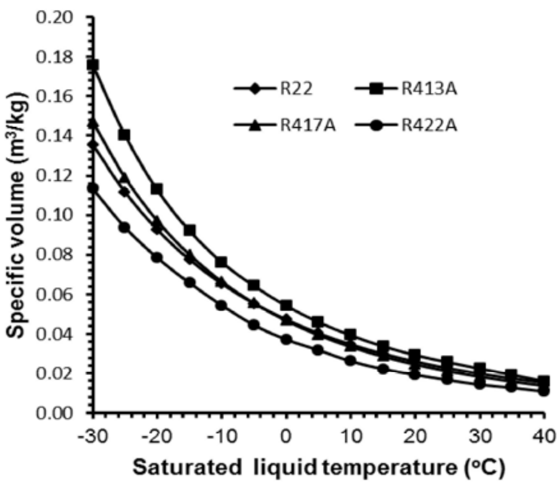

Fig. 3: Variation of specific volume of refrigerant vapour with saturated liquid temperature

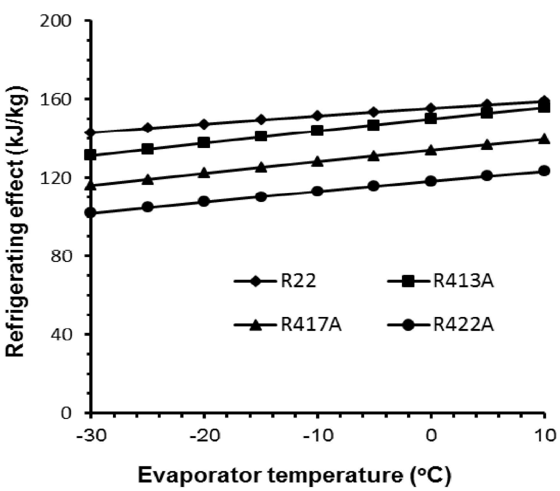

Fig. 4: Variation of refrigerating effect with evaporator temperature at condensing temperature of 40 °C.

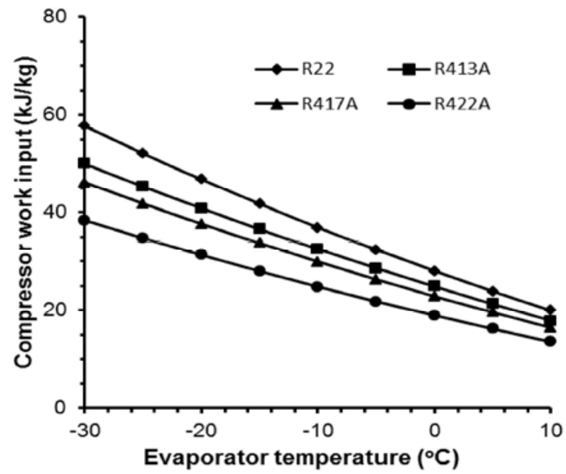

Fig. 5: Variation of compressor work input with evaporator temperature at condensing temperature of 40 °C.

R413A showed better refrigerating effect than the other two alternative refrigerants, but R22 has the highest refrigerating effect. The average refrigerating effect obtained for R413A, R417A and R422 were 4.9, 15.3 and 25.5 % lower than that of R22, respectively.

The effect of evaporator temperature on the compressor work input for the investigating refrigerants at condensing temperature of 40 °C is shown in Fig. 5. The work of compression decreases as the temperature of the evaporator increases which is due to the fact that when the temperature of the evaporator increases the suction temperature also increases. At high suction temperature, the vaporizing pressure is high and therefore the density of suction vapour entering the compressor is high. Hence the mass of refrigerant circulated through the compressor per unit time increases with the increases in suction temperature for a given piston displacement. The increase in the mass of refrigerant circulated decreases the work of compression. All the three investigated alternative refrigerant mixtures exhibited lower compressor work input than R22. The lowest compressor work was obtained using R422A. The average values obtained using R413A, R417A and R422A were 12.3, 19.2 and 32.9 % lower than that of R22, respectively.

The evaporator temperature versus condenser duty for 40°C condensing temperature is shown in Fig. 6. Similar trend was observed for all the investigated refrigerants. As clearly shown in the figure, the condenser duty slightly reduces as evaporator temperature increases. The increase in the work of compression increases the heat added to the hot refrigerant during compression process, which also increases the quantity

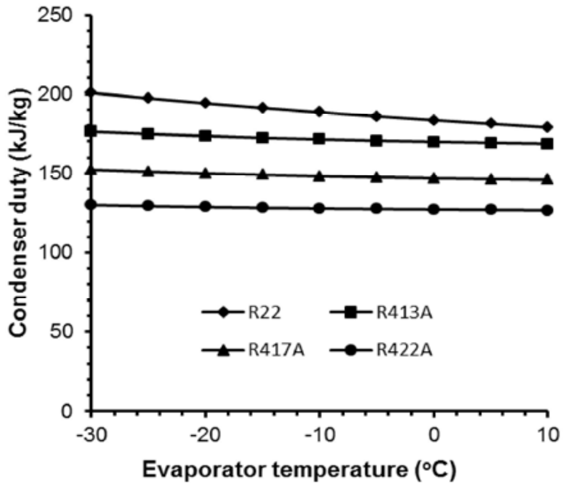

Fig. 6: Condenser duty versus evaporator temperature at condensing temperature of 40 °C.

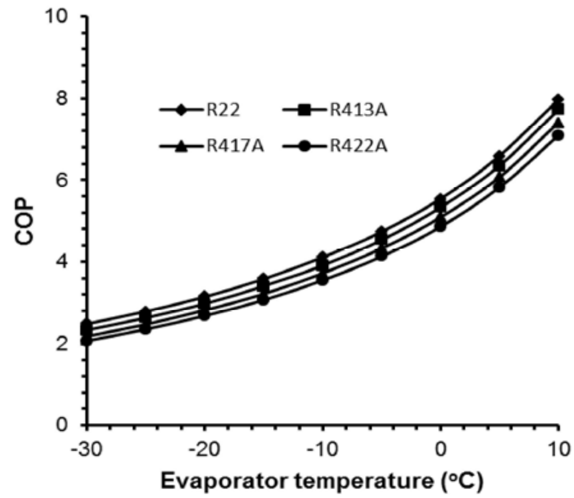

Fig. 8: Variation of coefficient of performance (COP) with evaporator temperature for condensing temperature of 40 °C.

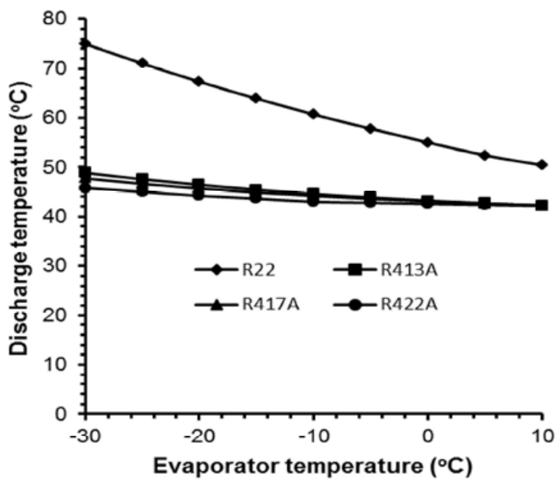

Fig. 7: Variation of discharge temperature with evaporator temperature at condensing temperature of 40 °C.

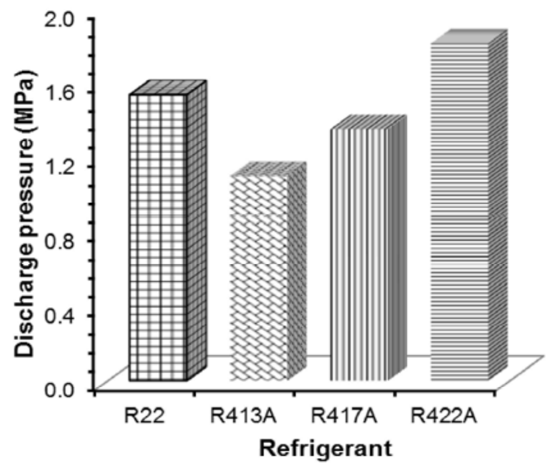

Fig. 9: Discharge pressure at condensing temperature of 40°C.

of heat to be removed by the condenser. R22 exhibited higher condenser duty than all the alternative refrigerants. The average condenser duty of R413A (171.8 kJ/kg) is close to that of R22 (189.0 kJ/kg), while those of R417A and R422A are 148.6 and 128.1 kJ/kg, respectively.

Fig. 7 shows the variation of the discharge temperature for R22 and the three investigated alternative refrigerant mixtures as a function of evaporator temperature for the condensing temperatures of 40 °C. The alternative refrigerants (R413A, R417A and R422A) showed lower values of discharge temperature than R22. The curves for alternative refrigerants are almost the same, which portray the same performance in the system. High discharge temperature is harmful to the performance of the system, therefore, low discharge temperature exhibited by the three alternative refrigerants indicates less strain on the compressor and hence a longer compressor life. The average discharge temperature obtained for R413A, R417A and R422A were 26.8, 27.6 and 29.3 % lower than that of R22, respectively.

The coefficient of performance (COP) of a refrigeration cycle reveals the cycle performance and is the major condition for choosing a new refrigerant as a substitute. The COP for R22 and its three alternative refrigerant mixtures at varying evaporator temperature is shown in Fig. 8. Similar trends were observed in the curve profiles for all the investigated refrigerants.

COP increases with increase in evaporator temperature. The COPs of the three alternative refrigerants are very close to that of R22. The average COPs obtained for R413A, R417A and R22A were 4.2, 9.0 and 12.6 % less than that of R22.

Fig. 9 shows the discharge pressure at 40 °C condensing temperature for R22 and its three alternative refrigerant mixtures. The performance of a refrigerating system depends greatly on compressor discharge pressure. It is an important parameter that influences both the stability of the lubricants and the compressor components. Refrigerants with lower discharge pressure are more suitable alternative and superior than those with high discharge pressure. R413A showed lower discharge pressure than other three refrigerants. The discharge pressure for R417A and R413A are 12.0 and 28.5 % lower than that of R22, respectively, while value for R422A is 18.0 % higher than that of R22.

CONCLUSIONS

This study investigated theoretically the performance analysis of refrigerant mixtures with the composition of both hydro-fluorocarbon and hydrocarbon refrigerants (R413A, R417A and R422A) as R22 substitutes in vapour compression refrigeration system. The performance parameters considered are vapour pressure, suction specific volume, refrigerating effect, compressor work input, discharge temperature and pressure, condenser duty and coefficient of performance. The following conclusions were drawn from the analysis and discussion of the results:

- All the three alternative refrigerants exhibited very close vapour pressure, specific volume and temperature characteristic profiles to those of R22, which shows similar properties and ability to serve as substitutes for R22. The curves of R417A are closer to those of R22 than the two other alternative refrigerants. R417, R422A and R413A in terms of vapour pressure-temperature characteristic profile deviated from that of R22 by 5.9, 11.1 and 14.8 %, respectively.
- The performances of the three alternative refrigerants in terms of the refrigerating effect, condenser duty and COP were similar to those of R22. R413A showed better performance of these three parameters than the other two alternative refrigerants, but R22 has the highest values. The average COPs obtained for R413A, R417A and R22A were 4.2, 9.0 and 12.6 % less than that of R22, respectively.
- All the three alternative refrigerant mixtures possessed better compressor work input than R22, which will compensate for their slightly lower refrigerating effect.
- Also, the three investigated alternative refrigerants exhibited desirable lower values of discharge temperature than R22. The average discharge temperature obtained for R413A, R417A and R422A were 26.8, 27.6 and 29.3 % lower than that of R22, respectively.
- The compressor discharge pressure of R417A and R413A were 12.0 and 28.5 % lower than that of R22, respectively, while value for R422A is 18.0 % higher than that of R22.

Generally, R413A performed better than other two alternatives in that it exhibited lower compressor discharge pressure, higher condenser duty, refrigerating effect and COP than R417A and R422A. R417A has the closest saturated pressure and suction specific volume curves to those of R22. Also, R422A was better in terms of lower discharge temperature and compressor work input.

CONCLUSION

The results obtained showed that the vapour pressure and specific volume of the three refrigerant mixtures are very close to those of R22. All the investigated refrigerants have similar performance in terms of refrigerating effect, condenser duty and COP. The average COPs obtained for R413A, R417A and R422A were 4.2, 9.0 and 12.6% less than that of R22. All the three refrigerants exhibited better compressor work input and discharge temperature than R22. R422A performed better in terms of lower discharge temperature and compressor work input.

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