A Performance Analysis of Low Pressure HFC Refrigerants in Vapor-Compression Refrigeration Cycles

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ABSTRACT

This study was initiated to identify the possible working fluids that could be used in a small centrifugal compressor-based air conditioning system for the mobile and non-mobile applications. The suitability of potential low density HFC refrigerants as a substitute for CFC low density or HFC high density refrigerants for a vapor-compression air conditioning system was investigated. A steady-state thermodynamic cycle analysis indicated an increase in refrigerating efficiency of 5 % to 15% with HFC-LVP and HFOC-LVP refrigerants compared to HFC-134a. Additionally, the positive impact of the low vapor pressure air conditioning system on the refrigeration cycle efficiency and on the environment are also addressed.

NOMENCLATURE

- h : Specific enthalpy, Btu/lb
- Q: Volumetric capacity, Btu/ft^3
- p: Pressure, psia
- T: Temperature, °F
- ΔT: Temperature difference, °F
- x: Vapor quality
- η_R: Refrigerating efficiency
- η_S: Compressor isentropic efficiency

Subscripts

- c: Condensing
- Carnot: Carnot cycle
- e: Evaporating
- R: Refrigerating
- s: Isentropic

INTRODUCTION

CFC refrigerants are in the process of being replaced with environmentally friendly refrigerants. The development of an environmentally-friendly air conditioning system for the appliance and automotive industries has led to many innovative design concepts (Nartron, 1994). Concurrently, as the awareness of the need for environmental protection increased, science developed technology to provide the air conditioning industry with environmentally-friendly climate control products. To this end, a non-CFC centrifugal compressor-based air conditioning system has been engineered. This advanced system incorporated (a) low density HFC refrigerants; (b) high refrigerating efficiency; (c) a compact centrifugal compressor; (d) solid state electronic control; and (d) parallel flow type heat exchangers (Nartron, 1995).

A centrifugal compressor-based air conditioner has the potential to utilize low density working fluids because of its ability to handle greater volumetric flow rates than the positive displacement devices

(ASHRAE, 1992). Since low density refrigerants in general correspond to low evaporating and condensing pressures, a higher safety standard is attainable, which extends application of the centrifugal compressor-based air conditioner to aircraft, land and water based transportation, homes, offices, modular equipment, etc.. In addition, low pressure systems can utilize lightweight materials, e.g., thin-wall aluminum and/or injection modeled plastic components, which substantially reduce the system weight and cost. Centrifugal compressors characteristically have low vibration and noise levels compared to the positive displacement compressor.

As part of the effort to reduce research and development time for this innovative air conditioning system, a model of system cycle performance was constructed to analyze the steady-state thermodynamic performance. The objective of this paper is to: (1) document the characteristics of various refrigerants including their effect on the environment; and (2) compare the refrigeration system efficiency of prospective low density working fluids with base fluid HFC-134a.

EFFECT OF VARIOUS REFRIGERANTS ON THE ENVIRONMENT

Today, refrigerant selection has been heavily influenced by environmental considerations. The environmental factors include ozone depletion and global warming potential. Values for a number of selected refrigerants are listed in Table 1. Recent environmental regulations restricting the use of common chlorofluorocarbons (CFCs) have created an urgent need for air conditioning systems using environmentally-friendly refrigerants. The replacement of hydrogenated chlorofluorocarbons (HCFCs) are also included in the phaseout schedule in the near future. Hydrofluorocarbons (HFCs) such as HFC-134a have become the most successful alternative to CFC-12 due to the consideration of environmental impact. As shown in Table 1, the HFCs and HFOC fluids possess zero ozone depletion potential and lower global warming potential.

Table 1. Comparison of environment-related effects of various refrigerants

Refrigerant	Atmospheric Lifetime (years)	Ozone depletion potential	Global warming potential
CFC-11	50	1.0	1.0
CFC-113	85	0.8	1.4
HCFC-123	2	0.02	0.02
HFC-134a	14	0.0	0.31
HFC-LVP*	15	0.0	0.2-0.3
HFOC-LVP*(estimated)	15-50	0.0	0.3-1.0

*: HFC-LVP and HFOC-LVP are confidential, experimental low vapor pressure working fluids.

COMPARATIVE REFRIGERANT PERFORMANCE

Identifying a refrigerant for a centrifugal compressor-based air conditioning system is a difficult task since such a system is inherently adaptable to the low density working medium. A high density refrigerant such as HFC-134a requires higher impeller tip speeds and may cause an increase in compression stages (Stoecker, 1994). Additionally, a low density working fluid in refrigeration systems typically exhibits a higher refrigerating efficiency than a high density working fluid. The refrigerating efficiency η_R is the ratio of the coefficient of performance of a refrigeration cycle to that of an Carnot cycle, that is,

$$\eta_R = \frac{COP}{(COP)_{Carnot}} \quad (1)$$

In spite of its simplicity, a steady-state thermodynamic analysis takes into account the major aspects of a refrigeration cycle. The calculated refrigerating efficiency of various refrigerants is compared in Fig. 1. The simple cycle conditions correspond to a 50 °F evaporating temperature and an 80 °F to 140 °F condensing temperature, which accounts for typical air-cooled heat exchangers. As far as the HFC or HFOC refrigerants are concerned, HFC-LVP has the highest refrigerating efficiency. The refrigerating efficiency of HFOC-LVP is comparable to that of HFC-134a, depending upon the condensing temperature, as indicated by Fig. 1.

The relationship between the vapor quality and the condensing temperature is shown in Fig. 2. Except for the high density HFC-134a, vapor quality is less than one for all of the low density refrigerants. This indicates the possibility of wet compression, as shown in Fig. 2. This possibility is limited because of the assumption of the ideal compression process. That is, the isentropic efficiency of the compressor is defined as 1. Additionally, a centrifugal compressor has a much higher tolerance for wet compression than a positive displacement compressor.

Fig. 3 illustrates the volumetric capacity at various condensing temperatures. It is clear that the volumetric capacity of high density refrigerant HFC-134a is superior to those of the low density refrigerants in Fig. 3. Both HFC-LVP and HFOC-LVP exhibit the volumetric capacities similar to CFC-113, while HCFC-123 has relatively higher volumetric capacity among the low density refrigerants. The condensing pressure of the refrigerants is related to the corresponding condensing temperature, as shown in Fig.4. As we can see from Fig. 4, the condensing side of HFC-LVP, HFOC-LVP, and CFC-113 refrigeration systems operates around atmospheric pressure. The low condensing pressure provides many advantages including high efficiency, safety, lightweight design, etc. (Nartron, 1994; 1995).

REFRIGERATION SYSTEM PERFORMANCE

In order to evaluate the refrigeration cycle on a more meaningful basis, the following analysis and discussion are focused on the working fluids including HFC-134a, HFC-LVP, and HFOC-LVP. To accomplish this goal, a refrigeration cycle at various compressor isentropic efficiencies and condensing temperatures, as illustrated in a *p - h* diagram in Figure 5, has been modeled. In the model, the evaporating temperature was set at 50 °F and the compressor suction superheat and the condenser exit subcooling were each set at 10 °F. In addition, no pressure drops were considered in the evaporator and condenser. Reversible work required by an isentropic compression between states *1'* and *2s* in Fig. 5 is known as adiabatic work, while the irreversible work done by the actual compressor follows the route from state *1'* to state *2*. Isentropic efficiency is defined as the ratio of adiabatic work to actual work:

$$\eta_s = \frac{h_{2s} - h_{1'}}{h_2 - h_{1'}} \quad (2)$$

The isentropic efficiency of a centrifugal compressor typically varies from about 0.63 to about 0.83.

HFC-LVP and HFOC-LVP, the prospective low density refrigerants for centrifugal compressor-based air conditioning systems, consistently show 5% to 15% higher refrigerating efficiency than that of

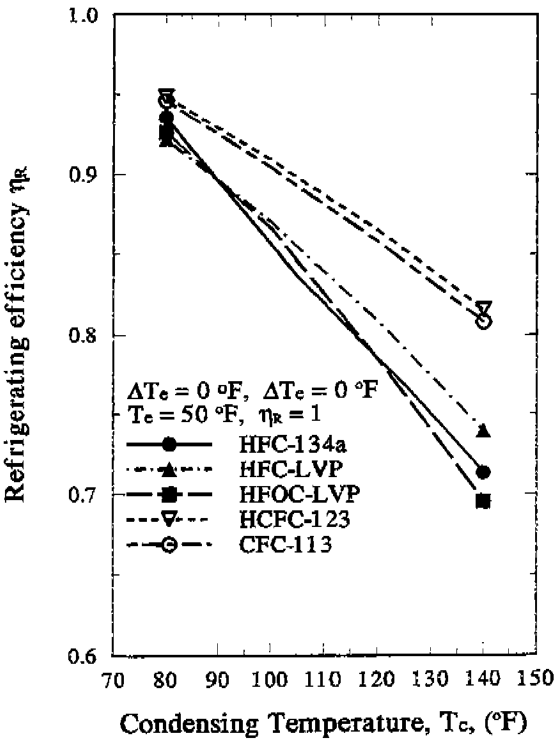

Fig. 1 Refrigerating efficiency η_R at various T_c

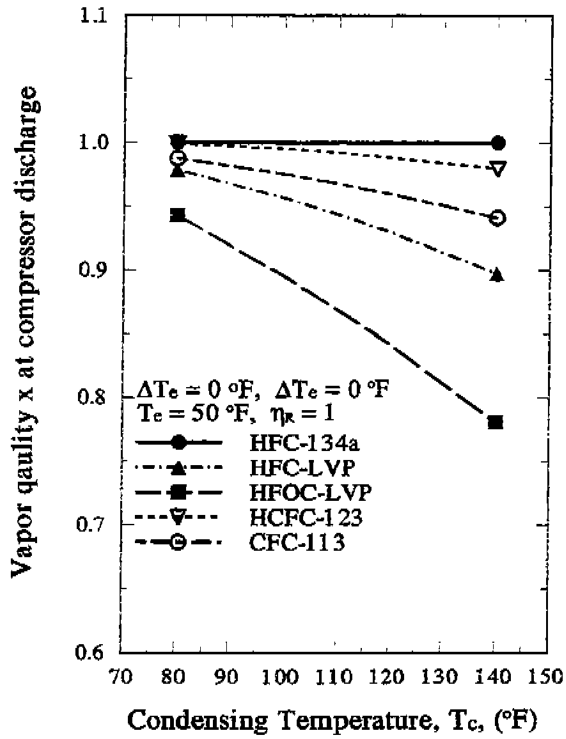

Fig. 2 Vapor quality x at various T_c

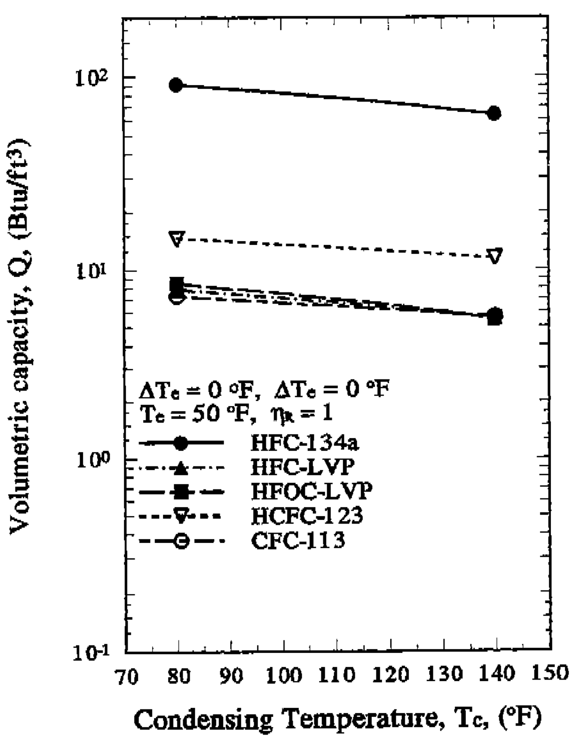

Fig. 3 Volumetric capacity Q at various T_c

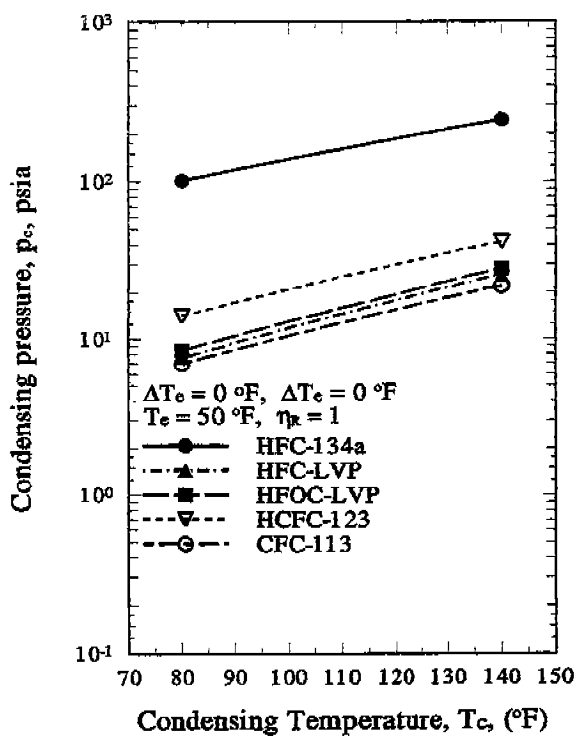

Fig. 4 Condensing pressure p_c at various T_c

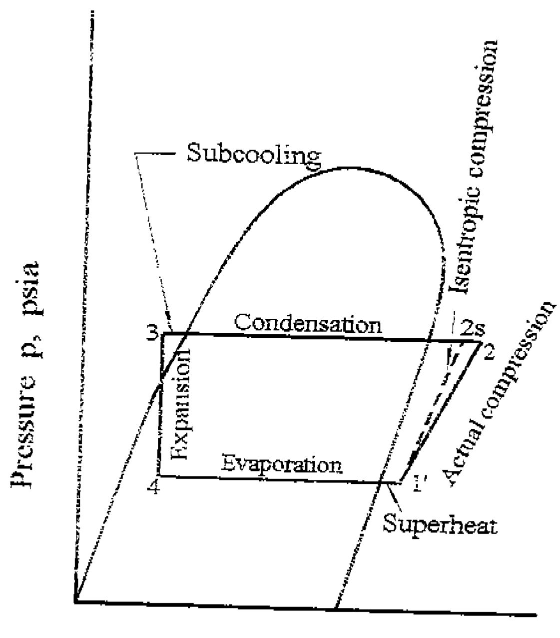

Fig.5 Specific enthalpy, h, Btu/lb

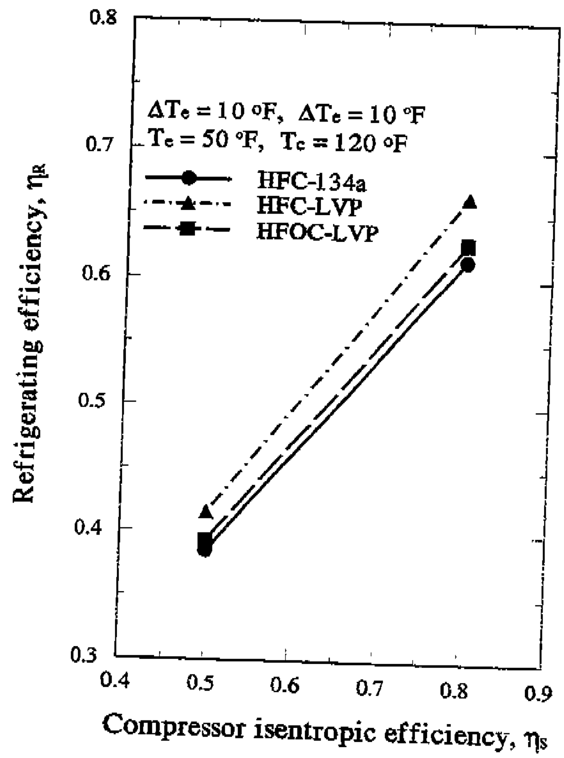

Fig. 6 Refrigerating efficiency η_R vs η_s

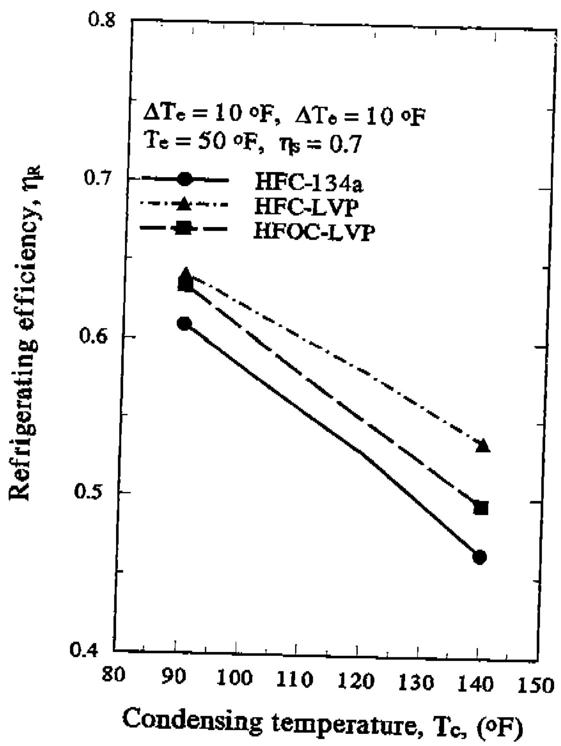

Fig. 7 Refrigerating efficiency η_R vs T_c

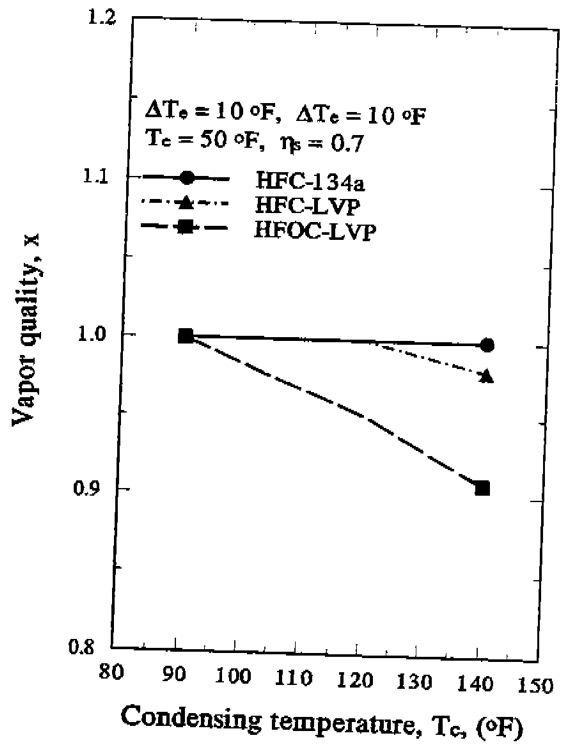

Fig. 8 Vapor quality x at various T_c

HFC-134a. The compressor isentropic efficiency varies from 0.5 to 0.8 (see Fig. 6). Considering the fact that centrifugal compressors are inherently more efficient than positive displacement devices, much better refrigeration performance can be expected for the centrifugal compressor-based air conditioning system. Figure 7 illustrates the refrigerating efficiency for HFC-134a, HFC-LVP, and HFOC-LVP as a function of condensing temperatures for a compressor isentropic efficiency of 0.7. Over the operating temperature range, HFC-LVP exhibits the best system performance ranking by refrigerating efficiency, while HFC-134a has the lowest coefficient of performance among the three environmentally friendly fluids. Finally, the vapor quality of refrigerants at the compressor discharge is plotted in Figure 8. The results were obtained at a compressor isentropic efficiency of 0.7 with condensing temperatures ranging from 90 F to 140 F. The prediction shows that wet compression occurs with the HFOC-LVP and that slightly wet compression occurs for the HFC-LVP when condensing temperatures vary from 120 °F to 140 °F.

CONCLUSIONS

Two low density environmentally-friendly refrigerants HFC-LVP and HFOC-LVP have been identified that are promising for an innovative, centrifugal compressor-based air conditioning system. A basic vapor compression cycle was simulated to compare refrigerant performance. This preliminary thermodynamic analysis shows that HFOC-LVP exhibits a comparable operating efficiency with HFC-134a, while HFC-LVP has higher refrigerating efficiency. In addition, the two environmentally-friendly refrigerants exhibit properties comparable to CFC-113 with reference to vapor quality, volumetric capacity, as well as condensing pressure. Further refrigeration performance analysis indicates that an increase in refrigerating efficiency of 5 % to 15% is possible with HFC-LVP and HFOC-LVP compared to HFC-134a at typical operating conditions.

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