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Review Article

Water as a Refrigerant for Heat Pump Technology: A Review

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Abstract

Even though water (R718) is one of the oldest refrigerants, it is very difficult to use it in compression refrigeration cycle due to its low molecular mass, high boiling point, low specific cooling capacity and a relatively higher value of kinematic viscosity. This paper gives us a glimpse about one of the technique which can be used to use water in compression cycle and also compares its theoretical analysis with the conventional refrigerants already being used. This paper can study the effect on various parameters under similar operation conditions for the comparative study of water and other refrigerants.

Keywords: *Water, Compressor, Temperature lift, pressure ratio, R-134a, Refrigerant*

1. Introduction

Water as a refrigerant is one of the ancient refrigerants being used for refrigeration applications down to about the freezing of water. When water is mixed with protective solutions like propylene or ethylene glycol to prevent freezing so it can be used below its freezing point in applications such as ice slurries. Water is easily available and has one of the best thermodynamics and chemical properties. In spite of these advantages, there are parametric challenges that result from its high specific volume at low temperatures. These challenges include high pressure ratios across the compressor and high compressor outlet temperatures. These difficulties have been solved by designing and manufacturing special compressors for water vapor compression applications. Water as a refrigerant has various applications which include heat pumps, water chiller, vacuum ice production, drying and separation. It also ranges up to applications in agriculture, gas turbine inlet cooling and various other industrial process cooling. A comparative study needs to be done in order to validate the performance characteristics of water and other refrigerants.

2. Literature Review

A very high latent heat of evaporation (2,270kJ/kg) and a high critical temperature (380°C – 386°C) makes water a potentially very efficient refrigerant. Researchers of University of Wisconsin studied that the theoretical COP of R134a is 8.47 which does not differ much from R718 whose COP is 8.39. (B.F. Lachner Jr. *et al.*) studied the economic analysis of the compressor system with respect to the refrigeration capacity and also compared theoretical properties of R718 with that of R134a. Many studies in the literature were based on the applications in which centrifugal compressors have been used. This paper provides the alternate system in which axial compressors with multi-staging is used in order to get improved efficiency. The overall objective of the paper is to compare extensively water as a refrigerant (R718) to the other traditional the refrigerants like, R22, R134a, and R290. (Ali Kilicarslan *et al.*) studied the comparison based on environmental issues (ODP and GWP), safety (flammability and toxicity), COP of the refrigerant in the refrigeration cycle and cycle parameters like specific volume, pressure ratio and discharge temperature. The effects of temperature lift across the evaporator on the COP of the system is been evaluated. A computer code was developed in order to calculate the cycle parameters like the pressure ratios, compressor outlet temperature and the range of evaporator temperature in which R718 gives higher COP than the other refrigerants.

3. Theoretical model

Let us consider a simple vapor compression cycle to compare the results of R-718 with other refrigerants.

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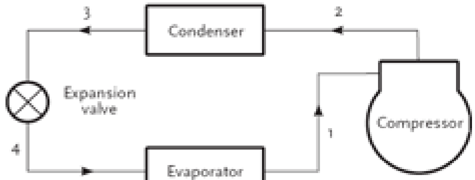
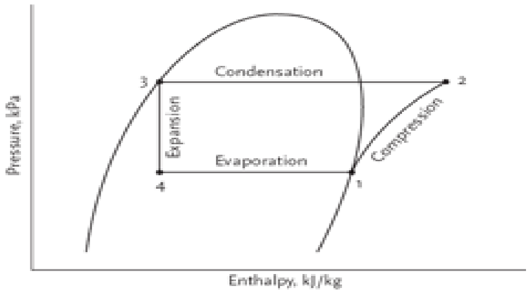


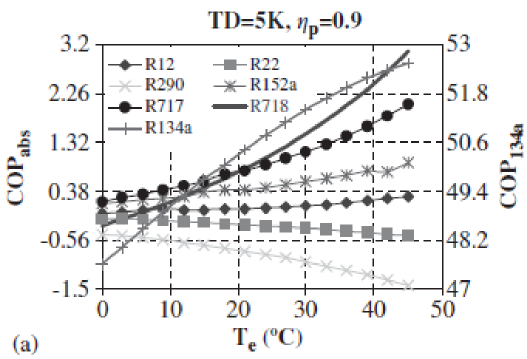
(a)

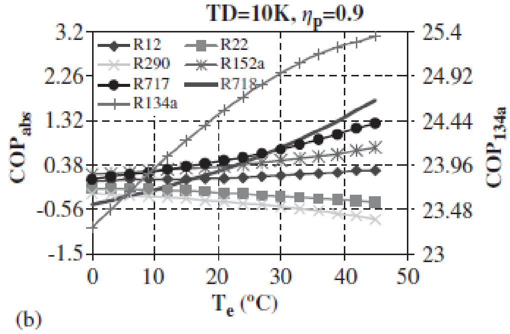


(b)

Fig.1 (a) schematic of a simple VCRC, (b) representation on P-h scale

In this theoretical vapor compression cycle, the refrigerant enters the compressor at state 1 at lower pressure, lower temperature, and at dry saturated state. From state 1 to 2, the refrigerant is compressed by the compressor and is discharged at state 2 as a higher pressure, higher temperature and superheated vapor condition. At state 2, it enters the condenser where it rejects heat to the environment. The refrigerant leaves the condenser at state 3 at higher pressure and liquid state. From there, the refrigerant enters the expansion valve where its pressure is reduced in a throttling process from high pressure to low pressure (i.e. from condenser pressure to evaporator pressure). After this it attains state 4 and enters the evaporator where it absorbs heat from the space from where the heat is taken and then it leaves the evaporator as dry saturated vapor. In this theoretical cycle it is assumed that there is no superheating in the evaporator as well as there is no sub-cooling in the condenser. It is also assumed that there is no pressure drop in between the processes in the entire cycle. The losses due to potential and kinetic energy changes have been neglected.





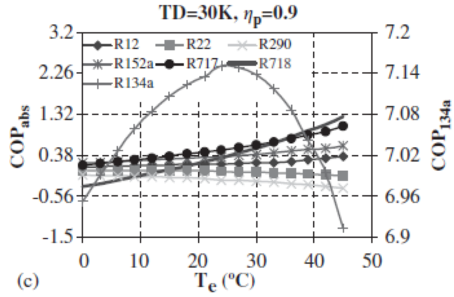


Fig 2 COP_{abs} as a function of evaporator temperature for different TD values

(a)TD=5K; (b) TD=10K; (c) TD=30K. [Ali Kilicarslan *et al.*]

As TD increases, the pressure ratio increases and in turn the compressor power increases. Simultaneously, with increasing pressure ratio the refrigeration effect decreases. Together, they result in a reduced coefficient of performance as can be seen by comparing the plots in Figure 2.

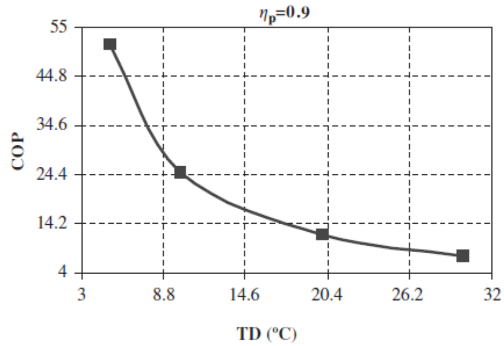


Fig.3 COP of R718 as a function of temperature lift representative for 0....45^{0}C. [Ali Kilicarslan *et al.*]

Fig 3 summarizes the results obtained in fig 2. The COP decreases with the increase in TD.

4. Theoretical comparison of R134a and R718

Table1 Characteristics of R718 vs. R134a [Brandon F. Lachner Jr *et al.*]

Quantity	R718	R134a
Theoretical COP	8.39	8.47
Carnot COP	9.88	9.85
COP/COPcarnot	0.85	0.86

Comp.Outlet Temp.(deg.C)	156	38
Throttling Loss Loss(%)	2	77
Superheat Loss(%)	98	23
Comp.Inlet sp.vol(m3/kg)	132	0.055
Comp. Suction Pressure(kPa)	0.97	370
Comp.Discharge pressure(kPa)	5.7	890
Compression ratio	5.75	2.4
Vol.flow rate(m3/s)	195	1.3
Enthalpy diff. in comp.(kJ/kg)	281	18

The table above shows the theoretical comparison of the characteristics of R718 and R134a. The theoretical COP is nearly same for both the refrigerants observed under a simple vapor compression refrigeration cycle. The data obtained in the table depicts the literature in which the properties of water have been differed from current refrigerants especially from one of the most commonly used refrigerants i.e. R134a. Major difference between the two refrigerants lies in the requirement of the volume flow rate, the compressor outlet temperature and the enthalpy difference across the compressor. Due to these parametric differences, there has to be a significant change in the compressor design and operating conditions so as to use water as a primary refrigerant.

5. Cost Analysis

Fig. 4 Cost of compressor material as a function of impeller tip diameter against the industry response. [Brandon F. Lachner Jr *et al.*]

The graph shows that as the refrigeration capacity is increasing, the cost of the compressor increases. This leads to the need of going for the improvement of efficiency of the compressor used in the system for the long time working cycle of the system. To have this improved efficiency a model which provides a better efficiency in theory has been proposed. There are still considerations on whether this system might actually be put into use. The literature and most of the applications throughout the world using water have been using centrifugal compressors but due to its limitations and above cost considerations, an alternate solution can be developed in order to get better results for a longer period of time.

6. Proposed Model

In this paper a system is proposed which uses an axial compressor in place of centrifugal compressor .This system is proposed in order to overcome the limitations of the centrifugal compressors which depend on the compressor design parameters and also on the properties of water.

Limitations of Centrifugal Compressor

- It has very low isentropic efficiency.
- It is not suitable for multi-staging.
- Requires huge frontal area for given mass flow rate of the fluid.

Properties of R718 causing the use of multi stage axial compressor instead of centrifugal compressor:

- Requirement of refrigerant flow rate of water when compared to R-134a is nearly 200 times.
- Pressure ratio of nearly 10 required by water is difficult to obtain in centrifugal compressors as it is not suitable for multi staging.
- Very high blade tip speed requirement of water also validates the use of axial compressor over centrifugal compressors.

Various configurations of centrifugal compressors were tested in order to obtain the most efficient one with optimum design parameters

Firstly, a single stage a centrifugal compressor was tested under a given set of operating conditions and it gave the following results:

- Low efficiency (less than 75% for radial bladed unit).
- Large impeller size (nearly 20ft dia.).
- Very high impeller tip speeds (2200ft/s leading to huge stresses and high Mach numbers).

Then a two stage centrifugal compressor was tested under the same operating conditions and it showed some improvement in efficiency rising nearly up to 80% with large impeller and relatively lower tip speed (1600ft/s).

The most promising configuration as proposed as a 6-7 stage axial compressor which gave a higher efficiency (nearly 85%) and more feasible size of the impeller (4ft dia.) with optimum blade tip speed (1400ft/s).

The only disadvantage of axial compressors compared to centrifugal compressors is that axial compressors are sophisticated and expensive devices. Thus the initial cost of the system increases making this system less popular to be applied in industries.

Conclusions

The above graphs shows that the use of water as a refrigerant can result in higher COP over the other traditional refrigerants at evaporator temperatures above 350C and at lower evaporator temperatures with either relatively small temperature lift (<10 K) or relatively high temperature lift (>30 K).

When compared to R-134a, R 290 and R 22, R-718 always shows higher COP at evaporator temperature above 160C irrespective of the temperature lift.

If only improvement of efficiency is taken into consideration neglecting other parameters, multi stage axial compressors must be preferred over centrifugal compressors.

Due to a large volume flow rate requirement of R-718 over R-134a, the system gets too bulky which is not always feasible for compressor impellers and outer casing which in turn would affect the cost of the system

At a constant isentropic efficiency of the compressor, the compressor work and pressure ratio increases resulting into decrease in COP with increase in temperature lift.

The cost analysis graph of the compressor material with increase in refrigeration capacity has led to the need of an alternate solution with better efficiency than the system already being used.

The high value of the enthalpy gain across the compressor leads to need for a better material.

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