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Performance Analysis of Isentropic Fluid Based Vapor Compression Refrigeration in Different Weather Conditions in Northern India

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Abstract

This study conducts an experimental analysis of a vapor compression refrigeration system (VCRS) test rig on the basis of first and second laws of thermodynamics. Performance analysis of the VCRS was conducted in winter and summer climatic conditions. The results show that high coefficient of performance (COP) is achieved in winter under both first and second law of thermodynamics analysis.

Keywords: energy analysis, VCRS, hydrofluorocarbon refrigerants, COP_I , COP_{II}

1. INTRODUCTION

Despite the high dependence of the coefficient of performance (COP) of vapor compression refrigeration systems (VCRS) on weather conditions, very little research is done to qualitatively and quantitatively analyze this dependence. Winter conditions do not require the same refrigeration effect like summers, but power and energy are still required for the system performance and its utilization in efficient manner. In northern India, the maximum and minimum recorded temperatures are 45°C during summer and 8-10°C during winter. Practical evaluation using an experimental VCRS machine helps to determine the performance and minimum energy consumption throughout a year. 40-45% of the total energy generated in the world is utilized by industrial processes, of which cooling is a major energy consumer [1]. As a large amount of heat is transferred between various thermal utilities and greatly affects the overall system performance, an in-depth understanding of energy consumption dynamics in cooling and refrigeration systems is important in a world facing climate change.

The main objective of this paper is to compare the performance indicators of VCRS in summer and winter conditions. It presents the results of an experimental analysis of a 1 ton of refrigeration (TR) VCRS test rig based on first and second laws of thermodynamics in winter and summer climatic conditions of northern India. The first law of thermodynamics deals with quantitative approach of energy and its conversion as per requirement, whereas the second law of thermodynamics speaks about actual useful energy supply and allocation of energy losses in the system through exergy analysis.

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2. LITERATURE REVIEW

Many researchers have carried out experimental and analytical work on VCRS using different working fluids and also reviewed the scope of nano-refrigerants. Chembedu [2] conducted a performance analysis on VCRS and found that by introducing components like high energy efficiency ratio (EER) compressor, diffuser at condenser inlet, passing waste heat from condenser to generator, ejector, and fan at evaporator in simple VCRS resulted in an improved performance. Hence, the combined effect of all these components in a single cycle would result in an appreciable improvement in performance when compared with a simple VCRS. Hermes [3] reported a reduction in refrigeration charge in VCRS with a liquid to suction heat exchanger. The analysis was carried out for different refrigerants and it was found that the amount of reduction in refrigerant charge depends on thermodynamic properties of the refrigerant and the working conditions. The real performance of a thermal system and the quality of energy transfer process could be estimated using the second law of thermodynamics, which involves the concept of exergy. Kumar [4] has studied exergy and reported that it is the maximum possible work obtained from a system at a given state when interacting with an environment. It clearly indicates the inefficiencies of a process by locating the degradation of energy. In short, exergy efficiency is the real efficiency and energy efficiency is an approximation of the real efficiency. Senthilkumar and Praveen [5] studied a method that uses natural gas to enhance the energy efficiency of refrigeration retorting method. Under this study, a new nano-refrigerant, produced by mixing CuO nanoparticles with R600a, was employed in the domestic refrigerator. Performance analysis by determining the cooling capacity and energy efficiency ratio of this nano-refrigerant showed that the cooling capacity increased by 10-20%. Another research carried out by VeeraRaghavulu and GovindhaRasu [6] studied the effect of nano-refrigerants on the performance of VCRS to find out which type of lubricant oil works better with nanoparticles. It was concluded that nanoparticles, when mixed with mineral oil, give enhanced results than when mixed with polyol ester (POE) oil. Mishra and Jaiswal [7] experimented with thermo-physical properties by addition of different nanoparticles to ecofriendly refrigerants and analyzed their effects on the COP. The experimental results showed that the thermal conductivity, dynamic viscosity, and density of nano-refrigerants increased when compared to the base refrigerants, while the specific heat decreased slightly. The nano-refrigerant Al₂O₃/R134a showed the highest COP of 35%. Wang et al. [8] proposed a combined power and refrigeration cycle, which combines the Rankine cycle and the absorption refrigeration cycle with binary ammonia-water mixture as the working fluid. He also studied different working fluids with thermodynamic systems. Alawi et al. [9, 10] presented a comprehensive review of fundamentals, preparation, and applications of nano-refrigerants. Physical properties of nano-refrigerants such as density, viscosity, surface tension, and specific heat have a significant effect on nucleate pool boiling, convective flow boiling, and condensation. They concluded that adding nanoparticles to the refrigerant enhanced the heat transfer and that the heat transfer coefficient increased with increased nanoparticle mass fraction. Another research work found that the thermal conductivities of nano-refrigerants are higher than those of pure refrigerants. The power consumption was reduced by about 2.4%, and the COP was increased by 4.4% when nano-refrigerants were used in the place of base refrigerants. The refrigerator's performance was found 26.1% better with 0.1% mass fraction of TiO₂ nanoparticles than that of a refrigerator with HFC134a and POE oil system. Singh and Kaushik [11] computed the thermodynamics of Trigeration (Brayton-Rankine-Kalina combined power cycle) power (TRIGEN) system. Upadhyay [12] examined the effect of sub-cooling on the performance of refrigeration system. In this system a diffuser is used after condenser which converts kinetic energy to the pressure energy of refrigerant, resulting in a reduction of power consumption and

condenser size. Singh and Lal [13] carried out an investigation into the performance of a Nano refrigerant (R134a+Al₂O₃) based refrigeration system. It has been found out that improvement in COP (7.2% to 8.5%) can be achieved with 0.5% Al₂O₃ (% wt.) nanoparticles. When the mass fraction of nanoparticles increased to 1% in refrigerant, COP is found to be lower than from pure R134a and this factor would result in decrease in the refrigeration effect. Shuxue and Guoyuan [14] analyzed thermodynamic model on the two-stage compression refrigeration/heat pump system with vapor injection. The results of comprehensive experiment for the prototype in the study showed that the cooling capacity and cooling COP can increase 5-15% and 10-12%, respectively. Also, the heating capacity with the evaporating temperature ranging from 0.3°C to 3°C is 92-95% of that under the rate condition with the evaporating temperature of 7°C, and 58% when the evaporation temperature is between 28°C and 24°C. Dubey and Mishra [15] studied the effect and performance of R134a ORC based condenser heat recovery system and showed the essential properties of R134a like non-toxicity and non-flammability with zero Ozone Depletion Potential (ODP) value. R134a has a high molecular mass (chemical expression; CF_3CH_2F) of 102 kg/kmol. It has a temperature and critical pressure of 101.1°C and 40.6 bar respectively. This allows it to operate at a higher pressure than atmospheric pressure at condenser part, which prevents any air leakage. Several articles have reported the application and implementation of ORC with R134a as ecofriendly working fluid. She et al. [16] proposed a new sub-cooling method for VCRS depending on expansion power recovery also drive the compressor and expander output performance for sub-cooling cycle. Liquid refrigerant was sub-cooled using evaporative cooler to make a hybrid refrigerant system. Analysis was done by using different refrigerants and results showed that hybrid VCRS have better COP than conventional design.

3. WORKING OF VCRS

Refrigeration is a process of reducing and maintaining the temperature below atmospheric temperature. Of the different types of refrigeration systems, VCRS is the most commonly used system in domestic and industrial applications. The process of a simple VCRS is as follows and the fundamental VCRS cycle is shown in Figure 1.

- Compressor: Low pressure and low temperature vapor refrigerant from evaporator gets compressed to high pressure and high temperature vapor refrigerant in the compressor and then passes to the condenser. This process is isentropic.
- Condenser: Vapor refrigerant gets condensed by rejecting latent heat and then passes to the expansion valve. This is an isobaric process.
- Expansion Valve: In the expansion valve, the pressure and temperature of the liquid refrigerant are reduced and the refrigerant stays in wet condition due to throttling. It is then passed to evaporator. The process occurring in the expansion valve is isenthalpic.
- Evaporator: The wet refrigerant from the expansion valve abstracts latent heat from surroundings/room to be cooled and produces the required refrigeration. The refrigerant is converted to vapor and passed to the compressor to continue the cycle.

4. THERMODYNAMIC ANALYSIS

The experimental system was installed at Refrigeration and Air-Conditioning laboratory of Dept. of Mechanical Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India (Figures 2 and 3). The experimental setup of VCRS has 1 TR cooling capacity for water cooling, ice making

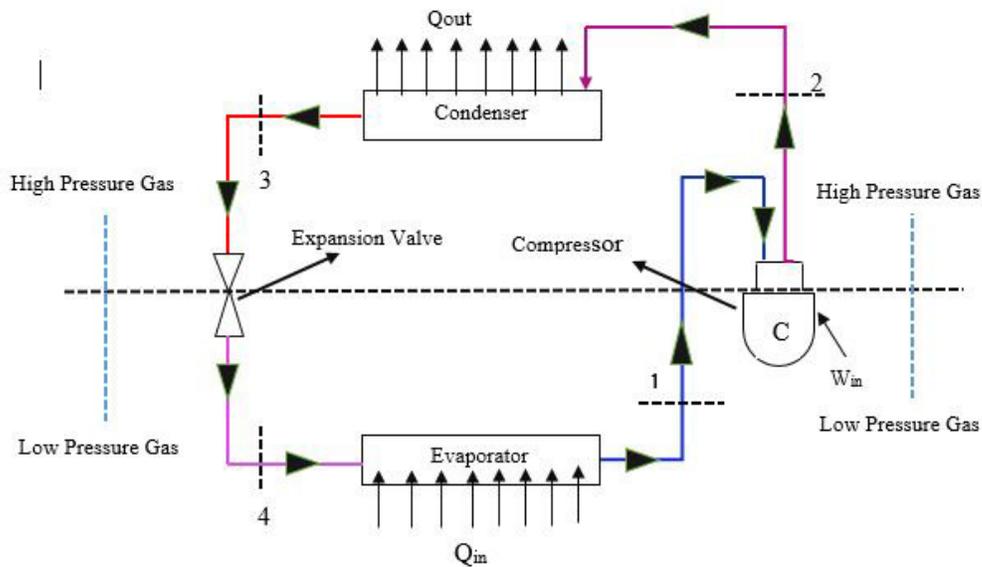


Figure 1: Schematic diagram of VCRS

and food preservation purpose. An R134a refrigerant is adopted for this machine because of its low global warming potential (GWP) and ODP values, non-toxic behavior, and low environmental impact.

The operating temperatures of the various components of the VCRS in summer and winter temperatures are provided in Table 1. This experimental work was carried out on 50-55 kg mass of water for investigating its cooling effect in both kinds of weather, the compressor performance, and the coefficient of performance. The specifications of the components of VCRS test rig are: (All values refer to design/manufacture)

- Compressor: Hermetically sealed compressor of 1/3 TR to work on 220 V AC 50 Hz and operate on refrigerant R134a with standard electrical accessories.
- Condenser: Fins and Tube type air-cooled condenser.
- Fan motor: 1/10 hp condenser fan motor with fan.
- Expansion valve: Capillary expansion valve.

Table 1: Operating temperatures of VCRS components

VCRS component	Summer temperature (°C)	Winter temperature (°C)
Evaporator	16	10
Compressor	60	45
Condenser	43	30
Expansion valve	-5	-10



Figure 2: Laboratory setup of the VCRS test rig



Figure 3: Compressor of the VCRS test rig

5. ENERGY BALANCE

Thermodynamic analysis of the VCRS system was done in consideration of the climatic conditions of northern India. The study follows the basic principles of first and second laws of thermodynamics. The performance of a VCRS is measured by COP, which is based on the first law of thermodynamics. It is the ratio of output, i.e., the cooling effect, to the input, i.e., the work done by the compressor, and is given by Equation 1. The first law of thermodynamics facilitates quantitative assessment of energy, i.e., it treats the work and heat interaction as the transfer of equivalent forms of energy between the system and its surroundings. The actual performance of VCRS is estimated from the experimental setup in the temperature conditions of both summer and winter.

$$COP_I = \frac{RE_{act}}{W_{act}} \quad (1)$$

where,

$$RE_{act} = \frac{M_w C_{pw} \Delta T}{Time} \quad (2)$$

$$W_{act} = \frac{N_p \times 3600}{T_p \times 3200} \quad (3)$$

where m_w is the mass of water; C_{pw} is the specific heat of water at constant pressure; ΔT is the change in temperature; N_p is the number of pulses and T_p is the time for the pulses recorded.

Actual performance of the system is estimated from its maximum (or Carnot) performance using the second law of thermodynamics as given by Equation 5. Carnot performance is computed using Equation 4.

$$COP_{CARNOT} = \frac{T_0}{T_1 - T_0} \quad (4)$$

$$COP_{II} = \frac{COP_I}{COP_{CARNOT}} \quad (5)$$

where COP_{II} is the second law coefficient of performance; COP_I is the first law coefficient of performance; and COP_{CARNOT} is the maximum coefficient of performance of Carnot VCRES cycle.

6. RESULTS

The experimental results have been examined. All performance indicators are shown in Table 2.

Table 2: Parametric results of VCRES experimental setup

Result parameters	Summer	Winter
Compressor work (W_c)	3.11 KW	1.99 KW
No. of pulses and time recorded by energy meter	$N_p = 166, T_p = 60s$	$N_p = 71, T_p = 40s$
COP_I	1.12	1.75
COP_{CARNOT}	1.66	1.81
COP_{II}	0.67	0.96

7. DISCUSSIONS

The present analysis of VCRES test rig deals with comparative performance evaluation in summer and winter temperature conditions of northern Indian climate. The following observations were made after this analysis. (1) Work consumption by compressor in winter is less than that in summer. This is determined by the energy meter pulse reading, which showed that the system consumed less RPM for maintaining 1 TR of cooling load under winter temperature conditions. (2) High values of first law efficiency (COP_I) and second law efficiency (COP_{II}) were recorded in winter, showing that the best performance of VCRES is achieved during the winter season. (3) First law of thermodynamics indicates the quantitative energy transformation, whereas the second law of thermodynamics helps to estimate the actual performance of thermal utilities or processes. (4) The comprehensive review of the present analysis concludes that R134a is a suitable refrigerant for domestic refrigeration applications because of its low value of GWP and ODP, which abides by the safe environmental parameters prescribed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) refrigerants properties report.

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