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Theoretical Investigation of the Performance of Vapour Compression Refrigeration System

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Abstract: Refrigeration plays a major role in the developing era. This study comparatively analysis the thermodynamic performance of refrigerants in a vapour compression refrigeration cycle. The results were analysed with the objective of studying the efficiency of a compression refrigeration cycle system of capacity 1.5 tons. In this analysis, the refrigerants R12 and R22 were considered. The theoretical analysis was conducted and the performance of each refrigerant had been found individually and the results were used to evaluate and compare the evaporating temperatures, condenser temperature, evaporating pressures, condenser pressures, and other parameters and their degree of effect on the performance for both refrigerants. The results showed that the theoretical COP and tonnage capacities of R22 is considerably higher than that of R12. The theoretical COP for R22 is higher by 2.67% when compared with R12. The tonnage capacity of R22 is higher by 7.36%. It was also found that the amount of heat transfer rate or the rate of heat addition and/or rejection for R22 is 35% higher than R12. In addition, the power input for the compressor was less for R22 by 35%. It was concluded that refrigerant R22 is better in all aspects considered in this study.

Keywords: Vapour Compression Refrigeration, Condenser, Evaporator, Refrigerant, COP.

I. INTRODUCTION

Refrigeration has become a major part of the modern living era. Household utilities that make use of the refrigeration concept are very familiar nowadays. Nature works much like a heat engine, heat flows from high-temperature elements to low-temperature elements. The vapor compression refrigeration cycle has four major components namely, compressor, evaporator, condenser, and expansion valve. The commonly used refrigeration cycle is the vapor-compression refrigeration cycle. In an ideal vapor compression refrigeration system, the refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser. It is then throttled to the evaporating pressure and vaporizes as it absorbs heat from the refrigerated space.

A refrigeration system utilizes work supplied by an electric motor to transfer heat from a space to be cooled to a high temperature sink (place to be heated). Low temperature boiling fluids called refrigerants absorb thermal energy to be vaporized in the evaporator causing a cooling effect in the region being cooled. While comparing the advantages and disadvantages of various cooling systems, two most important parameters; the operating temperature and the coefficient of performance are of vital importance in these systems. These systems can be evaluated using energy and energy analyses, which are based on first and second law of thermodynamics.

Vapour compression refrigeration systems are the most commonly used among all refrigeration systems. As the name implies, these systems belong to the general class of vapour cycles, in which the working fluid undergoes phase change. In a vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperatures. The input to the system is in the form of mechanical energy required to run the compressor. Vapour compression refrigeration systems are available to suit almost all applications with the refrigeration capacities ranging from few watts to megawatts. A wide variety of refrigerants can be used in these systems to suit different applications, capacities etc.

II. LITERATURE REVIEW

A very vast literature review has been conducted in vapour compression refrigeration system and is presented. Refrigerant subcooling could increase the refrigerating capacity and potentially improve the performance of refrigeration systems. A novel subcooling method is experimentally studied for the first time in a hybrid vapour compression refrigeration system. Performance of the integrated subcooling cycle is also evaluated; it has a low *COP*, with the maximum value of 0.13, due to the low-grade condensation heat (Xiaohui She et al., 2018) [1]. A parametric study of the condenser subcooling effect on the performance of vapour compression refrigeration system is presented to determine the COP of the refrigeration cycle with subcooling for the three used R12, R134a and R600a as refrigerants. The results obtained through this study have shown that, in the subcooling temperature interval from 0 °C to 14 °C, the condenser additive surface is lower for R600a refrigerant compared to R134a (Djelloul Azzouzi et al., 2017) [2]. Two-stage water vapour compression methods (cascaded centrifugal compressors and combined centrifugal and twin-screw compressors) were proposed and studied to deal with the water compression process with large suction volume flow rates and high compression pressure ratios. The analyses showed that the combined system had high-energy efficiency above 3.4 under all studied working conditions (Jiubing Shen et al., 2019) [3]. A thermodynamic methodology for designing a vapour compression refrigeration system aiming at mesoscale cooling has been presented. When the case where a 5 × 5 cm heat source at 40 °C with the surrounding air at 25 °C is considered, the optimal design provides a cooling capacity of 110 W with a COP of 1.6. If compared to a thermoelectric device available on the market operating at the same conditions, the thermoelectric cooler provided a COP of 0.3, nearly 5 times lower than that provided by vapour compression system analysed in this work (Ricardo and Christian, 2019) [4]. A proof of concept 10 kW cooling capacity hybrid refrigeration machine, designed and built at University of Warwick, is described. The hybrid system uses ammonia mixture R723 (40% Dimethyl ether, 60% Ammonia) which is compatible with conventional refrigeration copper alloy (Cu90Ni10) and environmentally friendly (G. Lychnos and Z. Tamainot-Telto, 2018) [5].

Experimental investigation and theoretical study of a different type of two-stage vapour compression cascade refrigeration system using R-134 as the refrigerant are presented. Performance evaluations of two single stage vapour compression systems and two-stage vapour compression refrigeration cascade system are performed with respect to theoretical model developed (A. Kilicarslan, 2004) [6]. The performance of an ejector refrigeration system using nano-refrigerants is investigated. A new hypothesis is proposed for flow boiling modeling, where nanoparticles are assumed to not migrate to the vapor phase as phase changes occur continuously; this causes a significant increase in nanoparticle mass fraction for high vapor quality values. This assumption shows a reasonable correlation with previously published data for R113/CuO mixtures, where an average deviation of 9.24% was obtained. Furthermore, the refrigerant vapor quality increases at the evaporator exit, leading to an enhanced COP of the cycle. The augmentation in COP reached 24.7% and 12.61% for R134a with 2 wt.% CuO and Al_2O_3, respectively, whereas the vapor quality for the refrigerant leaving the evaporator increased from 0.7616 for the case of the pure refrigerant to 0.8212 for R134a/CuO 2 wt.% nano-refrigerant (Bourhan M. Tashtoush et al., 2017) [7]. A practical miniature and portable vapour compression refrigerator was developed. The dimensions of the refrigerator are 190 mm × 190 mm × 100 mm and its weight is 2.75 kg. Experiments find that the operation of the system is smooth and reliable; the results show that it has a cooling capacity of 260 W, which is high enough for cooling one person with moderate working load, where the ambient temperature is as high as 50 °C and the inlet cold water temperature of the evaporator is 24 °C, respectively. Under these operation conditions, the system COP can reach 1.62 and the reversible efficiency is 0.324 (Weixing Yuan et al., 2015) [8]. A comprehensive investigation of an ejector refrigeration system using conventional and advanced exergy analysis has been presented. The advanced exergy analysis reflects the strong interactions between system components. The ejector has the highest priority to be improved, followed by the condenser and then the generator. The system performance can be largely enhanced through improvements of the ejector and the condenser as well as the generator (Jianyong Chen et al., 2015) [9]. Efforts are on to enhance the performance of adsorption systems through improvements in adsorbents properties, use of advanced cycles, etc. Recent application of nano-technology in the development of adsorbent material may be a big step forward towards making this technology competitive with available technologies in the market. The evolution of the technology and analyses the obstacles to wide spread use of adsorption chillers has been presented (Biplab Choudhurya et al., 2013) [10].

Dry out avoidance control for multi-evaporator vapour compression cycle cooling has been analysed. The control architecture consists of two loops: an outer loop to determine evaporator mass flow rate demand, and an inner loop to supply and distribute the coolant using system actuators. Simulations and corresponding experimental controller validations were conducted using a three-evaporator vapour compression cycle (VCC) testbed with transient imposed heat flux. The full closed-loop system is shown to be able to operate near CHF while avoiding CHF under transient heat flux, demonstrating both efficiency and robustness (Daniel T. Pollock et al., 2015) [11].

III. THEORETICAL ANALYSIS OF VAPOUR COMPRESSION REFRIGERATION SYSTEMS

A simple analysis of standard vapour compression refrigeration system can be carried out by assuming a) Steady flow; b) negligible kinetic and potential energy changes across each component, and c) no heat transfer in connecting pipelines. The steady flow energy equation is applied to each of the four components.

3.1. Evaporator

Heat transfer rate at evaporator, or refrigeration capacity, Q_e, is given by:

$$Q_e = m_r(h_1 - h_4) \tag{1}$$

Where m_r is the refrigerant mass flow rate in kg/s, h_1 and h_4 are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively. $(h_1 - h_4)$ is known as specific refrigeration effect or simply refrigeration effect, which is equal to the heat transferred at the evaporator per kilogram of refrigerant. The evaporator pressure P_e is the saturation pressure corresponding to evaporator temperature T_e.

3.2. Compressor

Power input to the compressor, W_c, is given by:

$$W_c = m_r(h_2 - h_1) \tag{2}$$

Where h_1 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor, respectively. $(h_2 - h_1)$ is known as specific work of compression or simply work of compression, which is equal to the work input to the compressor per kilogram of refrigerant.

3.3. Condenser

Heat transfer rate at condenser, Q_c, is given by:

$$Q_c = m_r(h_2 - h_3) \tag{3}$$

Where h_3 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor.

The condenser pressure P_c is the saturation pressure corresponding to evaporator temperature T_c.

3.4. Expansion Valve

For the isenthalpic expansion process, the kinetic energy change across the expansion device could be negligible as the kinetic energy gets dissipated due to viscous effects, thus:

$$h_3 = h_4 \tag{4}$$

3.5. Coefficient of Performance

The coefficient of performance (COP_T) is defined as the ratio of the heat transfer from low temperature source, to the energy consumption of the compressor.

$$COP_T = \frac{Q_e}{W_c} \tag{5}$$

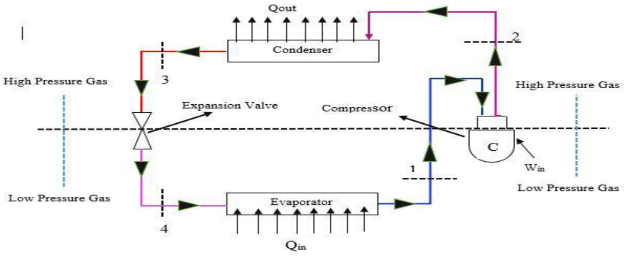


Figure 1: Schematic Diagram of VCRS Model

The refrigerants to be used for the analysis are Dichlorodifluoromethane (R12) and Difluoromonochloromethane (R22). Figure 1 shows a photograph of the model that was used in the study. This section involves tabulation and calculation of the theoretical COPs of the refrigeration system analysed. The analysis used two refrigerants, R12 and R22. The theoretical values were obtained by using software simulating to give results that are more accurate. Table 1 and table 2 indicates the relevant thermodynamics properties and technical data used in the analysis. These properties are needed to determine the heat input to the evaporator, the heat rejected from the condenser, the work input to the compressor, the refrigerant mass flow rate and the coefficient of performance of the system.

Table 1: Technical Data of Air

Density of Air	ρ	Kg/m^3	1.225
Specific Heat of Air	C_p	kJ/kg·K	1.005

Table 2: Technical Data of Compressor Unit

Manufacturer and Model			Tecumseh (AJ5513E)
Type			Reciprocating
Compressor Cooling:			Fan
Voltage, Frequency:	V, f	V, Hz	200-220V ~ 60Hz
Displacement	D	cc	37.55
Evaporating Temp. Range:	T_{eva}	°C	-23.3 to 12.8
Maximum Condenser Temperature	T_{con}	°C	54
Ambient Temperature	T_{amb}	°C	35
Return Gas Temperature	T_{gas}	°C	18.3
Liquid Temperature	T_{liq}	°C	46
Maximum Refrigeration Capacity	RC	Btu/h	20,000
Evaporator Area	A	m^2	0.068625

IV. RESULTS AND DISCUSSION

Figure 2 shows the refrigerant R12 Cycle on P-h Diagram and figure 3 shows refrigerant R12 Cycle Using CoolPack Software Simulator.

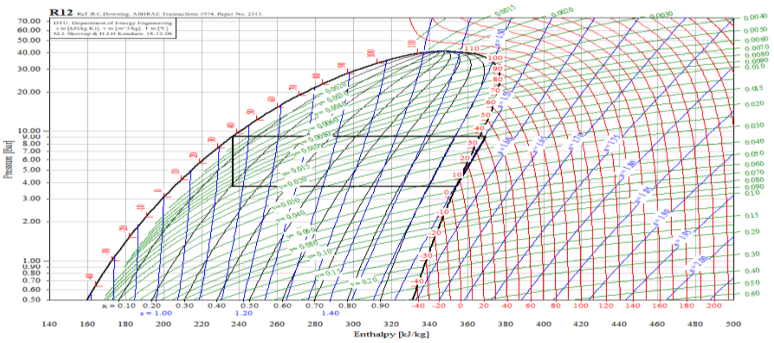
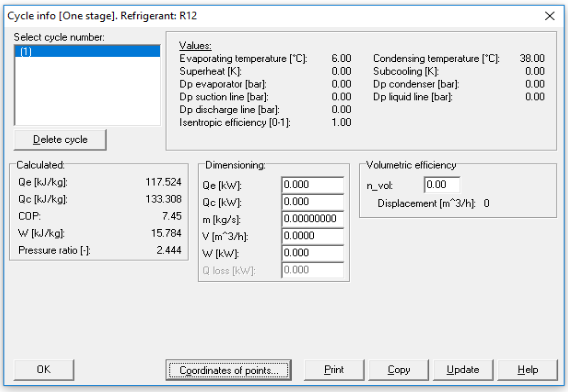


Figure 2: Refrigerant R12 Cycle on P-h Diagram


Cycle info [One stage]. Refrigerant: R12

Select cycle number:
(1)

Values:

Evaporating temperature [°C]:	6.00	Condensing temperature [°C]:	38.00
Superheat [K]:	0.00	Subcooling [K]:	0.00
Dp evaporator [bar]:	0.00	Dp condenser [bar]:	0.00
Dp suction line [bar]:	0.00	Dp liquid line [bar]:	0.00
Dp discharge line [bar]:	0.00		
Isentropic efficiency [0-1]:	1.00		

Calculated:

Qe [kJ/kg]:	117.524
Qc [kJ/kg]:	133.308
COP:	7.45
W [kJ/kg]:	15.784
Pressure ratio [-]:	2.444

Dimensioning:

Qe [kW]:	0.000
Qc [kW]:	0.000
m [kg/s]:	0.00000000
V [m^3/h]:	0.0000
W [kW]:	0.000
Q loss [kW]:	0.000

Volumetric efficiency
n_vol: 0.00
Displacement [m^3/h]: 0

Figure 3: Refrigerant R12 Cycle Using Cool Pack Software Simulator

The theoretical analysis of the vapour compression refrigeration system using R12 is illustrated in table 3.

Table 3: Theoretical Results of Refrigerant R12

Time	t	min	10	20	30	40
Heat Transfer Rate at Evaporator	Q_e	kJ/kg	117.499	117.600	117.482	117.524
Heat Transfer Rate at Condenser	Q_c	kJ/kg	133.405	133.461	133.321	133.308
Work of Compression	W_c	kJ/kg	15.906	15.861	15.839	15.784
Theoretical Coefficient of Performance	COP_T	-	7.39	7.41	7.42	7.45

Figure 4 shows P-h diagram of the vapour compression cycle using refrigerant R22 and the figure 5 shows the results from the CoolPack Software Simulator for refrigerant R22. Table 4 illustrates the theoretical analysis results of vapour compression refrigeration system using refrigerant R22.

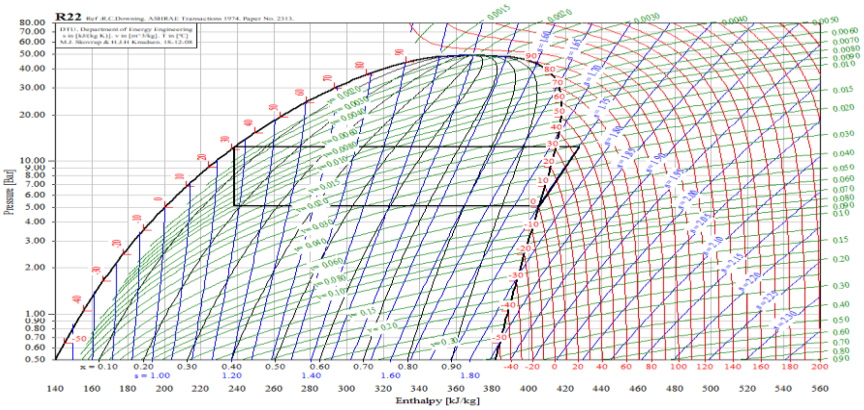
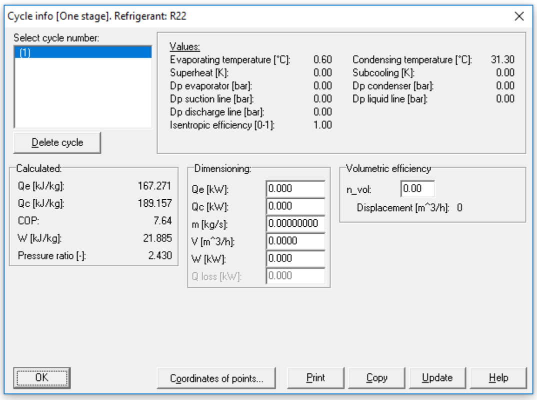


Figure 4: Refrigerant R22 Cycle at t = 40 min on P-h Diagram


Cycle info [One stage]. Refrigerant: R22

Select cycle number:
(1)

Values:
Evaporating temperature [°C]: 0.60
Superheat [K]: 0.00
Dp evaporator [bar]: 0.00
Dp suction line [bar]: 0.00
Dp discharge line [bar]: 0.00
Isentropic efficiency [0-1]: 1.00
Condensing temperature [°C]: 31.30
Subcooling [K]: 0.00
Dp condenser [bar]: 0.00
Dp liquid line [bar]: 0.00

Calculated:
Qe [kJ/kg]: 167.271
Qc [kJ/kg]: 189.157
COP: 7.64
W [kJ/kg]: 21.885
Pressure ratio [-]: 2.430

Dimensioning:
Qe [kW]: 0.000
Qc [kW]: 0.000
m [kg/s]: 0.00000000
V [m^3/h]: 0.0000
W [kW]: 0.000
Q loss [kW]: 0.000

Volumetric efficiency
n_vol: 0.00
Displacement [m^3/h]: 0

Figure 5: Refrigerant R22 Cycle at t = 40 min Using CoolPack Software Simulator

Table 4: Theoretical Results of Refrigerant R22

Time	t	min	10	20	30	40
Heat Transfer Rate at Evaporator	Q_e	kJ/kg	166.978	167.107	167.235	167.271
Heat Transfer Rate at Condenser	Q_c	kJ/kg	189.079	189.141	189.203	189.157
Work of Compression	W_c	kJ/kg	22.101	22.035	21.968	21.885
Theoretical Coefficient of Performance	COP_T	-	7.56	7.58	7.61	7.64

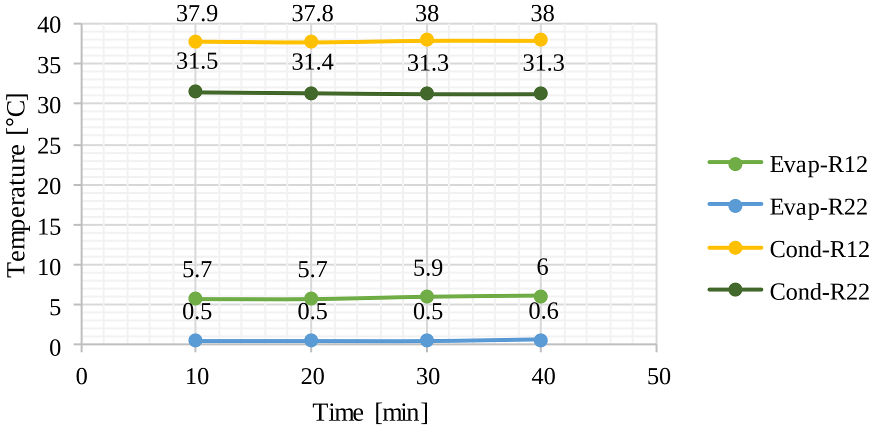


Figure 6: Evaporating and Condensing Temperatures Versus Time for R12 and R22

Figure 6 shows the evaporating and condensing temperatures for each refrigerant. It is noticed that R22 refrigerant has a higher refrigeration capacity. That is the amount of heat absorbed by unit mass of refrigerant in the evaporator is higher for R22.

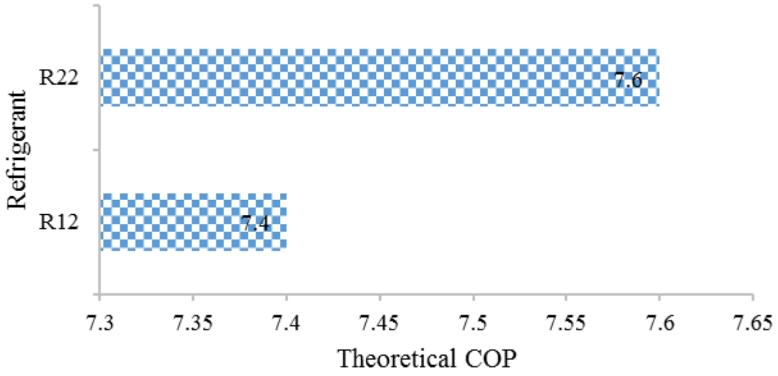


Figure 7: Comparision of Theoretical COP

The COP of refrigeration is another important parameter that gives the ratio of the desired output and the required work input. It is observed from the figure 7, R22 refrigerant is having high theoretical COP of 7.6 when compared with R12 having the COP of 7.4.

V. CONCLUSION

A computational model was followed for the theoretical analysis of the vapour compression refrigeration system with refrigerants R12 and R22. The investigation mainly included the effects of evaporating temperatures, condenser temperature, evaporating pressure, condenser pressure and their degree of effect on the COP for both refrigerants. It was observed that the theoretical COP of R22 is considerably higher than that of R12. The theoretical COP for R22 is higher by 2.67%. This analysis was performed at condenser temperatures ranging from 30 °C and 40 °C and evaporator temperature ranging from 6 °C to 0.6 °C. Conclusively, R22 possess better thermodynamic performances when compared with R12.

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