Combined Effect of Using Sub-cooling Regenerator and Porous Evaporator on the Performance of Refrigeration System

Mohammad Tarawneh

Abstract*: In this experimental comparative study, the combined effect of using sub-cooling regenerator and porous evaporator on the performance of a refrigeration system using R422A and R22 as refrigerants is investigated. The variations of different performance parameters with degree of sub-cooling, porosity of evaporator and effectiveness of regenerator were studied. The two refrigerants under study exhibited similar behavior during the saturation processes. The compressor discharge temperature of R422A was found to be lower than that of R22 when using sub-cooler regenerator and porous evaporator with an average decrease of about 7%. The COP of R422A is greater than that of R22when using empty and porous evaporators and it reached larger values at larger degrees of sub-cooling and lower porosity with increase percentages of about 16% and 10% respectively. The average increase in the refrigeration capacities of R422A and R22 at average regenerator effectiveness when using porous evaporator instead of empty evaporator are 27% and 10%, respectively. R422A has lower power consumption per ton of refrigeration than that of R22 when using porous by about 13% and this percentage reached 9% when using empty evaporators. The pressure drop of R22and R422A is increased with increasing degree of sub-cooling with an average percent decrease of about 29.6%when using R422A instead of R22.

Keywords: alternative refrigerants, liquid suction sub-cooler, Porous evaporator, Regenerator, R22, R422A, Sub-cooling.

I. INTRODUCTION

One of the innovative techniques that is proposed and used by many researchers in literature to enhance the performance of refrigeration system is the use of a regenerative sub-cooler or a liquid-suction sub-cooler which, can be fitted between the condenser and the expansion valve to regenerate the heat of cold gas coming from the evaporator in order to sub-cool the warm liquid refrigerant coming from the condenser to reduce the production of flash gas during the expansion process. The use of this sub-cooler can minimize the losses during the throttling process, reduce the reach of the liquid refrigerant to the compressor and improve the coefficient of performance of the refrigeration system. In this experimental investigation, R422A and R22 as Low -temperature refrigerants were used. Porous evaporator is used to increase the heat transfer rates of the used refrigerants during the evaporation process. Different degrees of sub-cooling in the sub-cooling regenerator were considered during the tests. Most of Low temperature refrigerants have relatively, low heat transfer coefficients and low heat capacities, so it is in need to enhance the heat transfer rates and the coefficients of performances of the refrigeration systems that use these refrigerants. S. A. Klein et al (2000) [1] studied the refrigeration system performance using Liquid-suction heat exchangers, they concluded that, the use of these heat exchangers can improve the refrigeration system performance. Bukola et al (2012) [2] presented a comparative analysis of the performance of hydrocarbon refrigerants with R22 in a sub-cooling heat exchanger refrigeration system. B.O. Bolaji (2014) [3] studied the influence of sub-cooling on the energy performance of two eco-friendly R22 alternative refrigerants, he used two alternative refrigerants, R432Aand R433A to replace R22, and concluded that, these refrigerants exhibited better performance than R22 in sub-cooling heat exchanger refrigeration system. Gustavo et al (2012) [4] conducted an experimental and numerical investigations on the effect of condenser sub-cooling on the performance of vapor compression refrigeration systems, they concluded that, as condenser sub-cooling increased, coefficient of performance reached maximum as a result of a trade-off between increasing refrigerating effect and specific compression work. Prayudi et al (2016) [5] studied the effect of sub cooling on the performance of vapor compression refrigeration systems with cooling load variation. Boloji (2010) [6] studied the effects of sub-cooling on the performance of R12 alternatives in a domestic refrigeration system. Ashish Kumar et al (2013) [7] studied the effect of sub-cooling and super-heating on vapor compression refrigeration systems using R-22 alternative refrigerants. E. G. Saturday et al (2017) [8] presented computer aided comparative analysis on the effects of superheating and subcooling on the performance of R134a and R717 in simple vapor compression systems. M. Tarawneh (2012) [9] presented an experimental heat transfer study on two-phase flow different refrigerants with sub-cooling and super-heating. A.S. Dalkilica et al (2010) [10] presented a performance comparison study using various alternative

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refrigerants in vapor compression refrigeration system. Sharmas et al (2017) [11] studied the performance of vapor compression refrigeration system using HFC and HC refrigerant mixtures as alternatives to replace R22. The effect of degree subcooling on the performance of refrigeration system with CFC, HFC refrigerants is studied by Prayudi et al (2017)]12]. Muhammad et al (2015) [13] investigated the effect of liquid suction heat exchanger sub-cooler on the performance of a freezer using R404a as working fluid. Joaquín et al (2005) [14] presented an experimental evaluation of internal heat exchanger influence on a vapor compression plant energy efficiency working with R22, R134a and R407C.

Based on the above literature, up to the author knowledge and up to the in-hand references, there is no work reported in literature for using porous evaporator combined with regenerative sub-cooler in the refrigeration systems. This experimental work is conducted to evaluate the combined effect of using subcooling regenerator (liquid suction heat exchanger) and porous evaporator on the heat transfer performance of the refrigeration system. The pressure drop behavior during the sub-cooling process of R422A as an alternative Low temperature refrigerant to R22 in vapor compression refrigeration system is investigated for different degrees of subcooling. The experiments were conducted at constant condensing temperature, constant evaporating temperature at 38°C and -20°C, respectively. The tests were run in three cases, once, by using empty evaporator (no porous media is used) using sub-cooler regenerator {[1], [2], [3], [6], [12], [14]}, the other, by using porous evaporator with porosity of 45% without, using sub-cooling regenerator and finally, with using sub-cooling regenerator and porous evaporator.

II. EXPERIMENTAL SETUP

The experimental work is conducted by using the setup shown in Fig.1.The experimental setup consists of vapor compression refrigeration system with evaporator filled with small metallic spheres as porous inserts in the flow passages of the working refrigerants with porosity of 45%. The evaporator consists of 19 mm diameter looped tube. A Subcooling regenerator is fitted between the condenser and the expansion valve at which the heat can be transferred from the warm saturated liquid coming from the condenser and the cold saturated gas coming from the porous evaporator. The test rig is equipped with pressure transducers, which are used to measure the refrigerant pressure throughout the system sections. K-type thermocouples with uncertainty of (±0.5°C) were used to measure the temperature throughout the cycle points. The thermocouples and the pressure transducers are connected with Data Acquisition system of 32 channels (model SCXI 1000, manufactured by National Instruments Company). A computer compatible with LabView software is used to record the pressures and temperatures of each sensor in the cycle and to monitor the steady state conditions during the tests. A hermetic compressor of 0.75 hp is used in the cycle. The test rig is also, equipped with expansion valve, sight glass and refrigerant dryer. R22 and R422A are used, alternatively as working refrigerants during the tests at which, R422A can retrofit R22 easily. Thermophysical properties and composition of these refrigerants compared with other refrigerants are shown in Table I, [3] and [15]. The variations of the saturation pressure and the saturation temperature during the evaporation process are recorded throughout the tests. The effect of inserting the regenerative sub-cooler during complete evaporation process inside a porous evaporator on the performance of the refrigeration system is studied. Pressure drop of the two refrigerant blends in the low-pressure side of the sub-cooler is recorded for different degrees of sub-cooling. The condensation and the evaporation temperatures are kept constants during the tests at 38°C, -21°C, respectively. The degree of sub-cooling is changed throughout the tests in the range of (0 °C to12 °C).

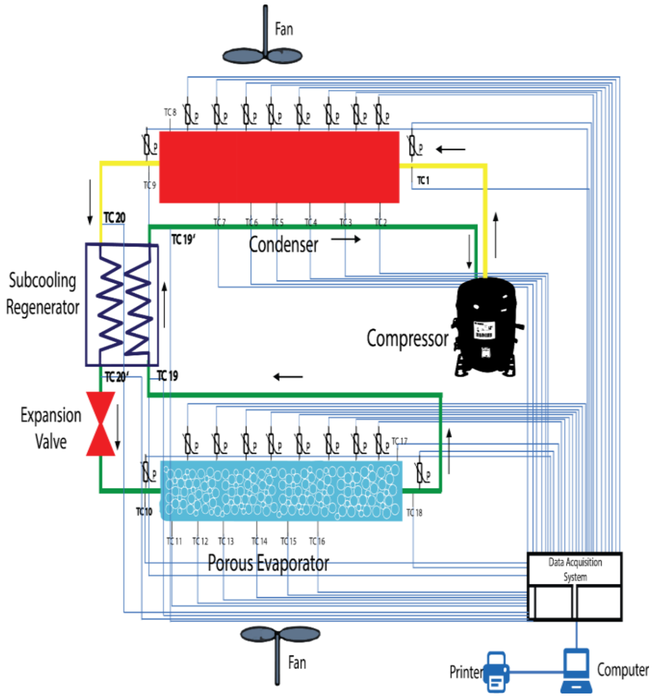

Fig1. Experimental Setup

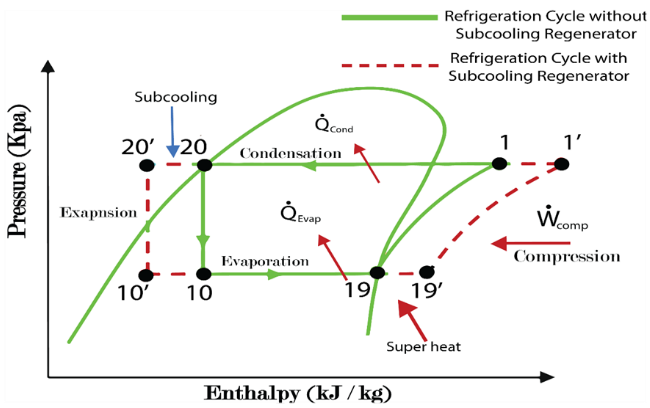

Fig2. P-h Diagram of the cycle

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Table I: Thermophysical Properties and Composition of The Tested Refrigerants Compared to other Refrigerants

#	Name	Critical pressure (bar)	Critical Temperature (°C)	ODP	GWP	Composition
1	R22	49.9	96.14	0.05	1810	HCFC-22
2	R404A	37.289	72.046	0	3920	R-125/R143a/R134a (44.1/51.9/4.0)
3	R422A	37.5	71.8	0	3144	R-125/134a/600a (85.1/11.5/3.4)
4	R407C	46.298	86.034	0	1525	R-32/R125/R134a (23.0/25.0/52.0)
5	R432A		97.3	0	4	R1270 (80%) RE170 (20%)
6	R433A		94.4	0	4	R1270 (30%) R290 (70%)

III. REFRIGERATION SYSTEM ANALYSIS

The combined effect of using porous evaporator and sub-cooling regenerator on the performance of refrigeration system when using two different Low- temperature refrigerant blends is studied during the evaporation process in porous media. Refrigeration capacity, COP, compressor discharge temperature, degree of sub-cooling, relative capacity index, regenerator effectiveness and pressure drop were studied during this experimental work. P-h diagram of the vapor compression refrigeration cycle with and without regenerative sub-cooler is shown in Fig.2. High pressure refrigerant flow meter with a pressure rating of 50 bar is used to measure the refrigerant volumetric flow rates. This flow meter is installed between the condenser and the subcooling regenerator. According to Fig.2, the compressor power in (kW)can be calculated according to the following relation:

$$W_{comp} = \dot{m}_R(h_1 - h_{19}) \quad (1)$$

$$\dot{m}_R = \dot{V}/_v \quad (2)$$

When considering the sub-cooling effect, the refrigeration capacity $(\dot{Q}_r)$in (kW) can be calculated according to the following equation:

$$\dot{Q}_r = \dot{m}_R(h_{10} - h_{19}) \quad (3)$$

When subcooling effect is not considered, the refrigeration capacity $(\dot{Q}_r)$in (kW) can be calculated according to the following equation:

$$\dot{Q}_r = \dot{m}_R(h_{10} - h_{19}) \quad (4)$$

Where: $\dot{m}_R$ is mass flow rate of refrigerant in (kg/s)

$h_{1'}$, $h_{20'}$, $h_{10'}$, $h_{10,}$ $h_{19'}$ are enthalpies of refrigerant at states 1',20',10',10, respectively as show in fig2.

$\dot{V}$ is volumetric flow rate in (m^3/s) and *v* is the specific volume of refrigerant in (m^3/kg)

The coefficient of performance of this refrigeration system is calculated according to the following equation:

$$COP = \frac{\dot{Q}_r}{W_{comp}} \quad (5)$$

The pressure-drop in (kPa) in the Low-pressure side of the regenerator can be calculated according to the following relation:

$$\Delta P = P_{19} - P_{19} \quad (6)$$

Where, $P_{19}$and $P_{19'}$ are the pressures in (kPa) at the inlet and exit of the low-pressure side of the regenerator, respectively. The degree of sub-cooling is calculated according to the following relation:

$$\text{Degree of sub-cooling} = T_{20} - T_{20'} \quad (7)$$

Where, T_{20} and T_{20} are temperatures of liquid refrigerant entering and leaving the regenerator, respectively. The regenerator effectiveness (ε_{Reg}) is calculated according to the following equation [1]:

$$\varepsilon_{Reg} = \frac{T_{19'} - T_{19}}{T_{20} - T_{19}} \quad (8)$$

Where $T_{19'}$ is the temperature of the vapor refrigerant leaving the regenerator, T_{19} is the temperature of the vapor refrigerant entering the regenerator and T_{20} is the temperature of the liquid refrigerant entering the regenerator. The power consumption per ton of refrigeration (PCPTR)in (kW/ ton of refrigeration) is calculated according to the following relation [3]:

$$PCPTR = \frac{3.5W_{comp}}{\dot{Q}_r} \quad (9)$$

IV. RESULTS AND DISCUSSION

Different performance parameters were considered in this experimental comparative study when using a regenerative sub-cooler and porous evaporator in a refrigeration system using R422A as an alternative refrigerant to R22.To ensure that, the two refrigerants under study have the same behavior during saturation processes, the variation of saturation pressure with saturation temperature is plotted in Fig.3. It can be noticed from this figure that the two refrigerants exhibited similar behavior during the saturation processes. The following parameters were studied during this experimental work:

A. Variation of Compressor Discharge Temperature with Degree of Sub-cooling

The variation of compressor discharge temperature with degree of sub-cooling of R22 and R422A at constant condensing and evaporating temperatures of 38°C and -21°C respectively, when using empty and porous evaporators is plotted in Fig.4. The figure showed that, compressor discharge temperature is increased by increasing the degree of sub-cooling and by using porous evaporator.

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The compressor discharge temperature of R422A is seen to be lower than that of R22 when using sub-cooler regenerator and empty evaporator with an average decrease of about 4% and it is still lower than that of R22 when using sub-cooler regenerator and porous evaporator with an average decrease of about 7%.

B. Variation of Refrigeration Capacity with Degree of Sub-cooling and Regenerator Effectiveness

The variations of refrigeration capacity with degree of subcooling and regenerator effectiveness are shown in Fig.5 and Fig.6.It is very clear from these figures that, the refrigeration capacities of the two refrigerants are increased with increasing the degree of sub-cooling as well as with increasing the regenerator effectiveness.

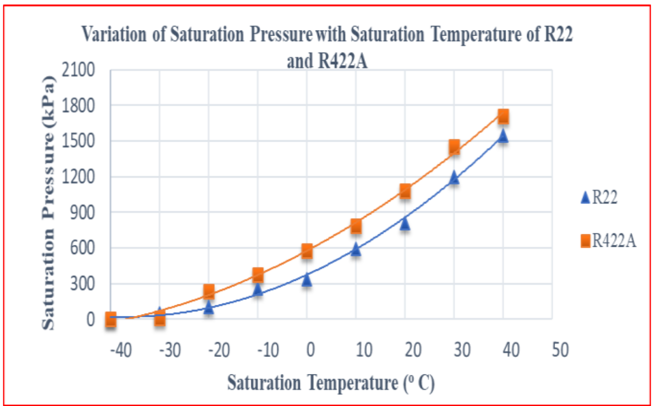

Fig3. Variation of Saturation Pressure with Saturation Temperature of R22 and R422A

The larger refrigeration capacity is achieved at larger degree of sub-cooling, lower porosity of the evaporator and larger effectiveness of the regenerator. R422A exhibited larger refrigeration capacity than that of R22 when using porous evaporator by an average increase of about 20%. It can be concluded from Figs. (5 and 6) that the average increase percentages in the refrigeration capacities of R422A and R22 at average regenerator effectiveness when using porous evaporator instead of empty evaporator are 27% and 10%, respectively.

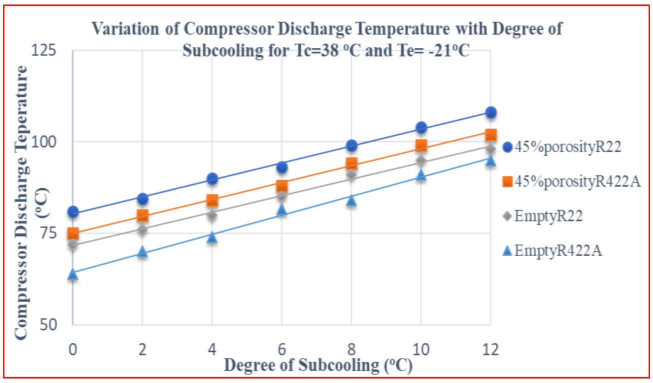

Fig4. Variation of Compressor Discharge Temperature with Degree of Sub-cooling of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous evaporators

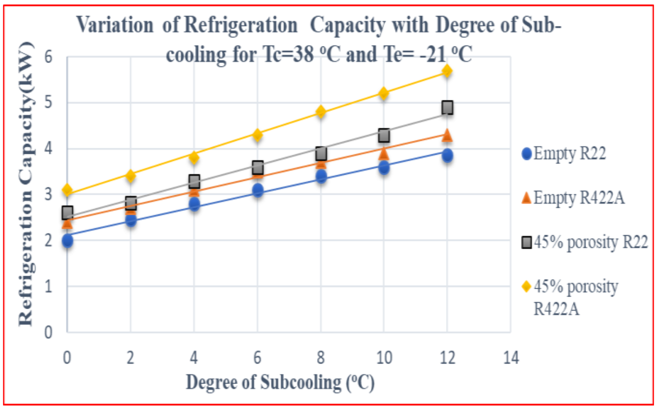

Fig5. Variation of Refrigeration Capacity with Degree of Sub-cooling of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous evaporators

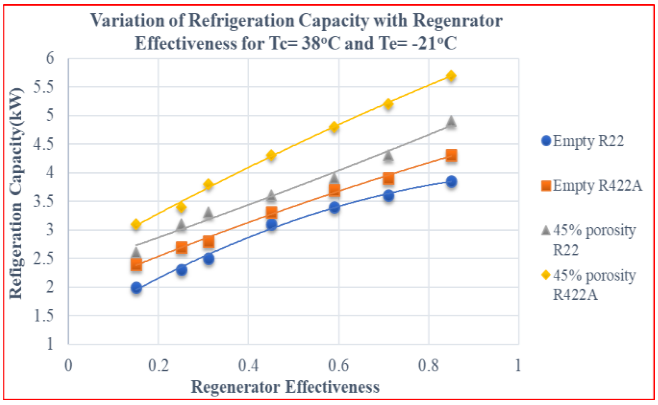

Fig6. Variation of Refrigeration Capacity with Regenerator Effectiveness of R22 and R422A at Tc=38°C at Te = -21 ° C for Empty and Porous Evaporators.

C. Variation of Coefficient of Performance (COP) with Degree of Sub-cooling

The coefficient of performance of R422A and R22 is increasing with increasing degree of sub-cooling in empty and porous evaporators as it is depicted in Fig.7. The experiments revealed that the COP of R422A is greater than that of R22when using empty and porous evaporators and it reached larger values at larger degrees of sub-cooling and lower porosities with increase percentages of about 16% and 10% respectively, as it can be noticed in Fig.7.

D. Variations of Compressor Power Consumption Per Ton of Refrigeration (PCPTR) and Regenerator Effectiveness with Degree of Sub-cooling

The variations of compressor power consumption per ton of refrigeration (PCPTR) and regenerator effectiveness with degree of sub-cooling are shown in Figs. 8 and 9, respectively.

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As it is indicated in these figures, the PCPTR is decreasing with increasing the degree of sub-cooling and decreasing the porosity of the evaporator and the effectiveness of the sub-cooling regenerator.

It can be concluded from Figs.8 and 9 that, R422A and R22 exhibited lower PCPTR at higher degree of sub-cooling, higher regenerator effectiveness and lower evaporator porosity. R422A has lower PCPTR than that of R22 when using porous and empty evaporators by an average decrease of about 13% and 9%, respectively.

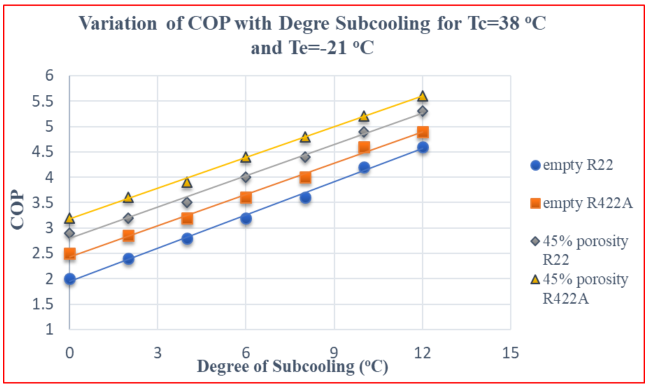

Fig7. Variation of Coefficient of Performance with Degree of Sub-cooling of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous Evaporators

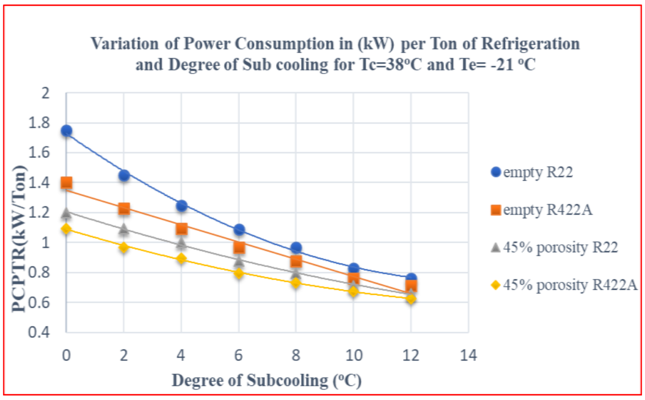

Fig8. Variation of PCPTR with Degree of Sub-cooling of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous Evaporators

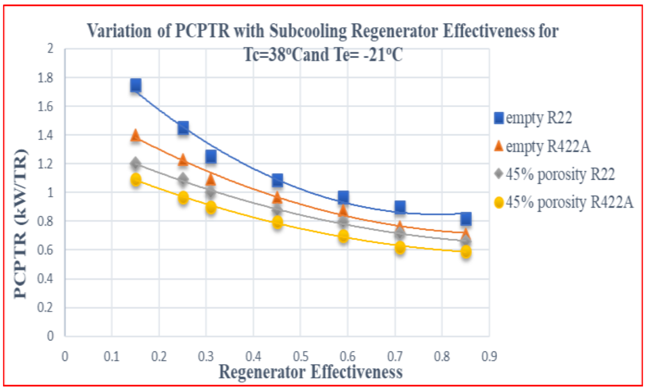

Fig9. Variation of PCPTR with Regenerator Effectiveness of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous Evaporators

E. Variation of Regenerator Effectiveness with Degree of Sub-cooling

The variation of regenerator effectiveness with degree of subcooling is shown in Fig.10.The results of the experiments revealed that the effectiveness of sub-cooling regenerator can be increased by increasing the degree of subcooling and by decreasing the porosity of the evaporators for the given condensing and evaporating temperatures. It can be concluded from figure 10, that the regenerator effectiveness reached largest value of about 85% when using R422A in porous evaporator at degree of sub-cooling of 12oC with an average percent increase of about 28.5% compared to the case, when using empty evaporator. Fig.10 also, showed that, the average percent increase of the regenerator effectiveness of R22 with degree of sub-cooling when using porous evaporator compared to that when, using empty evaporator is a about 32%.

F. Variation of Pressure Drop with Degree of Sub-cooling in Sub-cooling Regenerator

The variation of pressure drops of R22 and R422A with degree of sub-cooling in sub-cooling regenerator is checked for empty evaporator and plotted in Fig.11.As shown Fig.11, the pressure drop of the two tested refrigerants is increased with increasing degree of sub-cooling and the average percent decrease in pressure drop when using R422Ainstesd of R22 is about 29.6%.

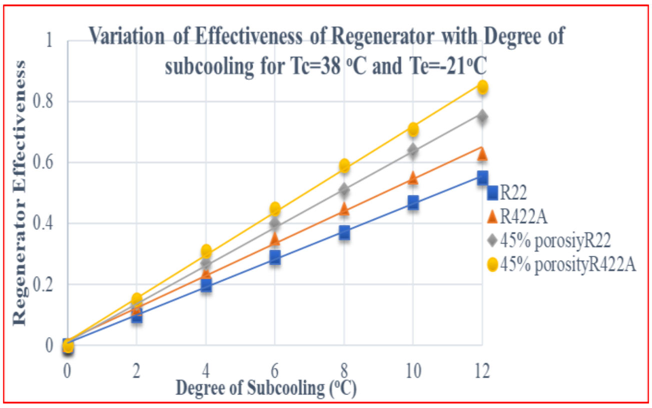

Fig10. Variation of Regenerator Effectiveness with Degree of Sub-cooling of R22 and R422A at Tc=38°C and Te = -21 ° C for Empty and Porous Evaporators

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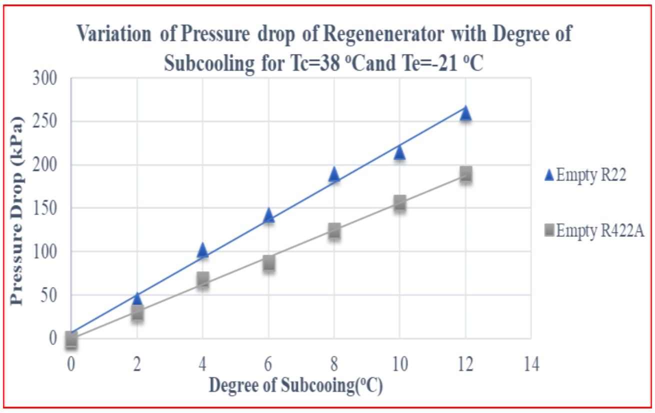

Fig11. Variation of Pressure Drop in Sub-cooling Regenerator with degree of sub-cooling of R22 and R422A at Tc=38oC and Te = -21 o C for Empty Evaporators

V. CONCLUSIONS

In this experimental comparative work, the performance of R422A in vapor compression refrigeration cycle when considering the combined effect of using sub-cooling regenerator and porous evaporator is studied at constant condensing and evaporating temperatures and compared to that of R22 operating at the same conditions.

This study showed that, the refrigerants R422A and R22 have the same saturation behavior during the evaporation process, which gives an indication that, R422A can replace R22 in the vapor compression refrigeration cycles.

It is very clear from the results of this study that, as the degree of sub-cooling increases and the porosity of the evaporator decreases, the refrigeration capacity, COP and regenerator effectiveness increase for the used operating conditions with average increase percentages of 27%,16% and 28.5%,respectively when using R422Acompared to that of R22 with average increase percentages of 10%,10% and 32%,respectively.

It can be concluded from this paper that, PCPTR decreases with increasing degree of sub-cooling and regenerative effectiveness with average percentage decrease of 13% and 9% when using R422A and R22,respectively.This experimental work showed that, the pressure drop of the two tested refrigerants is increased with increasing degree of sub-cooling with average percent decrease of about 29.6% when using R422A instead of R22.

The refrigerant R422A exhibited lower compressor discharge temperature than that of R22 when using empty and porous evaporators with sub-cooler regenerator with average percent decrease of about 7%.

VI. UNCERTAINITY ANALYSIS

An uncertainty analysis on the measured and calculated performance parameters of the used refrigeration system was performed and the results are shown in Table II.

Table II: Uncertainty Analysis

Uncertainty Analysis Results		Uncertainty
Measured Parameters	Volumetric Flowrate (flow-meter reading) (m^3/s)	±0.13 liter/min
	Pressure transducer reading(kPa)	±0.1 bar
	Temperature (^{o} C) (Thermocouple reading)	(±0.5°C)
Calculated Parameters	Refrigeration capacity (kW)	±0.09 kW
	COP	±0.10
	PCPTR (kW/ton)	±0.25(kW/ton)
	Compressor power((kW)	±0.03 kW

NOMENCLATURE

^{o}C: Degree centigrade
Tc: Condensing Temperature in (^{o} C)
Te: Evaporation Temperature in (^{o} C)
W: Watt
P: Pressure (kPa)
h : Enthalpy(kJ/kg)
R: Refrigerant
COP: Coefficient of performance
GWP: Global Warming Potential
ODP: Ozone Depletion Potential
COP: Coefficient of Performance
RCI: Relative Capacity Index
PCPTR: Power Consumption Per Ton of Refrigeration
HC: Hydrocarbon
HCFC: Hydrochlorofluorocarbons
CFC: Chlorofluorocarbon
HFC: Hydrofluorocarbon

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Member of Jordan Engineering Association since 1987.
Member of Jordan renewable energy society since 2009.
Member of National Community of Refrigeration (NCR) since 2011.
Member of International Institute of Refrigeration (IIR) since 2011.