

Research Article

Comparative Thermodynamic Analysis of Vapour Compression Refrigeration System with Dedicated Mechanical SubcoolingSanyam Jain^{1*}, Rohit Punetha², Rohan³, Md Taufique Umar⁴, Keshav Nandan⁵ and Vaibhav Jain⁶¹⁻⁵Student, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, 110086, New Delhi, India⁶Associate Professor, Department of Mechanical Engineering, Maharaja Agrasen Institute of Technology, 110086, New Delhi, India*Corresponding Author: Sanyam Jain Email: jainspirit96@gmail.com

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Abstract: It is known that in countries like India, the demand for high-grade energy is growing continuously. The cost of electricity is also going up with the demand. Many researchers have proved that the Mechanical Sub-cooling of the Vapour Compression Refrigeration (VCR) cycle improves its performance. In the present investigation, a dedicated mechanical sub-cooling system from the thermodynamic standpoint is considered. It was found that the system performance improved when operating in situations where the difference between the condensing and evaporating temperatures is large. The improvement of 6-8% in the Coefficient of Performance (COP) and 20- 170% in the capacity over the simple cycle. Using the sub-cooling, the Second Law efficiency of the cycle increased by 21% and this percentage is directly proportional to the ambient temperature.

Keywords: Refrigeration, VCRS, COP, Subcooling, thermodynamic.

1. Introduction

Globally, we use various devices that help us in our day-to-day lives. Some of them are used to comfort us during hot summers and when the temperature is high in the environment. The refrigeration cycle is a way of routing the heat far from the area you need to be cool. Basically, we need to have a refrigeration system in the devices we use to provide us with the desired temperature [1-3].

1.1 The Vapour Compression Refrigeration Cycle

It is a common system used for the transfer of heat from a low to a high temperature zone. Its purpose is to remove the heat. It has four components: evaporator, compressor, condenser, and expansion valve. It is the most widely used refrigeration cycle. This cycle is mainly finding its place in the majority of our refrigerators, freezers, and air conditioning systems used today. The performance of refrigerators and heat pumps is expressed in terms of the Coefficient of Performance (COP). In an ideal vapour compression refrigeration cycle [4-6].

From Reference[7 - 14], it consists of various parts, including: compressor, condenser, expansion valve/throttle valve, and evaporator. First, the refrigerant enters the compressor at a low temperature and pressure. Compression occurs and leads to a rise in temperature and pressure. After the compression, refrigerant enters the condenser for heat transfer. Here, the heat in the refrigerant is transferred to the stream of water. The water is then sent to the cooling tower for cooling. After processing at the condenser, refrigerant enters the throttle valve, where it expands and releases pressure, and this leads to a drop in temperature. The refrigerant leaves the valve as a mixture of liquid and vapour in a ratio of around 75% and 25% respectively. After the



throttle valve, the refrigerant reaches the evaporator. It is at a lower temperature than its surroundings. It evaporates and absorbs the latent heat of vaporization. Heat extraction from the refrigerant happens at low pressure and temperature. The compressor suction effect helps maintain the low pressure. The cycles continue to run in this way as long as the refrigeration device is in working condition and connected to a power supply [15].

1.2 Benefits of the Vapour Compression Refrigeration Cycle

- The size of the system is small when we compare it to an air refrigeration system for a given capacity of refrigeration.
- Volume of refrigerant used is low, hence the running cost is low as compared to the Vapour Absorption Refrigeration Cycle (VARC).
- The temperature range for operating the cycle is very wide, hence it can be used at almost all places, from your home to supermarkets.
- The cycle requires a small evaporator.
- The temperature of the evaporator is easily adjustable and can be controlled by the expansion valve.
- Latent heat involved in the phase change ensures a high value of heat removal, while the air refrigeration system has sensible heat only [16].

1.3 Drawbacks

- Compressor failure can occur from time to time, which is a costly affair. Some reasons for the failure are lubricating problems, overheating, and contamination.
- The initial cost for installation of the system is high, and refrigerant is also very expensive.
- Some of the refrigerants used are very harmful to the environment [17].

1.4 Different Methods of Subcooling

- Liquid Suction Heat Exchanger
- Dedicated Mechanical Subcooling
- Integrated Mechanical Subcooling

The above systems are generally used in the industry nowadays, but this project is based on dedicated mechanical subcooling.

2. Working of Dedicated Mechanical Subcooling

To increase the COP of the refrigeration system, we use different methods; among them, the authors have chosen a dedicated mechanical subcooling system for this research work. The schematic representation is shown in Figure 1, and the P-h diagram in Figure 2. In the Dedicated Mechanical Subcooling (DMS) cycle, authors used refrigerant ammonia (R-717) as base refrigerant in both main and subcooled cycle from (R-314a, R-32, etc).

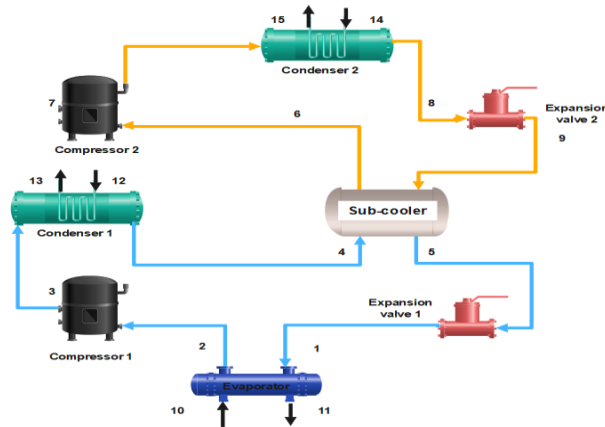


Figure 1: Shows a Schematic representation of the Dedicated Mechanical Subcooling Setup

Components chosen for this system were two compressors, two condensers, one sub-cooler, an evaporator, and two expansion valves, as the research was in an ice-cooled refrigeration system; hence, the temperature at the evaporator (T_e) -20°C and the temperature at the condenser (T_c) 40°C were taken[18]. The refrigerant of the main cycle leaves the evaporator (state-1) with a refrigerant mass flow rate given in equation-1:

$$\dot{Q}_{\text{evap}} = \dot{m}_{\text{ref},\text{main}}(h_2 - h_1) \quad (1)$$

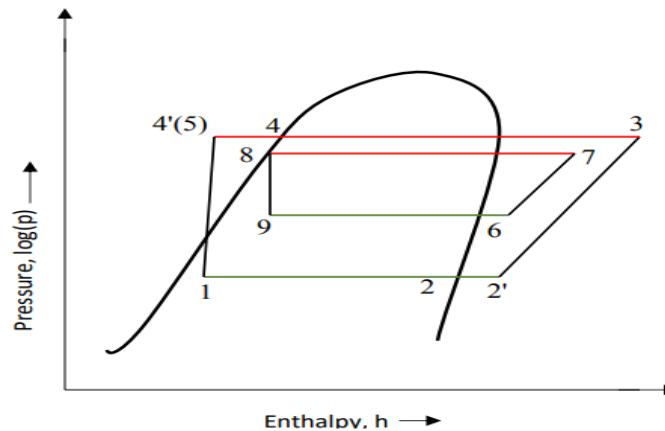


Figure 2: Shows the P-h curve for dedicated mechanical subcooling

From the Reference, it is a saturated vapor with low temperature and low pressure, where air cooling is done on it with a temperature of $(T_e + 10^\circ\text{C})$ to take away further heat from the refrigerant. Now the refrigerant is converted into vapor form due to heat absorbed from the evaporator and then transferred into the compressor (state-2), where it is converted into superheated high-pressure and high-temperature vapor form isentropically with an isentropic efficiency ($\eta = 0.8$) using power given in equation-2:

$$\dot{W}_{\text{comp},\text{main}}^{\text{isen}} = \dot{m}_{\text{ref},\text{main}}(h_2 - h_3) \quad (2)$$

Now, hot refrigerant will pass through the condenser with a refrigerant flow rate given in equation 3

$$\dot{Q}_{cond,main} = \dot{m}_{ref,main}(h3 - h4) \quad (3)$$

The condenser will remove heat from the hot refrigerant gas vapor until it condenses into a pressure-saturated liquid state, or condensation. Further air cooling is done in the condenser using heat exchangers to further cool the refrigerant, whose modelling is done using Log Mean Temperature Difference (LMTD) given in equation 4

$$LMTD_{cond,main} = \frac{T_{13} - T_{12}}{\ln \frac{T_c - T_{12}}{T_c - T_{13}}} \quad (4)$$

Now the saturated liquid refrigerant will enter the sub-cooler (state-4) for the subcooling cycle, where it will be cooled below saturated liquid temperature at constant pressure, and to lower the temperature further, so as to protect the expansion device, refrigerant flow from the sub-cooler is given in equation-5

$$\dot{Q}_{sub} = \dot{m}_{ref,sub}(h4 - h5) \quad (5)$$

Also, in the sub-cooler, the Log Mean Temperature Difference (LMTD) will occur as given in equation 6

$$LMTD_{cond,sub} = \frac{(T_4 - T_6) - (T_5 - T_9)}{\ln \frac{T_4 - T_6}{T_5 - T_9}} \quad (6)$$

Now the refrigerant leaves for (state-5), which is from the expansion valves of the main cycle, and it leaves this (state-5) as low vapor for the evaporator (state-1), where it will be evaporated to a saturated vapor state at constant pressure, and hence the process continues.

From the sub-cooler, the refrigerant of the subcooler cycle will go through the normal VCRS cycle to work as a heat exchanger refrigerant for the main cycle, and it enters the sub-cooler cycle compressor (state-6) as a low temperature and low pressure saturated vapor, where the work done by the compressor was calculated by equation-7

$$\dot{W}_{comp,sub}^{ideal} = \dot{m}_{ref,sub}(h7 - h6) \quad (7)$$

Now the refrigerant left for the condenser(state-7) from the compressor as superheated vapor was calculated as given in equation 8

$$\dot{Q}_{cond,main} = \dot{m}_{ref,sub}(h7 - h8) \quad (8)$$

As the refrigerant leaves the condenser as saturated liquid, it enters the expansion valve (state-8) of the sub-cooler cycle, and leaves it as low-quality vapor to enter the sub-cooler (state-9) with the refrigerant flow rate at the sub-cooler as given in the equation below 9

$$\dot{Q}_{sub,main} = \dot{m}_{ref,sub}(h6 - h9) \quad (9)$$

Hence, the value of the refrigeration effect decreases with constant work with the help of a sub-cooler. Coefficient of Performance (COP) for the main cycle was calculated using equation 10

$$COP_{main} = \dot{Q}_{evap} / \dot{W}_{comp,main}^{isen} \quad (10)$$

The coefficient of Performance (COP) for the sub-cooler cycle was calculated using equation 11

$$COP_{sub} = \dot{Q}_{sub,main} / \dot{W}_{comp,sub}^{ideal} \quad (11)$$

Overall Coefficient of Performance calculated by equation 12

$$COP_{overall} = \dot{Q}_{evap} / (\dot{W}_{comp,sub}^{ideal} + \dot{W}_{comp,main}^{isen}) \quad (12)$$

2.1 Assumptions in Modelling

- Kinetic difference and potential difference are considered zero.
- Friction losses and transfer of heat from the system to the environment are considered negligible in pipes.
- An isenthalpic process is considered in expansion valves.
- Under steady-state conditions, the present analysis is done with imperceptible pressure loss in the pipelines of system components

2.2 Thermodynamic Modelling

To evaluate exergy and energy performances of the system, a thermodynamic model is being constructed in this research. Minimum work required to bring the system from a dead state to a given state is known as exergy, given in below equation-13

$$\sum \dot{E}_{x_{in}} - \sum \dot{E}_{x_{out}} = \sum \dot{E}_{x_Q} - \sum \dot{E}_{x_W} - \sum \dot{E}_{x_{dest}} \quad (13)$$

Conservation of energy, which is energy entering the system, is totally converted into work used and shown in equation 14

$$\dot{Q} - \sum \dot{m}_{in} \dot{h}_{in} = \dot{W} + \sum \dot{m}_{out} \dot{h}_{out} \quad (14)$$

Mass balance is the conservation of mass; that is, the mass of refrigerant entering and leaving the components of the system is the same. The mass balance equation is shown in equation 15

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (15)$$

2.3 Performance indicator

The COP is defined as the energy conversion efficiency in the system; the net cop is the ratio of total heat transfer to the total work done by the compressor. Equation (12) shows the formula for net cop (cop_{net}).

$$COP_{net} = \frac{\dot{Q}_{e1}}{(\dot{W}_{comp1} + \dot{W}_{comp2})}$$

The irreversibility of each component of the system can be calculated from the Gouy-Stodola principle in equation (16), such as:

$$i_k = T_o S_{gen,k} \quad (16)$$

$$\forall k \in EQS \cap \{\text{evap1, comp1, cond1, exp1, sub, comp2, cond2, exp2}\}$$

The detailed equation for irreversibility (i_k) of different components is given in Table 3. The total irreversibility(i_t) of the system is calculated through equation (17)

$$i_t = i_{\text{evap1}} + i_{\text{comp1}} + i_{\text{exp1}} + i_{\text{cond1}} + i_{\text{sub}} + i_{\text{comp2}} + i_{\text{exp2}} + i_{\text{cond2}} \quad (17)$$

The Second Law efficiency of the proposed system is calculated by the equation (17), where $\dot{E}_{in}$ is the total work input to the system through compressors, as shown in equation 18

$$\eta = 1 - \frac{i_t}{\dot{E}_{in}} = 1 - \frac{i_t}{\dot{W}_{\text{comp1}} + \dot{W}_{\text{comp2}}} \quad (18)$$

3. Results

3.1 Process data

R717 is taken as a refrigerant for the main and sub-cooler cycle for the study of dedicated mechanical subcooling, where the temperature of the evaporator is -25 °c, as our system was a making system and the condenser temperature chosen was 40°C with 5°C as the degree of overlap. Further, EES code is developed for the analysis of the refrigeration cycle.

3.2 Base case result

The reference was a simple vapour compression cycle with R-717 as the only working fluid. The System was examined for twenty-five different operating Scenarios and the Performance results. The COP of the Main Cycle is 2.966, the COP of the Sub-Cooler Cycle is 28.72, and the Net COP of the Cycle obtained 2.959 with an Efficiency of 0.5107 (Table 1).

3.3 Parametric study

Table 1: 2nd Law efficiency and Net COP of different types of refrigerants

Type of Refrigerant in the sub-cooler cycle	2 nd Law Efficiency	Net COP
R-717	0.5107	2.959
R-134a	0.4907	2.837
R-32	0.4824	2.787
R-290	0.4842	2.798

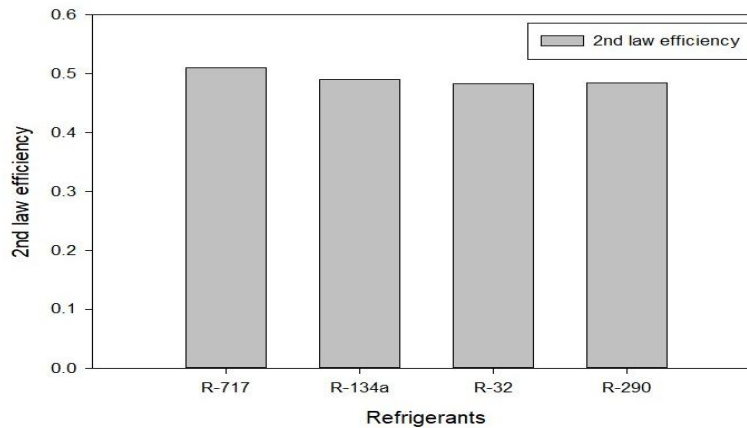


Figure 3: Shows the Effect of alternative refrigerants on 2nd law of efficiency

It is clear in Figure 3 that R717 gave the highest Second Law efficiency of 0.5107 as compared to other refrigerants.

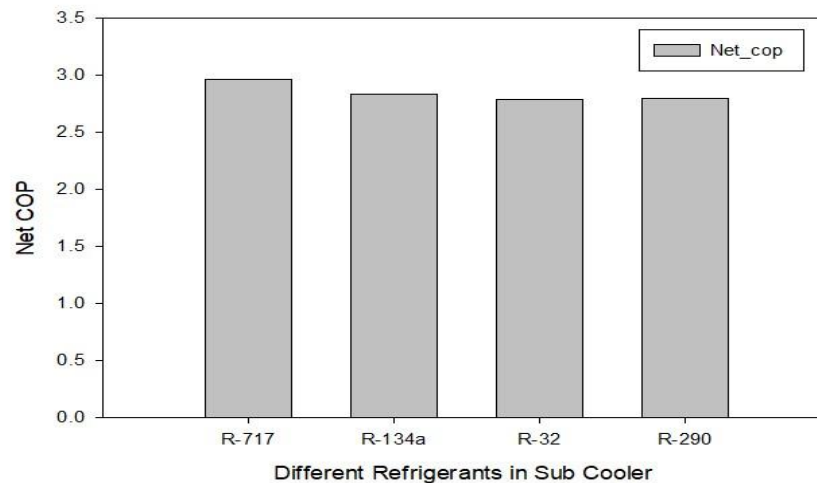


Figure 4: Effect of Alternative Refrigerants on Net COP

In Figure 4, it is shown that Net COP is highest in the case of R717 compared to other refrigerant

4. Conclusion

1. Using R717 in the VCRS cycle, including the Dedicated Mechanical Subcooling Cycle (DMS), maximum efficiency is achieved.
2. The net COP and the 2nd Law of efficiency are increasing when the degree of subcooling increases.
3. Maximum net COP is made at -20°C as the net COP and the 2nd law of thermodynamics both will reduce.
4. Some optimization can be done by taking some of the variables, like the environment temperature of the main cycle, the degree of subcooling, and the degree of overlap.

5. Nomenclature

P Pressure

T	Temperature
°C	Celsius
K	Kelvin
dest	destruction
net	Net
μ	Efficiency
Σ	Summation
VCRS	Vapor-Compression Refrigeration System
EES	Engineering Equation Solver
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
COP	Coefficient of Performance
RAC	Refrigeration and Air Conditioning
HFC-134a	Hydrofluorocarbon-134a
CFC-22	Chlorofluorocarbon-22
LTC	Low Temperature Circuit
HTC	High Temperature Circuit
T	Temperature (k)
P	Pressure (kPa)
Exp	Expansion
Cond	Condenser
Subs	Sub-cooler
Comp	Compressor
$\dot{m}_{out}$	Mass flow rate out
h_{out}	Enthalpy out
$\dot{Ex}_{in}$	Exergy in
$\dot{Ex}_{out}$	Exergy Out
$\dot{Ex}_Q$	Exergy transfer through heat
$\dot{Ex}_W$	Exergy transfer through work
$\dot{Ex}_{dest}$	Exergy transfer through destruction
COP_{net}	Net Cop

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