

Research Article

Theoretical Evaluation of Vapor compression refrigeration cycle with integrated mechanical subcooling

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Abstract: This paper analyzes a vapor-compression refrigeration system with integrated mechanical subcooling. With the increasing power demand of the VCRS cycle, the need for its cop improvement has increased. To reduce its power requirement, the subcooling is studied theoretically. The theoretical analysis is done on the Engineering Equation Solver software. Different variations are plotted using the software, and reasons are stated for the different variations. Different optimization techniques are used for optimizing the system variables. The variables optimized include evaporator temperature, condenser temperature, subcooling temperature, and overlap temperature. The cop is found to increase by 3.5%. The optimization algorithm used is the gradient search method. The results will be used by the industry to improve refrigeration systems.

Keywords: R134a, Subcooling, Theoretical, Refrigerant, VCRS.

1. Introduction

The Vapour compression refrigeration system is the most economical refrigeration cycle. It provides great COP to all kinds of systems. It is used in almost all kinds of refrigeration spaces. It is widely accepted worldwide. But this cycle has its drawbacks. The first one consumes more energy [1]. The ASHRAE Society is always seeking renewable solutions in the HVAC industry. The positive aspects of this cycle are endless, but with the increasing demand for energy and HVAC as a whole, the industry needs innovation in this technology. The most prominent way is to introduce the subcooling cycle in the main cycle. This will improve the system's COP. Hence, it reduces its power requirement. There are two kinds of systems in this domain. The dedicated cycle and the integrated cycle[2-3].

Srivastava & Bajpai (2018) compared simple VCRS with the VCRS system with Integrated Mechanical Subcooling. It's seen that the cooling capacity increased by 30.33% compared with the simple VCRS. Various COPs at different degrees of subcooling are calculated and plotted. System design shows that the COP will increase when a VCR with integrated Mechanical Subcooling is used in a larger refrigeration system. Zubair used the first and second laws of thermodynamics to investigate a mechanical subcooling loop for better COP. According to the first law of thermodynamics, the COP increases with the temperature difference between



the condenser and the evaporator. But it couldn't identify the source of the losses when the Second Law analysis was performed on both, a simple VCRS and a VCRS with a mechanical subcooling loop. It was found that COP improved significantly by reducing irreversibility during the expansion process. The notable observations were an 85% reduction in power input, a 65% reduction in irreversibility rate, and a 20% reduction in refrigerant flow rate. Khan & Zubair (2000) demonstrated that COP improves and that this improvement is related to the refrigerant saturation temperature of the Subcooler. The model used can predict the optimal distribution of the total heat exchanger area between the evaporator and the condenser. At the exit of the condenser, subcooling the refrigerant allows it to absorb more heat in the evaporator, thereby increasing the COP. In this paper, an experimental study is done by using different hydrocarbon blends in the mechanical Subcooling system integrated with the main vapour compression refrigeration system[4].

Hamad (2016). worked with a Blend of R-290/R-600a is, with mass fractions of (60/40, 50/50, and 40/60), compared with R-134a. Results show a 14% increase in COP, 6% increase in refrigeration effect while hydrocarbons are used. On comparison, the lower values of pressure ratio and discharge temperature are noticed for R-290/R-600a.

This shows that hydrocarbon blends are an efficient, economically feasible, and eco-friendly alternative for R134a, in VCRS with a subcooling circuit[5].

But they are highly flammable; therefore, these hydrocarbons require a specific system design and suitable operating and regular maintenance to prevent leakage. In this paper, an experimental study is done on a residential 1.5-ton simple VCRS with and without the dedicated subcooling cycle, to maintain the temperature between 18 °C and 22 °C. R22 and R12 are used in the main cycle and the Subcooling cycle, respectively. Outcomes show that load carrying capacity increased by 0.5 KW approx when R22 is subcooled in the main cycle by 5-8 °C. The second law efficiency increases by an average 21%. The general trends show that efficiency is incredibly proportional to the ambient temperature variation.

In this research paper, the trend of various temperature changes is noticed, and their effects on the COP of the system are discussed. The software used for mathematical modelling is the EES software. The trends are explained with reasons.[6-7] The cop is varied with Evaporator, condenser, subcooling, and overlap temperature. Further conclusions are drawn and evaluated, paving the way for experimental work.

2. Cycle Description

Two cycles made up the VCRS cycle with integrated subcooling. The principal cycle and the supporting cycle. Evaporator, compressor, subcooler, receiver, and condenser are components of the main cycle. The 1/3 Tr compressor is included in the auxiliary cycle. The subcooler and condenser are shared by the main cycle and the auxiliary cycle. The cycle's subcooling is carried out via the auxiliary cycle. A specific kind of heat exchanger is the subcooler. It is in charge of carrying out the heat exchange. The main cycle's subcooling is brought on by heat exchange[8]. The refrigerant and cycle are able to obtain a greater coefficient of performance with additional expansion in the main cycle. At state 1, the saturated low-pressure, low-temperature vapour enters the main cycle compressor. From state 1 to state 2, the refrigerant absorbs heat from the environment through the suction line. When it reaches state 3, it exits the compressor as a high-pressure, superheated vapour with a high temperature. The refrigerated mixture enters the condenser after mixing with the sub-cooler cycle refrigerant that is being released from the sub-cooler cycle compressor from State 3 to 4. After leaving the condenser, the mixture is collected in the receiver.

A portion of this liquid refrigerant mixture is taken out of the receiver, expanded during the subcooler cycle's expansion valve, and then sent through the subcooler.

The subcooler cycle refrigerant cools the remaining liquid refrigerant in the receiver to a state six below the saturated liquid state at a steady pressure. It enters the main cycle expansion valve, exits as a low-quality vapour at state 7, and then enters the evaporator[9] to the saturated vapour stage in the evaporator under a constant pressure. After chilling the main cycle refrigerant in the subcooler, the subcooler-cycle refrigerant exits as a low-pressure, low-temperature, saturated vapour at state nine and enters the compressor at state 10. The refrigerant in numbers 9 and 10 absorbs heat from the environment. After leaving the compressor in state 11 as a superheated vapour, it mixes with the main cycle refrigerant to reach state 13 by doing so[10]. Figure 1 and Table 1 show the systematic representation of the vapor compression refrigeration cycle with integrated mechanical subcooling and Process parameters.

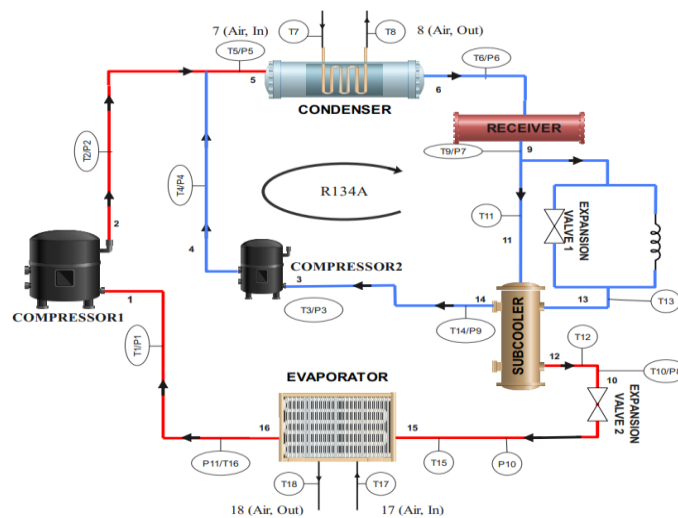


Figure 1:Systematic representation of vapor compression refrigeration cycle with integrated mechanical subcooling.

Table 1: Process parameters

Process Parameters	Temperature(<i>t</i>)
Temperature of evaporator (<i>T_e</i>)	0degree C
Temperature of condenser (<i>T_c</i>)	40degree C
Degree of overlap	5degree C
Degree of range	5degree C
Degree of subcooling	5degree C

3. Results

The VCRS cycle with integrated subcooling is modelled using EES software. The trend of evaporator, condenser, subcooling, and overlap temperature is noticed and explained with relevant details. It is noticed that COP is increased with increasing subcooling; the cop of the system increased continuously[11-12].

3.1 Results at base case

Increase the cop using various methods like diffuser, sub-cooler, different using certain refrigerant blends Increasing the cooling capacity of VCRS cycle. The base condition that we have is $T_e = 0^\circ\text{C}$, $T_c = 40^\circ\text{C}$, $dT_{\text{overlap}} = 5^\circ\text{C}$, $dT_{\text{sub}} = 5^\circ\text{C}$, and the refrigerant is R134a. These are the base conditions of individuals, based on which we vary them 5° up or down for each one.

3.2 Parametric study

Parametric study is a method of calculating the variation in different parameters by changing one or more parameters. Tables can be formed for putting different values. The resulting variable can then be noticed. The changes can be measured and plotted using the graph section. The parametric study is the concept used in the Engineering Equation Solver software extensively.

We measured the variations of all parameters using a parametric study. The difference is plotted using a graph.

3.2.1 Refrigerant

There are a lot of refrigerants on the market. For example, R 717, R410a, R407c, R134a, etc. There are properties that are used to classify ideal refrigerants. These properties include non-corrosive and nontoxic. The refrigerant should be according to the system requirement. Our requirement matches with one refrigerant with pressure and temperature at optimum levels. The most important properties are the boiling point. We use R134a against R410a due to its easy availability in the market. The optimum pressure of R410a is 150-200 psi, and R134a is 60-70 psi. Both refrigerants are good with desirable properties, so either refrigerant will work. We chose R410a according to our needs.

3.2.2 Evaporator temperature (T_e)

The Evaporator temperature is varied with the COP of the system. The COP is increasing with increasing Evaporator temperature. This is due to the decreasing work input of the cycle. Since COP and the work input of the compressor are inversely proportional. Hence, COP will increase. The Evaporator temperature is varied by 10 degrees, from -5 to 5 degrees. The percentage increase in COP is 23.2%. The results are verified by Optimization algorithms. Figure 2 shows the Evaporator temperature(T_e)

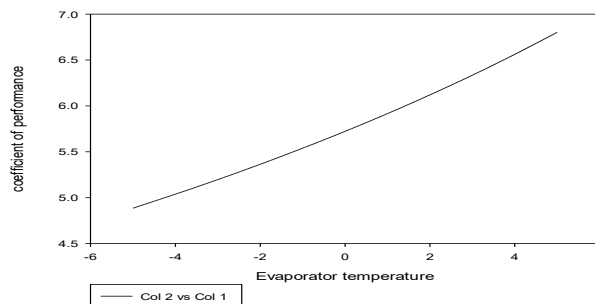


Figure 2:Evaporator temperature(T_e)

3.2.3 Condenser temperature (T_c)

The trend in COP of the system is decreasing with increasing Condenser Temperature. The temperature varies from 35 to 45 degrees. With the change in condenser temperature, the COP also changes. The work input of the compressor is increased. Hence, the cop is decreased. The work input and cop are inversely proportional. The Cop decreased by 17%. The trend is verified using an optimization method. Using the Golden search method. The results found that the COP is minimum when the condenser temperature is maximum. Figure 3: The Condenser temperature (T_c) variation with COP.

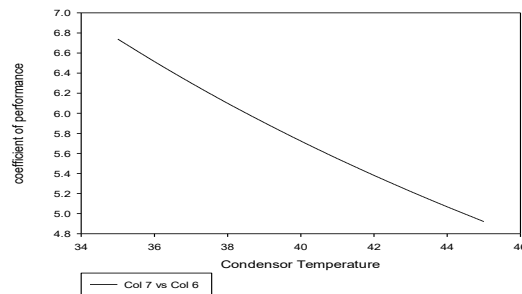


Figure 3: Condenser temperature (T_c) variation with COP

3.2.4 dT_{overlap}

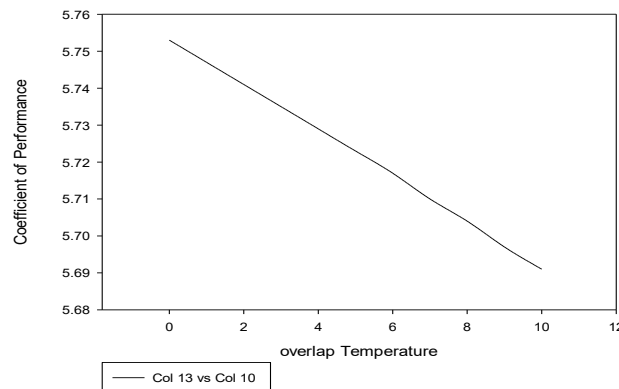


Figure 4: The variation of the cop with overlap temperature

The cop is varied with the overlap temperature of the cycle. The COP decreases with increasing overlap temperature. The reason for this trend is the increasing subcooling cycle compressor work by 223 %. Hence, the Cop is increased by 1.58%. Since work input is inversely proportional to COP, the amount of the cycle. The work of the main cycle compressor is constant. Hence, COP is not increased drastically. Figure 4. The variation of the cop with overlap temperature

when overlap temperature is 0°C, the cop is at the higher side between 5.67 and 5.76. After increasing the temperature, the COP goes down to 10°C. The COP will become lower near 5.69.

3.2.5 dT_{sub}

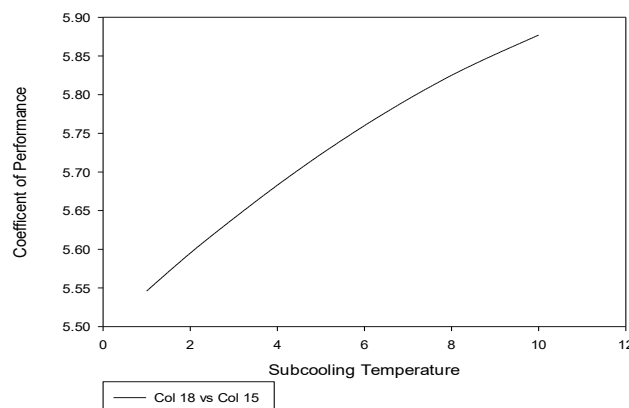


Figure 5:Subcooling Temperature

The COP varies with the subcooling temperature of the subcooling cycle. The Cop is noticed to increase with increasing subcooling temperature. Figure 5: Subcooling Temperature. The reason for this trend is that the work of both compressors is changing. The work of the Main cycle compressor is reduced by 8.4%. The work of the subcooling cycle is increased. The trend is due to a mix of both compressors working as the heat input is kept constant at 2 TR. When the dT_{sub} temperature is 0°C , the COP is at the lower side, near 5.5. Then, we increase the temperature, and the COP becomes higher at 10°C . The COP is at the higher side, near 5.9.

3.3 Optimization

In optimization, we take the combination of the variables that are suitable for our cycle and help us to increase the cop.

As we can see from the graph and its curve, which shows the relation between the temperature. Or cop. There are four different temperatures. Which we focused on T_e , T_c , $dT_{overlap}$, and dT_{sub} . After calculation in EES, we come to an optimum parameter which can help us to increase the cop. The optimum value is T_e at c , T_c at $^{\circ}\text{C}$ overlap at 5°C , and dT_{sub} at 5°C .

Optimization to maximize the coefficient of performance (COP) of a refrigeration system involves adjusting various parameters of the system to achieve the highest possible efficiency. This can include things like properly matching the size of the evaporator and condenser to the load on the system, adjusting the compressor speed to optimize efficiency, and properly controlling the system through the use of thermostats and other sensors.

In addition to these factors, it may also be necessary to consider the properties of the refrigerant being used, as different refrigerants have different thermodynamic properties that can affect the COP of the system.

By carefully optimizing these and other parameters, it is possible to achieve a higher COP and improve the efficiency of the refrigeration system. This can result in lower energy consumption and operating costs, as well as a smaller carbon footprint.

Independent variable optimization is a technique that can be used to optimize the coefficient of performance (COP) of a refrigeration system by adjusting independent variables within the system to achieve the desired results. These independent variables are parameters that are not directly influenced by other variables in the system, and can therefore be adjusted without affecting the performance of other parts of the system.

We have used two independent variables, which are subcooling temperature difference and overlap temperature differences.

The range of subcooling temperature difference variable is 0 to 15°C .

The range of the degree of overlap variable is 0 to 15°C .

The conjugate direction method is an optimization algorithm that is used to find the minimum or maximum of a function by iteratively adjusting the values of the variables in a particular direction, called the search direction.

The search direction is chosen to be conjugate to the previous search direction, meaning that it is orthogonal to the previous direction. This ensures that the algorithm is able to explore a wide range of possible solutions and avoid getting stuck in local minima or maxima.

The conjugate direction method is often used in conjunction with other optimization algorithms, such as gradient descent, to improve the efficiency and convergence of the

optimization process. It is particularly useful for optimization problems with large numbers of variables, as it allows the algorithm to explore the search space more efficiently.

Overall, the conjugate direction method is a powerful tool for finding the optimal solution to a wide range of optimization problems.

The procedure for optimizing a system using the independent variable method involves the following steps:

1. Identify the independent variables: The first step is to identify the independent variables in the system
2. That can be adjusted to optimize the performance of the system. These are variables that are not directly influenced by other variables in the system, and can therefore be adjusted without affecting the performance of other parts of the system.
3. Determine the objective function: The next step is to determine the objective function, which is the performance measure that you want to optimize. This could be something like the coefficient of performance (COP) of a refrigeration system, or the fuel efficiency of an internal combustion engine.
4. Set the initial values for the independent variables: Once the independent variables and the objective function have been identified, the initial values for the independent variables must be set. These values will be used as the starting point for the optimization process.
5. Iteratively adjust the independent variables: The independent variables are then adjusted iteratively,
6. using an optimization algorithm such as gradient descent or the conjugate direction method, to minimize or maximize the objective function.
7. 5. Evaluate the results: After the optimization process is complete, the final values of the independent variables and the resulting value of the objective function are evaluated to determine the optimal solution.

4. Conclusion

In the conclusion, the paper summarizes the results of the theoretical studies done on EES Software. Various studies are conducted, including optimization studies to find the best configurations for increased Coefficient of Performance. Various parameters like Subcooling, overlap, Evaporator temperature, and condenser temperature are varied with the COP of the system, and trends are noted. The trends are explained with specific reasons for that variation.

- The system parameters are optimized using the golden search method, and the subcooling value for maximum cop is 10°C.
- The maximum value of cop is 5.942
- With the increasing subcooling, the cop of the system increases; with the increasing overlap temperature, the COP of the system decreases.
- The cop is increasing with increasing evaporator temperature, and it decreases with increasing condenser temperature.
- The reasons are explained in detail in the results section. The paper presents a theoretical base for calculating the improved cop of the system when subcooling is incorporated. The cop increases with subcooling.

Nomenclature

VCRS Vapour compression refrigeration system
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COP	Coefficient of performance
EES	Engineering Equation Solver
The	Evaporator Temperature
Tc	Condenser Temperature
Tsub	Subcooling Temperature
Toverlap	Overlap Temperature
T	Temperature (K)
P	Pressure (kpa)
Exp	Expansion
Cond	Condenser
Subs	Sub-cooler
Comp	Compressor
R134a	Tetrafluoroethane

Symbols

°C	Celcius
r	Referigerant
T	Temperature
P	Pressure

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