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Performance Improvement of Vapour Compression Refrigeration System with Integrated Mechanical Subcooling: A Review

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Abstract—*Subcooling is a known technique in literature to improve the COP of a vapour compression refrigeration cycle. Recently, much progress has been made into its different areas and aspects that can help to put it into real life practices and applications. Experimental and numerical approaches are taken into account to highlight this progress. One technique to utilize subcooling for the purpose of improving performance is incorporating an integrated sub-cooling loop to refrigeration and air-conditioning systems. This methodology is identified as 'Integrated mechanical sub-cooling'. It is one of the types of subcooling in which the condenser is common for both main and subcooler cycle. This paper reviews various studies carried out around the world on integrated mechanical subcooling to improve the performance of a vapour compression refrigeration system by discussing some important points in the area of respective research. Finally, some suggestions have been made for the future research work in this area.*

1. INTRODUCTION

The rapidly growing world energy consumption has already raised concerns over supply difficulties, exhaustion of conventional energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). Refrigeration and air conditioning systems consumed a large amount of energy in maintaining thermal comfort for occupants and suitable climatic conditions for cooling cases, which made upto 50% of building energy consumption. The mechanical vapour compression technology is laying down the basis of many important industrial, agricultural and household refrigeration and air conditioning applications .Various methods have been proposed to improve the energy efficiency of Vapour compression refrigeration systems. From thermodynamic standpoint, further cooling of liquid refrigerant leaving condenser can significantly improve refrigeration capacity and can also improve the system performance. This methodology is identified as Subcooling . Subcooling has been mainly used in medium and low-temperature refrigeration systems wherein a simple vapour-compression refrigeration system is provided with some kind of subcooling arrangement to save energy consumption and to improve the cooling capacity of the system. Subcooling techniques are of following types: 1)Ambient Subcooling, 2)By utilizing suction-line heat exchanger as heat sink, 3)By using an external heat sink ,4)Dedicated mechanical subcooling and 5)Integrated Mechanical subcooling. Each will now be explained briefly with focus on Integrated mechanical subcooling in detail.

1.1 Ambient Subcooling

In this type of subcooling additional heat exchange surface is used, which interacts with the ambient, to subcool the liquid refrigerant. There are two ways to provide ambient subcooling (ASHRAE, 1983):

1. The subcooler and condenser are combined in an oversized condenser.
2. A separate heat exchanger (called the subcooler) is used downstream of the condenser.

The degree of subcooling is restricted by the heat sink temperature.

1.2 By utilizing suction-line heat exchanger as heat sink

According to ASHRAE[18] and [19], liquid-suction heat exchangers can be used in improving system performance by subcooling liquid refrigerant flowing out of the condenser to prevent flash gas formation at the inlet of expansion device. Also, this technique is useful for evaporating any remaining liquid in the suction line before entering the compressor. In it, the high-temperature liquid exiting the condenser is sub-cooled by an indirect exchange of heat before entering the throttling device. It should be taken into account that although the subcooling obtained with the help of suction line heat exchanger is always beneficial since the refrigerant charge diminishes but the size effect of rise in specific volume at the compressor inlet may lead to lower COPs.

1.3 By using an external heat sink

In this methodology, the system contains a subcooler (i.e. heat exchanger) and a small cooling tower or a water loop which is ground-sourced. Refrigerant flowing out of the condenser is passed through a counter-flow heat exchanger. Here, the refrigerant is subcooled by the circulating water. In the cooling tower, rejection of gained heat is performed by evaporating some water. A pump is required for the circulation of water through the cooling tower and heat exchanger. Also, a fan is needed for circulating ambient air within the system. Laboratory experiments show that for every°C1 of subcooling, there is a 1% increase in cooling capacity[13].As cooling capacity is increased, the size of the compressor and condenser unit can be reduced, which results in lower energy consumption.

1.4 Dedicated Mechanical Subcooling

Energy can be saved by incorporating a subcooling loop to already existing refrigeration system based on vapour compression cycle. This method is termed as dedicated mechanical subcooling in which both main and subcooler cycle has its own condenser. Both these cycles are attached with a subcooler which is situated after the main cycle condenser. This subcooler acts as evaporator for subcooler cycle by extracting the heat from the main cycle refrigerant which is flowing out of main cycle condenser. Syed M.Zubair et al.[20] provided a study of the behavior of this system,using a refrigerant-property-based model. The most important effect of dedicated subcooling is the increase in cooling capacity of system due to entrance of the lower quality refrigerant in the main cycle evaporator.

1.5 Integrated Mechanical Subcooling

Energy can be saved by integrating a subcooler cycle with the Vapour compression refrigeration system. This method is termed as integrated mechanical subcooling in which both main and subcooler cycle have a common condenser. A certain amount of refrigerant is bled off from the main cycle and is used in the subcooler cycle. A subcooler is used which acts as an evaporator for subcooler cycle . Syed M. Zubair et al.[1] provided a study of the behavior of this system, using a refrigerant-property-based model. The most important effect of integrated subcooling is the increase in cooling capacity of system which is discussed further in detail.

2. CYCLE DESCRIPTION

In this cycle Fig.1 [1] , two refrigerant loops are employed. The outer bigger loop is main cycle while the smaller inner loop is the subcooler cycle. Main system components are condenser, two expansion valves, two compressors, one sub-cooler and an evaporator. The cycles contain the same refrigerant. Both the refrigerant loops are connected through a common heat exchanger ie. subcooler. Heat transfer takes place inside the subcooler ie. the main cycle refrigerant subcools whereas the subcooler cycle refrigerant takes the heat and the subcooler hence acts as an evaporator for the subcooler cycle. It should be noted that the refrigerant exits the main cycle condenser at state 5 as a saturated liquid at high-pressure and then enters the subcooler. Inside the subcooler, the refrigerant is cooled below the saturated liquid state by exchanging heat with the subcooler cycle refrigerant from state 5 to state 6 and then enters the expansion device of the main cycle. On the other hand, the subcooler-cycle refrigerant enters the subcooler at state 8 and after cooling the main cycle refrigerant, it exits at state 9, as a low temperature & low pressure saturated vapour. The main cycle refrigerant enters the evaporator at state 7 and leaves at state 1. The refrigerant vapour gets compressed from state 2 to state 3 in main cycle compressor and from state 10 to state 11 in subcooler cycle compressor respectively. The state after state 4 and state 12 is state 13. From state 5 to state 8 the refrigerant which is bled off for the subcooler cycle is expanded in the capillary. The main cycle refrigerant is expanded from 6 to 7 in the capillary.

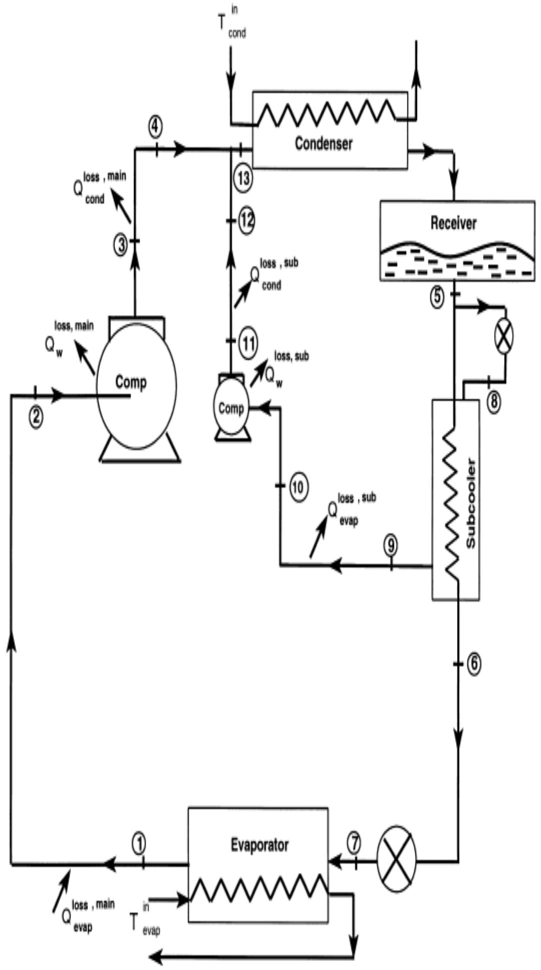

Figure 1. Schematic Cycle Of Vapor Compression Refrigeration System With Integrated Mechanical Subcooling

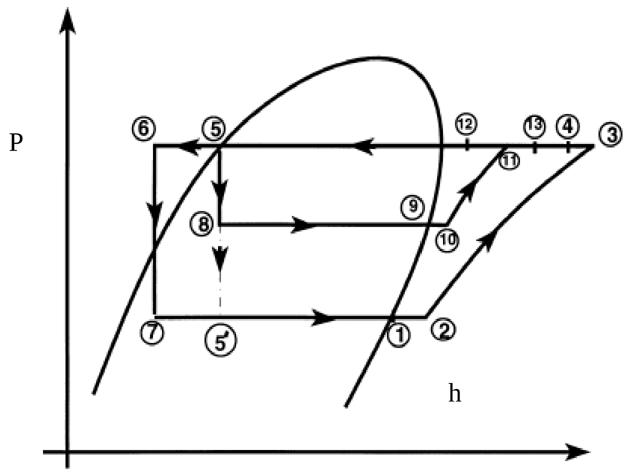

Figure 2. P-h Diagram Of the Cycle

To perform this study we have to take some assumptions into account, which are:

1. There are no heat losses in the lines,
2. There are no pressure losses in the lines.

Some important equations [1] will now be used to calculate heat and work load in different heat exchangers of the system are:

The main cycle mass flow rate is calculated by applying energy balance on the main cycle compressor.

$$\dot{W}_{comp,m} = \dot{m}_m (h_3 - h_2) \quad (1)$$

The heat transfer rate in the evaporator can be obtained from the following equation:

$$\dot{Q}_{evp} = \dot{m}_m (h_1 - h_7) \quad (2)$$

COP is calculated as the ratio of cooling load to the work from both the compressors. The fan power is neglected because its value is very small as compared to total consumption. The configuration without subcooling is termed as ‘base configuration’ and the one with subcooling is termed as ‘subcooler configuration’. The second-law efficiency is employed to evaluate both the configurations instead of the COP to handle the effect of changing ambient conditions, which is defined as follows:

ηII=COP/COP$_{max;}$
Where COP= Refrigeration effect
Both compressors work
and COP$_{max}$ = T$_{ambient}$
T$_{ambient}$ – T$_{room}$

3. SOME IMPORTANT RESULTS AND DISCUSSIONS

Bahel and Zubair [2], Zubair [3] and Zubair et al. [4] have investigated an integrated mechanical subcooling system by creating thermodynamic models and then analysing them on EES(Engineering Equation Solver) and finding results. No experimental work has been done till now by anyone. In either of these studies, they found that the system performance improved when operating in situations where the difference between the condensing and evaporating temperatures is large.

Zubair [3] and Zubair et al. [4] have investigated the second-law analysis of an integrated mechanical-subcooling system using an ideal refrigerant cycle model. They showed that the irreversible losses in the expansion device (the major source of irreversibility) can be significantly reduced by operating the system at the optimum subcooling conditions. This optimum condition was found to occur at a subcooler saturation temperature about halfway between the condensation and evaporation temperatures.

Some results of Zubair et al.[1] are-

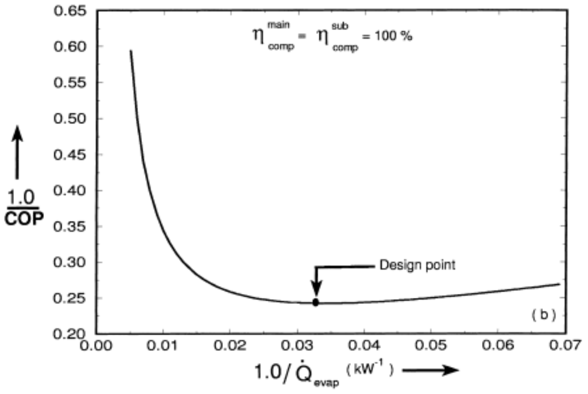

Figure 3(a) . Characterisitc performance curve when considering efficiencies of both compressors as 100 %

The plots are drawn for a particular set of input data.From the plots obtained in EES we can see the COP value comes out as 4.1297 when the efficiencies of both the compressors is considered as 100 % . The design point is the minimum point.

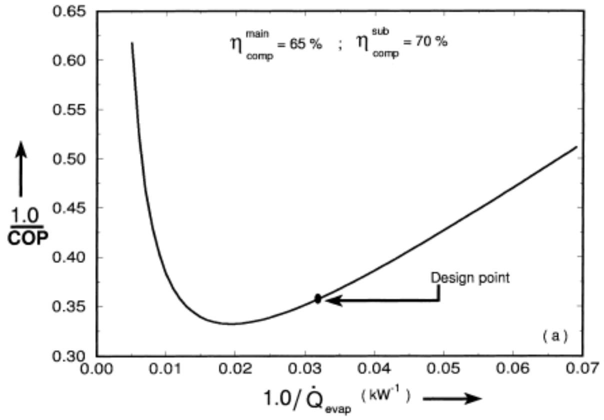

Figure 3(b) . Characterisitc performance curve when considering efficiencies of main cycle compressor and subcooler cycle compressor as 65 % and 70 % respectively

The plots are drawn for a particular set of input data.From the plots obtained in EES we can see the COP value comes out as 2.763 when the efficiencies of main cycle compressor and subcooler cycle compressor are considered as 65 % and 70 % respectively. The design point is located away from the minimum point because of the losses mainly due to non-isentropic compression in the compressors.

The shapes of the curves obtained are similar to that obtained for a simple cycle[6].It shows that the COP increases with evaporator capacity upto the minimum point,due to irreversibilities such as fluid friction in the compressors and expansion valves while at evaporator capacities greater than the minimum point,COP decreases significantly because of the losses due to finite rate of heat transfer in the heat exchangers of the system.The performance of the system considering various losses is similar to the performance of a simple cycle discussed by Gordon and Choon[7].

4. CONCLUSIONS

Using Integrated mechanical sub-cooling with simple vapour compression refrigeration systems, improvement in cooling capacity and coefficient of performance(COP) of the system is seen. Integrated subcooling is a known method in literature but only theoretical analysis has been done and no experimental investigation has been performed so far. This review will not only help in motivating many present researchers in this field but also encourage the future researchers to further examine integrated mechanical subcooling keeping in mind the optimum operational performance as well as management of refrigeration and air-conditioning systems. Following suggestions are made in this regard:

- For the establishment of the proof of concept, experimental work needs to be done on commercial and industrial units, based on the integrated subcooling cycle.
- Experimental, Environmental and Thermo-Economic analysis should be performed on integrated subcooling based systems. It will provide more realistic results regarding the effects on environment and how the capital investment effect the operational performance of the system.
- To get the best results from the system, regarding cooling capacity and COP, Exergy analysis should also be performed on such systems. It will help plant and project engineers, designers and managers to explore the possibilities to improve performance in a cost-effective manner.

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