Performance Evaluation of Vapour Compression Refrigeration System Using Double Effect Condensing Unit (Sub-cooler)

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Abstract

Keywords: Vapour compression, Refrigeration system, Sub-cooling cycle, Double effect condensing unit system, Refrigerating effect, Coefficient of performance.

This report presents a study on development and analysis of double effect condensing unit vapour compression refrigeration system (DECU VCR system). The system is composed by two refrigeration cycles working with R134a. Tests under a wide range operating temperature interval conditions were carried out on the developed system. Experimental data was generated to observe the performance of the basic VCR system and DECU VCR system for an important parameters such as condensation (35 to 55°C) and evaporation temperatures (-5 to 15°C). Performance evaluation of the system was characterized in terms of cooling capacity and coefficient of performance (COP). In the present study, both COP and refrigerating effect of the developed system have been found, in general, to be greater than the corresponding basic VCR system values, but the degree of enhancement varies depending on the test conditions. Additionally, by using dedicated subcooling cycle, up to 11 and 11.7 % performance improvement ratio of VCR system are observed at evaporation temperature of 15 °C and condensation temperature of 35 °C respectively. It can be concluded that the use of dedicated sub cooling cycle in VCR system is most efficient and suitable for the betterment of thermal system performance.

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1. Introduction

Cooling in industrial process, air-conditioning of buildings and refrigeration of perishable products are common practice throughout the world [1]. As pointed out in the study of [2], these refrigeration systems on the whole, consume a large amount of
energy since hundreds of millions are currently in use, and dozens of millions are coming onto the market every year. Generally refrigeration systems can be classified into 3 main cycle systems which are vapour compression refrigeration system, vapour absorption refrigeration system and gas cycle refrigeration system. According to [3], the most commonly used system in refrigeration and air-conditioning industry is vapour compression refrigeration system. As reported in the study of [4], a considerable part of the energy produced worldwide is consumed by refrigerators and it is crucial to minimize the energy utilization of these devices. In order to reduce this energy consumption, a high energy efficiency system should be adopted. Typical vapour compression refrigeration system uses a single condenser unit component to remove heat from high pressure superheated vapour refrigerant, sub-cooled it to saturated vapour state and then condenses into a saturated liquid state. Theoretically, the condensation process is considered under constant pressure. It is well known that the more the heat rejection in the condenser, the subcooling of the liquid increases the refrigerating effect without increasing the work requirement and, consequently, increases the efficiency of the system. [5], also pointed out that the COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. Therefore, consideration of double effect condensing unit vapour compression refrigeration system (DECU VCR system) for improving performance of the system becomes very worthy to be investigated. [6], discovered that adding extra internal heat exchanger in a single-stage cycles prior to expansion process subcools the liquid refrigerant. [7], presented a concept of a sub-cool system in which the liquid receiver is installed before the last pass to a parallel flow micro channel condenser rather than at the exit of the condenser. They observed COP improvement benefitted from subcooling due to an increase in enthalpy difference across evaporator. [8], carried out experimental investigation of the effect of condenser liquid subcooling on a refrigeration system performance. Their result revealed that the COP and refrigeration cooling capacity of refrigerants; R134a (12.5%), R12 (10.5%) and R152a (10%), benefited from subcooling increase from 6°C to 18°C, while condensing temperature was kept artificially constant. [9], evaluated the performances of the selected refrigerants R23, R32, R134a, R143a and R152a in terms of heat exchanger effectiveness, capacity index and coefficient of performance in vapour compression refrigeration system by using a subcooling heat exchanger as a tool. [10], investigated the performance characteristics due to use of different refrigerant combinations in vapour compression cycles with dedicated mechanical sub-cooling. They reported that dedicated mechanical subcooling is more suited to cycles using R-134a as the main cycle refrigerant rather than R-717. [11], developed a refrigeration cycle which combines a basic vapour compression refrigeration cycle with an ejector cooling cycle for enhancement of the basic vapour compression refrigeration cycle. The authors concluded that the COP of the modified vapour compression refrigeration cycle improved by 9.1%.

The objective of the present paper is to evaluate the performance improvement of a double effect condensing unit vapour compression refrigeration system (DECU VCR system). The performance evaluation was based on comparison between the basic vapour compression refrigeration system and
the modified vapour compression refrigeration system dedicated to double effect condensing unit. The effects of condensation and evaporation temperatures on refrigerating effect and coefficient of performance (COP) of the system were also reported.

2. Description of the system and methodology

Figure 1 shows a schematic diagram of the vapour compression refrigeration system with dedicated subcooling cycle. The components of the subcooling cycle are designed and coupled to the basic VCR system. Process 2-3 (Condensation process) represents the removal of latent heat which changes the dry saturated refrigerant into liquid refrigerant. The process 3-4 represents the subcooling of the liquid refrigerant leaving the basic VCR system condenser before passing through the expansion valve (4-5) for the onward throttling of the liquid refrigerant from the condenser pressure to the evaporator pressure and then evaporate in the evaporator (5-1), in this study these processes are enhanced using a dedicated subcooling cycle (6-7-8-9). With the dedicated subcooling modification, liquid refrigerant leaving the condenser is further cooled at constant pressure to an intermediate temperature, $T_4$, as shown in Figure 1. Finally, the vaporized refrigerant is circulated through the compressor (1-2) and then condensate in the condenser (2-3). In this way, less work is used to operate the compressor of the DECU VCR system and, consequently, enhance the performance of the system.

Fig. 1: schematic diagram of the vapour compression refrigeration system with subcooling cycle.

3. System development and analysis

A simple VCR system consist of a compressor, air cooled condenser, expansion device and evaporator. Due to the need of high energy efficiency refrigeration system a double effect condensing unit vapour compression refrigeration system is hereby proposed in this study. This study involves development and analysis of a double effect condensing unit vapour compression refrigeration system. This investigation begins with thermal analysis of the developed refrigeration system taking into consideration the system cooling load which is made up of (i) The heat transferred through the refrigerating space wall, (ii) Heat added
to the refrigerating compartment whenever the system door is opened otherwise known as infiltration load and (iii) The heat gained from the products otherwise known as the product load. The thermal analysis results were used to predict the capacity/volume of each component in the developed system. Shown in Figure 2 is the pressure-enthalpy diagram of the developed double effect condensing unit VCR system where the basic VCR system and subcooled system cycle are represented by processes 1-2-3-4-5 and processes 6-7-8-9 respectively. The process 6-7 is the evaporator of the subcooling cycle which serves as the subcooler of the basic VCR system condenser. However, more focus of this study is given to the heat rejected by the condenser of the basic VCR system, since it is a fundamental input for the design of the double effect condensing unit vapour compression refrigeration system components.

The basic VCR system refrigeration capacity is calculated as follows:

\[ Q_{\text{basic}} = \dot{m} \left( h_1 - h_{5'} \right) \]  

where the subscript 1 and 5' refers to the enthalpies at the exit and inlet of the basic VCR system evaporator respectively.

The work done by the basic VCR system compressor is calculated as follows:

\[ W_{c,\text{basic}} = (h_2 - h_1) \]

where, the subscript 2 refers to the enthalpy at the exit of the basic VCR system compressor.

And the compressor power required by the basic VCR system is estimated as:

\[ P_{c,\text{basic}} = \dot{m} W_{c,\text{basic}} \]

The heat rejected by the basic VCR system condenser is calculated as follows:

\[ Q_{c,\text{basic}} = \dot{m} \left( h_2 - h_3 \right) \]

where, the subscript 3 refers to the enthalpy at the exit of the basic VCR system condenser.

The refrigeration capacity of the subcooling VCR system is calculated as follows:

\[ Q_{\text{E,sub}} = \dot{m} \left( h_7 - h_6 \right) \]

The work done by the sub-cooling VCR system compressor is estimated as follows:

\[ W_{c,\text{sub}} = (h_8 - h_7) \]

where, the subscript 8 refers to the enthalpy at the exit of the sub-cooling VCR system compressor.

Thus, the compressor power required by the subcooling VCR system is estimated as:
\[ P_{\text{sub}} = \dot{m}W_{\text{sub}} \]  
(7)

The heat addition to the sub-cooling VCR system evaporator must be rejected in the sub-cooling VCR system condenser at the cost of the work of the sub-cooling VCR system compressor. Thus resulting in a trade-off between the amount of sub-cooling provided to the basic VCR system and the amount of work performed by the sub-cooling VCR system compressor.

Hence, the heat rejected by the sub-cooling cycle condenser is calculated as follows:

\[ Q_{\text{sub}} = \dot{m}(h_8 - h_9) \]  
(8)

where, the subscript 9 refers to the enthalpy at the exit of the sub-cooling VCR system condenser.

4. Performance evaluation

Experimentally, evaporation temperatures of both the basic VCR system and the double effect condensing unit VCR refrigeration system are obtained for condensation temperatures range from 35°C to 55°C at temperature interval of 5°C, using Refrigerant 134a as a working fluid. Similarly, the corresponding condensation temperatures of both refrigeration systems are obtained across a range of evaporation temperatures from −5°C to 15°C at a temperature interval of 5°C. It should be noted that when one of them is varied, the other parameters remain constant at a practical value. Performances of both systems are evaluated based on the experimental data obtained. The evaluation of both refrigeration systems are characterized by refrigerating effect in terms of cooling capacity, compressor power and coefficient of performance (COP) of the systems.

The cooling capacity is calculated as:

\[ Q_{\text{sub}} = \dot{m}(h_1 - h_5) \]  
(9)

The compressor power is obtained as follows:

\[ P_{\text{sub}} = \dot{m}(h_1 - h_2) \]  
(10)

Thus, the coefficient of performance of the developed system is calculated as:

\[ \text{COP}_{\text{sub}} = \frac{Q_{\text{sub}}}{P_{\text{sub}}} \]  
(11)

The COP improvement \( \text{COP}_{\text{imp}} \) expressed in % is calculated as follows;

\[ \text{COP}_{\text{imp}} = \frac{\text{COP}_{\text{sub}} - \text{COP}_{\text{basic}}}{\text{COP}_{\text{basic}}} \times 100\% \]  
(12)

where, the \( \text{COP}_{\text{basic}} \) is the COP at the same evaporator and condenser temperatures of the basic VCR system.

5. Results and discussion

The effects of important parameters such as condensation and evaporation temperatures on the systems performances are analysed in this section.

5.1. Effect of condensation temperature on COP of the system

Figure 3 shows variation of condensation temperature on the coefficient of performance for both the basic VCR and the DECU VCR systems. From this figure, it can be noticed that the COPs for both systems decrease as the condensation temperature increases but with different rates. These trends are similar to those observed in the study of [5]. Basically, increasing of condensation temperature causes increase in the compressor power, decreasing the system cooling capacity, and consequently decreases the COP of the system. Moreover, COP of the modified system at lower condensation temperature is observed to be more sensitive higher than the COP of the basic VCR system which confirms the efficiency of system with double effect condensing unit as compared with the basic VCR system counterpart.

Additionally, as condensation temperature decreases from 55 to 35°C, the improvement ratio in COP increases from 2.9% to 11.7% as shown in Figure 4. This trend can be attributed to lesser work used to operate the compressor of the DECU VCR system than the basic VCR system.
5.2. Effects of evaporator temperature on COP of the VCR system

Figure 5 illustrate the effects of the evaporation temperature on COP of both the DECU VCR and basic VCR systems. According to this figure, the first law efficiency of vapour compression refrigeration system (COP) increases as expected with increasing the evaporation temperature of both systems. This trend is similar to those observed in the studies of [4] and [12]. The DECU VCR system is more sensitive to increase in evaporation temperature as higher COP is observed at any application (air conditioning refrigeration and freezing). Such behavior is related to the fact that less work is used to operate the compressor of the DECU VCR system. Moreover, high energy efficiency of the modified VCR system can be noticed in Figure 6 as evaporation temperature increases from -5 to 15°C, the COP improvement ratio increases from 3.1 to 11. Consequently affirming that sub cooling a vapour compression system using double effect condensing unit improves performance of the system.

5.3. Effect of refrigerating effect on COP of the system

Figures 7 and 8 display variation of refrigerating effect of both basic VCR and DECU VCR systems considering effects of both condensation and evaporation temperatures. According to Figure 7, it can be noted that refrigerating effect increases with decreasing condensation temperature. This is due to reduction in exergy loss of the system under this operating condition. (i.e decreasing condensation temperature). Also, as can be observed in Figure 8, the refrigerating effect of both cycles is directly proportional to evaporation temperature. This effect is more pronounced for DECU VCR system. These behaviors can be attributed to lower pressure lift of modified system than basic VCR system. Thus, dedicated subcooling modification is responsible for the betterment of the system performance.

Fig. 3: Variation of coefficient of performance with condensation temperature.
Fig. 4: Variation of performance improvement rate with condensation temperature.

Fig. 5: Variation of coefficient of performance with evaporation temperature.
Fig. 6: Variation of performance improvement rate with evaporation temperature.

Fig. 7: Variation of refrigerating effect with condensation temperature
6. Conclusions
A double effect condensing unit VCR system was developed and presented in this paper. Performance evaluation of the system was characterized by refrigerating effect in terms of cooling capacity, compressor power and coefficient of performance (COP) of the system using R134a as a working fluid. The effects of condensation and evaporation temperatures were studied on the system operation and performances. From the present study, the following main conclusions can be drawn:

i. The COP and Refrigerating effect of DECU VCR system is higher compares with the basic VCR system counterpart.

ii. By using dedicated subcooling cycle, up to 11 and 11.7 % performance improvement ratio of vapour compression system are observed at evaporation temperature of 15 °C and condenser temperature of 35 °C respectively.

iii. As the condensation temperature decreases the COP of the VCR system increases. Similarly, Refrigerating effect of the system increases.

iv. Condensation temperature has the highest effect on the system performance improvement ratio. As the condensation temperature decreases from 55 to 35 °C, the performance improvement ratio of the system increases geometrically.

v. As the evaporation temperature increases, the COP and the Refrigerating effect of the VCR system increases.

vi. According to the preceding analysis on performance evaluation of both basic VCR and DECU VCR systems. It can be concluded that the use of dedicated subcooling cycle in VCR system is most efficient and suitable for any cooling system application (air conditioning refrigeration and freezing).

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