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REVIEW OF MECHANICAL VAPOUR COMPRESSION REFRIGERATION SYSTEM PART 2: PERFORMANCE CHALLENGE

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Reducing energy consumption and providing high performance for a vapour compression refrigeration system are big challenges that need more attention and investigation. This paper provides an extensive review of experimental and theoretical studies to present the vapour compression refrigeration system and its modifications that can be used to improve system's performance and reduce its energy consumption. This paper also presents the challenges that can be considered as a gab of research for the future works and investigations. Cooling capacity, refrigerant effect, energy consumption can be improved by using vapour injection technique, natural working fluid, and heat exchanger. Based on the outcome of this paper, vapour injection technique using natural refrigerant such as water can provide ultimate friendly refrigeration system. Future vision for the vapour compression refrigeration system and its new design technique using Computational Fluid Dynamic (CFD) is also considered and presented.

Key words: vapour compression, refrigeration systems, cycle, coefficient of performance (COP).

1. Introduction

Vapour compression refrigeration systems have been widely used in various industrial applications such as food storage, building, manufacturing and medicine [1]. The vapour compression refrigeration system consists of four main components named: compressor, condenser, expansion device, and evaporator [2-8]. These components are connected in order to produce the refrigeration effect through thermodynamic processes: compression, condensation, expansion, and evaporation [9-14]. There are man thermodynamic losses associated with isentropic vapour compression and constant enthalpy expansion due to high discharge temperature of the refrigerant, large power consumptions, rise in the condenser heat rejection, large throttling losses and drop in refrigeration capacity. These losses are big challenges that need to be considered to provide high system performance. Some technical improvement methods such as an injection technique, and

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intercooling technique can be used to improve the system performance [15-19]. In addition, refrigerant selection is another challenge that also needs to be considered to provide high performance and environmentally friendly vapour compression refrigeration systems.

There are many studies such as Mahmood, Buttsworth [20], Tuo and Hrnjak [21], Dhumane, Qiao [22] and Pathak, Binder [23], in which it was reported that the injection technique has a significant effect on the system performance and it can be used to improve the system capacity.

A gravitational vertical flash tank separator is one of the components that can be used to produce in the vapour compression refrigeration system. The vertical flash tank vapour injection (FTVI) is used to separate out the liquid of refrigerant from the gas-liquid two-phase flow and feed only liquid to the evaporator [23], while the vapour of the refrigerant is injected to the compressor. The FTVL technique reduces the thermal stress that would be generated in the compressor as a result of the electrical current flowing in the electrical coil of the compressor and compression process [24]. In the second stage cycle, the injected liquid of refrigerant will be sent to the second expansion device to feed the second stage evaporator. Consequently, the discharge temperature is decreased at the compressor outlet, that leads to an increase in the capacity with low ambient temperature conditions [25].

The gravitational vertical flash tank separator needs more attention to provide an optimum design. The optimum design of the separator demands some of the critical design parameters such as: the size of the pipe and its layout, cooling capacity, the volume of all evaporators and pipes that affect the separator, system dynamics [26].

Refrigerant's selection based on the thermodynamic performance and physical properties that influence system performance also need to be considered to ensure design of an effective vapour compression refrigeration system with high performance. In the open literature, there are many studies about the vapour compression refrigeration system. These studies focused on the improvement of the vapour compression refrigeration system performance based on system modification and refrigerant type. However, the vapour compression refrigeration system still needs to be improved to meet the user needs and obtain minimum energy consumption.

This paper will present a comprehensive review of the experimental and theoretical studies which were carried out to investigate the modification of the vapour compression refrigeration systems. This paper will assess and analyse the state of art of the theoretical and experimental studies to present a summary of the modification techniques that can be used to improve the performance of vapour compression refrigeration systems and reduce energy consumption. Future vision for the vapour compression refrigeration system and how to decrease the energy consumption will be presented in this paper.

2. Vapour compression cycle

A vapor compression refrigeration cycle has four elements: evaporator, compressor, condenser and expansion valve, respectively, as shown in Fi.1. [24, 27-32]. It uses the refrigerant as a working fluid which absorbs heat from the surrounding space to be cooled and subsequently rejects that heat elsewhere [28, 33, 34].

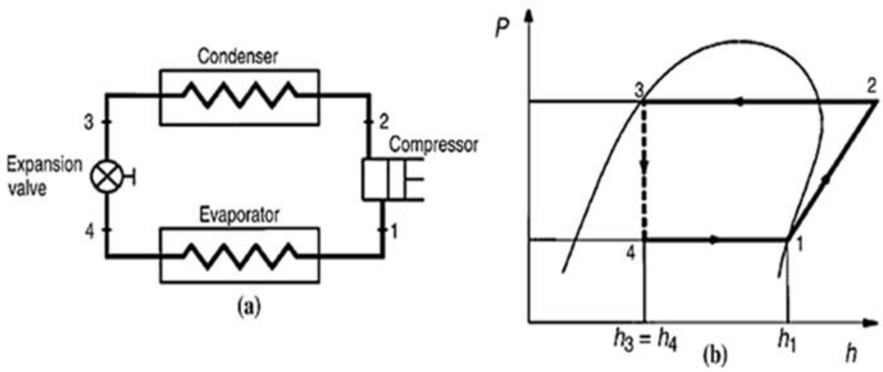

Fig.1. (a) Schematics and (b) P-h diagram of a vapor compression system [24].

The coefficient of performance (COP) and energy consumption need more attention to provide high performance with low energy consumption of a vapour compression refrigeration system. The vapour injection technique using vertical gravitational flash tank separator was used to improve the COP [11, 15, 35-37]. Winandy and Lebrun [38] reported that the vapour injection contributes to raise the compressor capacity with constant COP. The compressor discharge temperature is affected by using liquid injection. Wang, Hwang [8] reported that the COP is increased to *23%* when the flash tank separator is used.

Many experimental and theoretical investigation studies have been made on the vapour compression refrigeration system and its modifications. Table 1 summarizes the result of research on vapour compression refrigeration systems.

Table 1a. Summary of research on vapour compression systems.

References	Modification	Remarks
Bolaji [39]	Using R22 and ozone friendly alternative refrigerants (R404A and R507).	• Experimental results showed that R22 had the lowest pressure ratio and discharge temperature closely followed by R507. • The average discharge temperature obtained using R507 and R404A was *4.2%* and *15.3%* higher than that of R22, respectively. • The average refrigeration capacities of R507 and R404A were *4.7%* higher and *8.4%* lower than that of R22, respectively. • The investigation has revealed that R507 can be used successfully as a retrofitting refrigerant in existing window air-conditioners originally designed to use R22 in the event of HCFC phased out.
Sun, Wang [40]	Using heat pipe	• The cooling capacity of the system has a nearly constant value of 200 kW, and EER changes from *21.2* to *3.1* when the outdoor temperature increases from *−5* °C to *45* °C.
Tao, Hwang [41]	Electrochemical compressor for the vapor compression refrigeration cycle running with ammonia or carbon dioxide as its working fluids.	• The electrochemical compressor does not use any moving parts, it does not need to use lubrication oil neither does it produce any noise or vibration. • It can potentially approach an isothermal compression for even higher energy efficiency and thus improve the system performance.
Agrawal, Patil [42]	Using the mixture of R134a and LPG with mass fractions of 28:72 as an alternative to R134a	• results show that the compressor power consumption, compressor discharge temperature and pull down time obtained with R134a/LPG (28:72) of *118g* and capillary tube length of *5.1m* in vapor compression refrigeration system are about 4.*4% 2.4%* and *5.3%*, respectively, lower than that obtained with R134a in the studied range.
Shaik and Babu [43]	Thermodynamic analysis of window air conditioner with R431A, R410A, R419A, R134a, R1270, R290 and fifteen refrigerant mixtures consisting of R134a, R1270 and R290 was carried out based on actual vapour compre-ssion cycle.	• COP for the refrigerant mixture R134a/R1270/R290 (50/5/45 by mass percentage) is *2.10%* higher among the R22, R431A, R410A, R419A, R134a, R1270, R290, and fifteen studied refrigerant mixtures. The compressor discharge temperature of all the studied refrigerants were lower than that of R22 by *4.8ºC-22.2ºC*. • The power consumption per ton of refrigeration for the refrigerant mixture R134a/R1270/R290 (50/5/45 by mass percentage) is *2.01%* lower among R22, R431A, R410A, R419A, R134a, R1270, R290, and fifteen studied refrigerant mixtures.

Table 1b. Summary of research on vapour compression systems.

Choudhari and Sapali [44]	Analyses the possibilities of R290 as a potential substitute for R22.	• Coefficient of performance with R290 is slightly lower than that of R22. • Higher COP can be expected in specially designed systems due to the properties of R290. • R290 can be a better substitute for R22 in real applications because of its excellent environmental and thermophysical properties.
Samuel, Govindarajulu [45]	Use R-22, R407C and R410A with different capillary pitches.	• R410A with a capillary pitch of *18mm* gave the best coefficient of performance to retrofit window air conditioner working on R22.
Devotta, Padalkar [46]	Experimental performance study of a window air conditioner with propane (HC-290), a natural refrigerant, as a drop-in substitute for HCFC-22.	• HC-290 had *6.6%* lower cooling capacity for the lower operating conditions and *9.7%* lower for the higher operating conditions compared to HCFC-22.
Santini, Bianchi [47]	Using Co_2 as a working fluid.	• Coefficient of Performance (COP) is strongly dependent on the entrainment ratio; a value greater than 0.6 seems to lead to higher COP values, even at low external temperatures.
Poachaiyapoom, Leardkun [48]	Using R134a with electronics cooling technique.	• The highest COP gained is *9.069* at a compressor speed of *3000RPM* and a heating power of *200W*, which yields the heater surface temperature of *73.3°C*. • The proposed system is not suitable for electronics cooling at a heating power of *100W* and *150W*, because the heater surface temperature is less than *40°C*.
Branch and Khalkhal [49]	Modelled the thermodynamic properties of refrigerants, condenser and evaporator seconddary fluid using an artificial neural network	• Benefits and disadvantages of R407C as an alternative for replacing R22 in refrigeration cycle were reported.
Devotta, Padalkar [50]	R-407C as a substitute for R-22.	• R-407C has *2.1%* lower cooling capacity for the lower outdoor conditions and *7.93%* lower for the higher outdoor conditions compared to R-22. • The cooling efficiency for R-407C is *7.9%* lower for the lower outdoor conditions and *13.47%* lower for the higher outdoor conditions. • The discharge pressures measured for R-407C were higher in the range *11-13%* than for R-22.
Choi and Kim [51]	Effect of expansion device on the performance of a water-to-water heat pump using R407C.	• R407C with electronic expansion device shows a more stable compressor discharge temperature at off-design charge than the R407C capillary tube system.

Table 1c. Summary of research on vapour compression systems.

Deymi-Dashtebayaz and Valipour-Namanlo [52]	Optimise mass flow rate of the injected refrigerant.	• The optimization method indicated that a better performance is obtained at injection mass flow rate of *5.9 kg/s* depending on the exergy analysis. • The ambient temperature and temperature of chilled water entering the evaporator variation has no influence on the optimum mass flow rate of the injected refrigerant.
Agarwal, Arora [53]	Using HFO-R1234ze, R1234yf and HFC-R134a	• The R1234ze may be an alternative to HFC-R134a and supersedes R1234yf.
Jain, Jain [54]	Using vapor injection in scroll compressors for air-conditioning and refrigeration applications.	• COP increase of around *6-8%* and a reduction in compressor displacement of *16%* for air-conditioning.
Hwang, Xu [55]	Vapor refrigerant injection cycle with a flash tank.	• The system was found to be operating steady with the liquid refrigerant in the flash tank maintaining a level of *40%* to *60%* of the tank height to ensure the reliable system operation.

3. Components design and sub-cooler

Many studies have been done to provide new successful design for the vapour compression refrigeration system; the main aim of all previous studies was to improve the performance of the system. Some of these studies provided new modification and design for the vertical flash tank separator, new design for the compressor and using the intercooling technique (Mahmood, Buttsworth [36], [56, 57], Llopis, Nebot-Andrés [58]). Some of other studies used Computational Fluid Dynamic (CFD) to predict the effect of refrigerant flow development and its effect on separation and flow characteristic (Jangir and Jana [59], Kumar and Chandrasekar [60], and Sharifi, Sabeti [61]).

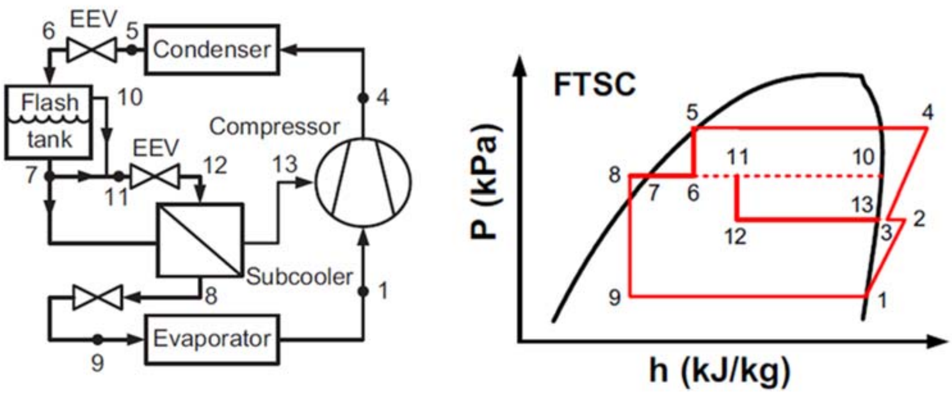

Fig.2. Flash tank and sub-cooler vapour injection air source heat pump [9].

Heo, Jeong [9] presented an experimental investigation to study the effect of a combination of the flash tank with subcooler (FTSC) cycle. Double expansion sub-cooler (DESC) with R410A was used and compared to a sub-cooler SC and flash tank FT cycle, as shown in Fig.2. The heating sizes of DESC, FTSC and FT cycles showed an improvement of *3.8%, 6.0%* and *14.4%* respectively, as compared to the SC cycle.

Table 2. Summary of research on different components.

References	Modification	Remarks
Marti, Erdal [62]	Gas-Liquid cylindrical cyclone (GLCC) separator	• The separation efficiency drops exponentially when the bubbles have smaller diameter than that of *100%* separation efficiency.
Kouba and Shoham [63]	Effects of gas-liquid cylindrical cyclone (GLCC) separator parameters.	• The performance of GLCC depends on the tangential velocity of the swirling fluid.
Rosado, Chávez [64]	Using intercooler technique.	• The COP enhanced by *8.28%* that lead to the reduction in ice freezing time by *22.25%* or *3h* and *39min*.
Kılıç [65]	Intercooler using refrigerants R507, R404a, and R407c.	• The energy efficiency and COP of the R407c system is better than for other refrigerants. • The R507 refrigerant system has worst results due to the total irreversibility rate. • The refrigerants R407c, R507 and R404a may be used as substitutes to replace CFCs refrigerants.
Zheng, Zhao [66]	Using vertical T-junction separation into two phase flow of R134a.	• The separation efficiency deteriorated dramatically as the vapor phase Froude number in the upward tube increased.
Kim, Jeon [67]	Numerical work to compare the performance of liquid, vapour, and two-phase injection heat pumps with a scroll compressor based on the numerical model using R410A.	• The improvement in COP is more with decreasing outdoor temperature.
Ruochen, Shuxue [68]	Experimental study to investigate the injection subcooling method to improve the heating performance of heat pump at cold regions using R32 and compare it with single stage, vapor injection and liquid injection systems	• The discharge temperature is decreased and the heating performance is affected by the ratio of subcooling flow rate. • The COP of the new method system can be enhanced.
Min, Jang [69]	Theoretical work to study the effect of vapor injection in a multi-split VRF system using injection cycle and injection cycle in hot season. Results are validated experimentally.	• Increase in the cooling sizes with values of *3.22%.* • Energy efficient ratio (EER) with values of *1.98%* and *1.72%*, respectively. • There is a reduction in the input power of the injection cycle up to *4.45%* when the bypass cycle and injection cycle are compared with conventional cycle.

An experimental study was made to investigate the flash tank vapor injection FTVI effects on the performance of heating for a 2 stage heat pump with an inverter-driven twin rotary compressor with frequency range between *50* to *100Hz* at ambient temperatures of *-15, -5,* and *5 ℃* [11]. The heating capacity and COP of the FTVI cycle increased by *10%* and *25%*, respectively at-15°C ambient temperature. An increase in the total mass flow rate of the FTVI is *30-38%* higher than that of the conventional cycle. Figure 3 summarize the results.

All the previous studies focused on the improvement and reducing energy. Table 2 presents a summary of research on different components that can be used to improve the system performance.

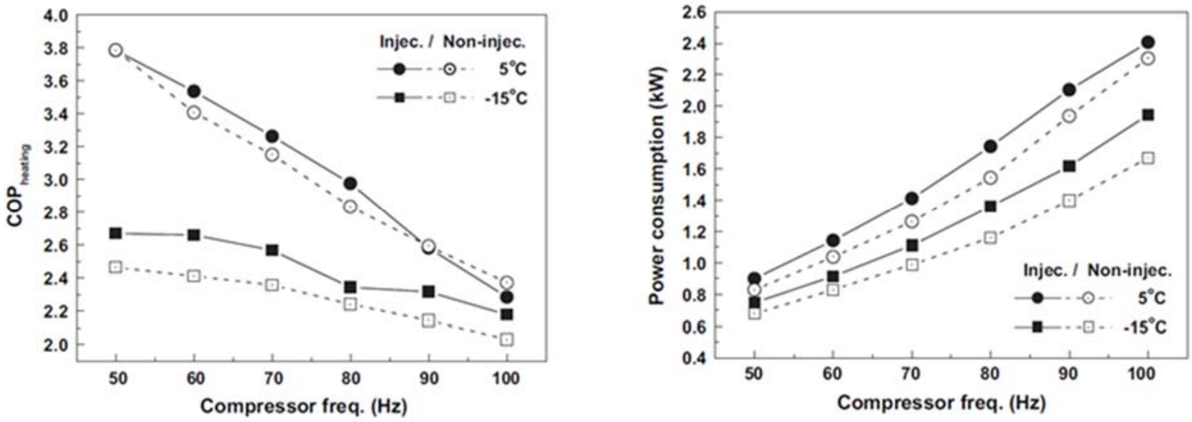

Fig.3. COP and power consumption [11].

4. Future vision for vapour compresion refrigeration system

The future vision for the vapor compression refrigeration systems should meet the high-performance and sustainability requirements. The future refrigeration system can be used without any negative effects on the system's reliability. From the system performance point of view, the system's reliability and efficiency are important parameters that need to be considered in the future design to meet the application and environmental needs . Therefore, many studies have provided different techniques to enhance the system performance such as Wang, Hwang [8], Wang, Shi [5], Wang, Shi [70], Heo, Jeong [9] , Mathison, Braun [12] and Baek, Heo [71].

The vapour injection is one of the effective techniques which is used to obtain high performance of refrigeration systems. However, natural refrigerants need to be considered and used for the future refrigeration systems. Many studies are started to develop a suitable refrigeration system by redesign of the main component such as a compressor and/or addition of a new part to be suitable to work with the natural refrigerant (Wang, Wang [72], Wang and Müller [73] and Li, Piechna [74], Raid *et al.* [75]). Suggestions for the future research and investigations can be summarised as follows:

- System components such as vapour injection technique, subcooled technique, and vertical gravitational separator need to be investigated for the vapour compression systems to obtain high performance.
- Experimental investigation of natural refrigerants such as water need to be considered for the future refrigeration systems.
- Computational fluid dynamic (CFD) can be used to design the components of the vapor compression system and it can be used to predict the flow characteristics in refrigeration systems.
- CFD can be used to optimize the new design and enhance the vertical flash tank separator and other system's components such as the condenser and evaporator.
- More experimental studies on reducing losses in vapour compression refrigeration systems should be made.

5. Conclusion

An extensive review of the experimental and theoretical studies has been made to give a summary of the improvement of system performance for the vapour compression refrigeration systems. System modification using different techniques such as vapour injection has been presented through deep assessment of the literature. The results revealed that the vapour injection technique provides low energy consumption, high performance and reduces the thermal stress on the compressor because of reducing the discharge temperature. The review can be summarized as follows:

- Injection subcooling method can improve the COP.
- Injection subcooling methods can decrease the discharge temperature.
- Vapour injection can be used with scroll compressor to improve the COP.
- Intercooling technique can enhance the COP by *8.28%.*
- R1234ze and R1234yf are alternative refrigerants that can be used to improve the COP.
- R-407C has lower performance compared with R22.
- R507 is an alternative refrigerant that can be used to improve the COP.
- CFD approach can provide high quality design and refrigerant flow prediction.
- Vertical gravitational flash tanks are very effective components that can improve the capacity and performance efficiently.
- Improvement of vertical flash tank separator leads to an improvement of the COP.
- Future vision of the refrigeration system discussed the future system design and requirements to meet the environmental and performance needs.
- More attention should be paid to CFD numerical modelling.

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