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Vapor compression refrigeration system with refrigerant injection: a review

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ABSTRACT
Overheating is the major problem ofhermetic compressor due to extra amount of heat added from the motor windings to the shell. It reduces the mass flow rate of the system which results in reduced compressor volumetric efficiency and extremely high discharge temperature. The refrigerant injection is a technique to improve the system performance. This paper reviews the major research on refrigerant injection techniques in detail. The refrigerant injection technique divided into two categories, first is vapor injection and another is liquid injection. Flash tank and internal heat exchanger are two cycles for refrigerant injection. These two cycles are discussed in detail.

Introduction

Refrigeration may be defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool some product or space to the required temperature. One of the most important applications of refrigeration has been the preservation of perishable food products by storing them at low temperatures. Refrigeration systems are also used extensively for providing thermal comfort to human beings by means of air conditioning. Air Conditioning refers to the treatment of air so as to simultaneously control its temperature, moisture content, cleanliness, odour and circulation, as required by occupants, a process, or products in the space. As in most of the refrigeration system compressors used are operating at the high compression ratios associated with low or medium temperature conditions. It can cause extensively high discharge temperatures, this can chemically degrade oil and refrigerant and can cause thermally induced mechanical failure. It is possible to provide adequate cooling by injecting the liquid refrigerant from the condenser outlet to directly into the compressor suction or into the sealed compression space. Refrigerant injection can be classified into two types: liquid refrigerant injection and vapour refrigerant injection. The former is commonly used for decreasing the extremely high discharge temperature of the compressor and ensuring the reliable system operation. The latter is used for so-called “economizer cycle” to improve the cooling/heating capacity at the same stroke volume of the compressor. [17]

Liquid refrigerant injection

Liquid refrigerant can be defined as injecting the liquid refrigerant to the hot gas before entering the condenser, or into the suction side of the compressor, or directly into the sealed compressor pocket. Operating compressors at high compression ratios can result in excessively high discharge temperatures, which can chemically degrade refrigerant oil and lead to mechanical failure. Therefore, employing liquid injection is a good option when high-pressure ratios are reached. Kang et al. [1] investigated the effect of liquid refrigerant injection on the performance of a refrigeration system with an accumulator heat exchanger. It was found that the liquid refrigerant injection into the accumulator heat exchanger controlled the subcooling and the discharge temperature properly to minimize the degradation of system performance and achieve reliable system operation at high ambient temperature. Ayub et al. [2] investigated the effect of liquid refrigerant injection directly into the sealed compression pocket with scroll compressors operating at high compression ratio in a HVAC system, heat transferred to the suction gas has the effect of reducing the gas density and thus reducing mass flow or capacity through the compressor. It was found that the objective of discharge temperature control through injection of liquid refrigerant may be easily achieved. Dutta et al. [3] investigated the influence of liquid refrigerant injection on the performance of a scroll compressor both experimentally and theoretically. The oil temperature was maintained to be constant in the firstexperiments. It was found that the injection increased the compressor power and decreased the compressor efficiency. Later the system was operated without controlling the compressor oil temperature. Slight improvement was observed for the system performance. This was due to the fact that the liquid injection tended to decrease the oil temperature, which led to improvement in the system performance. Cho et al.[4] studied an inverter-driven scroll compressor with liquid injection at different compressor frequencies. The liquid injection under high frequency was very effective in attaining prominent performance and reliability of the compressor. Some disadvantages were found with injection at low frequency with respect to the compressor power, capacity and adiabatic efficiency due to high leakage through the gap in scroll wrap. Cao et al. [5] studied the performance of a heat pump water heater using suction stream liquid injection. It was found that the suction liquid injection explicitly lowers the discharge temperature of the compressor and the heating capacity of the unit, but the power consumption increases with COP decreasing. In addition, the highest injection ratio must be controlled fewer than 50%.

The suction liquid injection has a better effect on the HPWH at the temperature ranging from 15 ̊ C to 20 ̊ C. Within this temperature range, the 5% ratio suction liquid injection

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decreases the discharge temperature of the compressor by 10˚C, while the heating capacity of the HPWH decreases by less than 5%, power consumption increases by less than 1.5%, and COP decreases by less than 7%. Winandy et al. [6] studied scroll compressor using gas and liquid injection with experimental analysis and modelling. The experiment involves the analysis of scroll compressors using different methods of injection. First one is without injection, the second one uses vapor injection and third one liquid injection. It was found that vapor injection permits one to increase slightly the cooling capacity of the compressor keeping a quite constant coefficient of performance. The main effect of liquid injection is seen on the compressor discharge temperature, it was 1.2 K for each percentage of injection ratio. Liu et al. [7] studied the liquid injection using a rotary compressor for a heat pump water heating system. It was found that the compressor discharge temperature decreased significantly due to the liquid injection. The liquid refrigerant injection mass flow rate was quite small compared to the mass flow rate of the main circuit; therefore the capacity remained almost the same when compared to the case without the injection. Wang et al. [8] investigated the effects of refrigerant injection on the scroll compressor.

Based on simulations and experiments, the effects of refrigerant injection on the general performance and inner compression process of scroll compressor has been researched. As a result, it is found that the refrigerant injection process can be considered as a continual parameter-varying "adiabatic throttling + isostatic mixture" time-varying process. The indicated efficiency of the injection scroll compressor will acquire the maximum when the ratio of inner compression ratio and outer compression ratio is a right value.Zaltanovic et al. [9] studied experimentally the evaluation of desuperheating and oil cooling process through liquid injection in two-staged NH_3 refrigeration system with screw compressors. While economizing can improve the performance of vapour compression cycles, the cost of multi-stage compressors has limited its implementation to large-scale applications. However, the development of compressors with injection ports presents new opportunities for economizing in smaller-scale applications. In addition to eliminating the need for a costly multi-stage compressor, multiple injection ports can be added at relatively low cost to further improve cycle performance. Mathison et al. [10] investigated the performance limit for economized cycles with continuous refrigerant injection. The model used in the analysis predicts that continuous injection, in which economized refrigerant is injected at an infinite number of ports to maintain saturated vapour in the compressor, provides very significant performance improvements for air conditioning and refrigeration applications. At standard operating conditions, the COP increases between 18% and 51% depending on the application, with higher temperature lift cycles benefiting most significantly.

Vapour Refrigerant injection

Vapor refrigerant injection typically refers to injecting vapor refrigerant to the intermediate location of the compressor. Compared to liquid refrigerant injection, more benefits were found for the vapor injection technique:

1. System capacity can be varied by controlling the injected refrigerant mass flow rate, which permits some energy savings by avoiding intermittent operation of the compressor.
2. The compressor discharge temperature of a vapor injection cycle is lower than that of a conventional single-stage cycle.

Therefore the working envelop of the compressor is improved.Baek et al. [11] experimentally studied a CO2 heat pump system coupled with vapour injection. The heating capacity ratio and COP ratio increased with the increase of the gas injection ratio at all outdoor temperatures due to the increase of the total mass flow rate. The heating capacity and Coefficient of Performance (COP) of the system with vapour injection were improved by 45% and 24%, respectively, over the non-injection system at the outdoor temperature of – 8˚ C. Wang et al. [12] worked out the optimization of refrigeration system with gas injected scroll compressor, it has been proven that the vapor refrigerant injection is an effective method to improve the performance of the scroll compressor and its refrigeration system working under high compression ratio. As a result it was found that the heating and cooling capacity of the system increases due to vapor injection. COP of the system also increases considerably. Shuxue et al. [13] experimentally studied an enhanced vapor injection refrigeration / heat pump system using R32 as a refrigerant. The results show that this system reduces the discharge temperatures for both cooling and heating, with the heating capacity of the EVI system using R32 3 - 9% higher than that of the single stage system. The cooling capacity, cooling EER and heating COP depend on the refrigerant intermediate pressure and the operating conditions so they can be bigger or smaller than for the single-stage system. The best range of relative vapor injection mass is 12 - 16% for the best overall cooling and heating performance. Vapor injection changes the systems operating conditions, and increases both the evaporating and condensing temperatures by 0.8 - 1˚ C. Xu et al. [14] studied the performance comparison of R410A and R32 in vapor injection cycles. Through experimentation, it was found that the capacity and coefficient of performance (COP) improvements using R32 can reach up to 10% and 9%, respectively, as compared to an identical cycle using R410A. It is concluded that R32 is an excellent alternative to replace R410A in terms of performance and can be further enhanced by component optimization. Rho et al. [15] studied the effect of intermediate pressure on the heating performance of a heat pump system using R410A vapor-injection technique. Effects of the intermediate pressure on the heating performance with various injection ratios were measured and analyzed according to the compressor frequencies ranging from 60 to 100 Hz. Unlike conventional vapor-injection cycle, the maximum injection ratio was highly affected by the intermediate pressure. The high intermediate pressure provided high initial heating capacity and COP; but it restricted the available range of vapor-injection within narrow limits. The result indicates that a proper operating strategy is needed for the vapor injection cycle. Zhao et al. [16] studied the vapor injection heat pump cycle employing a flash tank coupled with a scroll compressor. The system demonstrated sufficient heating capacity of 8.15 kW at a condensing temperature of 45˚ C and an evaporating temperature of -25˚ C, which they concluded was sufficient for heating in severely cold regions. Cao et al. [17] studied a heat pump water heater using a vapor injection system with a mixture of R22/R600a. It was found that compared with using R22 as the refrigerant, the heating capacity and COP of the system with the mixing refrigerant of R22/R600a were higher when vapor injection was used. Moreover, the compressor discharge temperature could be controlled below100˚ C.

Refrigerant Injection Cycles

There are two basic cycles used for refrigerant injection as follows:

Internal Heat Exchanger Refrigerant Injection Cycle

The schematics and Pressure - Enthalpy (P-h) diagrams of the internal heat exchanger cycle are shown in Fig. 1 and Fig. 2.

Table 1. Review Summary of Refrigerant Injection Technique

Name of researcher	Cycle		Injection type		Compressor type				Refrigerant type			Injection research		
	IHX cycle	Flash tank cycle	Vapor	Liquid	Screw	Rotary	Recipr-ocating	Scroll	R22	R410A	CO_2	Inj port location	Inj press	Inj ratio
Abel et al.,2007		√	√					√						
Atsumi et al.,1985		√	√											
Baek et al., 2008		√	√			√					√			
Bertsch and Groll 2008	√		√					√		√				
Bush et al., 2004				√	√									
Cao et al., 2009a	√		√					√	√				√	
Cao et al., 2009b	√			√				√	√				√	
Cavallini et al.,2005	√						√				√		√	
Cho et al., 2003a				√				√	√			√	√	√
Cho et al., 2009		√	√								√			
Dutta et al., 2001	√			√				√						√
Fan et al., 2008		√	√					√	√					
Haselden, 1976				√	√									
Ignatiev and Caillat 920080		√		√				√						
Ishii et al., 1998		√	√					√				√		
Kang et al., 2008	√			√										√
Lifson et al., 2006			√	√	√									
Lifson et al., 2008	√		√					√					√	
Liu et al., 2008	√			√		√								
Ma et al., 2003	√		√					√	√					
Ma and Chai, 2004	√		√					√	√				√	
Ma and Zhao,2008		√	√					√	√					
Moriwaki et al., 2008		√	√	√										
Park et al., 2002								√						√
Pham et al., 2007; 2008; 2009														
Reynolds, 1950; 1955														
Tian et al., 2006a	√												√	

The cycle operates as follows: the refrigerant exiting the compressor circulates through the condenser first, and is then separated into two paths. One path passes through the upper-stage expansion valve and enters the internal heat exchanger, where it provides sub-cooling to the refrigerant coming from the other path.

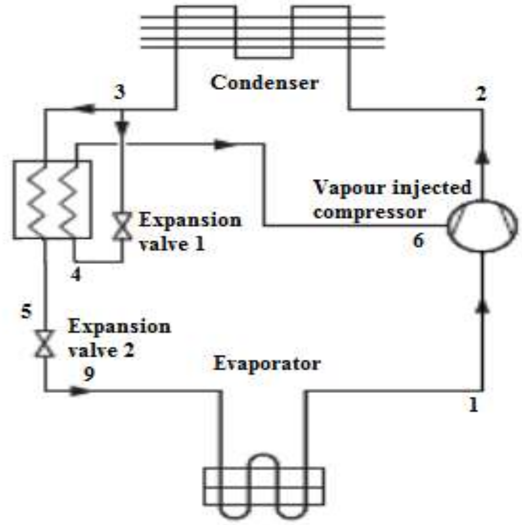

Figure 1. Schematic diagram of an internal heat exchanger refrigerant injection cycle [12]

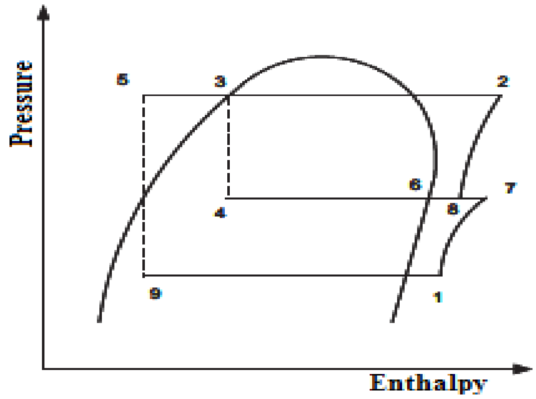

Figure 2. P-h diagram of an internal heat exchanger refrigerant injection cycle [12]

The two-phase refrigerant absorbs heat in the internal heat exchanger and turns into vapour state, which is then injected to the compressor. The sub-cooled liquid enters the lower-stage expansion valve, through the evaporator, and flows to the compressor suction. The essential reason that the internal exchanger cycle can improve both the capacity and COP compared to the single stage cycle is as follows: the liquid refrigerant entering the internal heat exchanger is sub-cooled by the two-phase refrigerant entering the internal heat exchanger from the other path. From Fig. 1 it can be seen that state 3 is extended to state 5. Therefore after the lower-stage expansion, the enthalpy difference across the evaporator islarger than the casewithout two-stage expansion. Although the vapour injection reduces refrigerant mass flow rate through the evaporator, the increased enthalpy difference increases the two-phase heat transfer area in the evaporator. Therefore the overall effect is that the system capacity is increased. In addition, the vapour injection effectively reduces the compressor discharge temperature because the injected vapour temperature is less than that of the vapour in the compressor. Therefore the compression process is closer to isentropic process compared to the single-stage cycle. Thus the compression power can be reduced, leading to the increase of system COP. A number of studies have shown the potential capacity and COP improvement by employing the internal heat exchanger cycle.

Flash tank refrigerant injection cycle

Fig. 3 and Fig. 4 shows the schematic and P-h diagram of the flash tank cycle. The working principle is as follows: the refrigerant discharged from the compressor flows through the condenser and then through the upper-stage expansion valve; then it is separated into liquid phase and vapour phase in the flash tank. The liquid refrigerant enters the lower-stage expansion valve and then circulates through the evaporator, and enters the compressor suction. The vapour refrigerant is injected to the intermediate pressure location of the compressor.From Fig. 3 it can be seen that due to the two-phase separation in the flash tank, the liquid entering the evaporator has lower enthalpy compared to that of a single-stage cycle. Thus the enthalpy difference across the evaporator is greater than that of a single-stage cycle. Similar to the internal heat exchanger cycle, the vapour injection reduces refrigerant mass flow rate through the evaporator. However, the increased enthalpy difference increases the two-phase heat transfer area in the evaporator. Therefore the overall effect is that the system capacity is increased. The saturated vapour from the flash tank also has lower temperature than that of the vapour in the compressor, which helps to reduce the compressor discharge temperature.Reduced compressor power consumption leads to higher system COP. A number of patents have detailed the refrigerant injection cycle coupled with a flash tank. From a thermodynamics point of view, the performance of the internal heat exchanger cycle and the flash tank cycle should have similar performance.

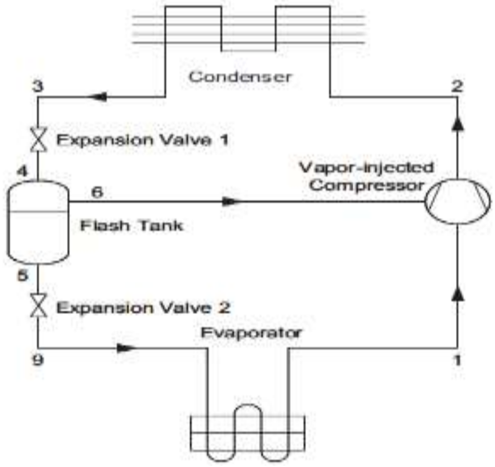

Figure 3. Schematic diagram of flash tank refrigerant injection cycle [12]

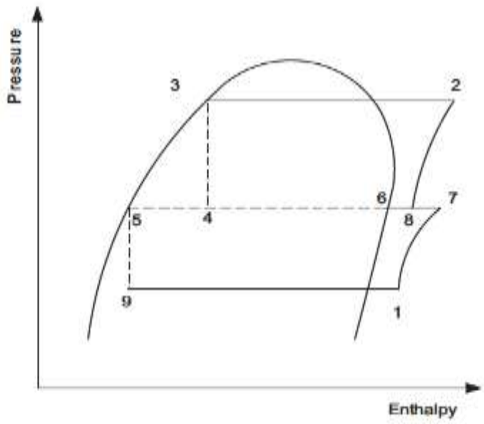

Figure 4.P-h diagram of flash tank refrigerant injectioncycle [12]

From the P-h diagrams in Fig. 2 and 4 it can be seen that the working principle is to decrease the evaporator inlet enthalpy by two-stage expansion. The only difference is whether to achieve it by subcooling through the additional heat exchanger or by two phase separation in the flash tank. However, the actual performance of the flash tank cycle is superior to that of the internal heat exchanger cycle. Wang et al. [12] has experimentally shown that the flash tank cycle has 2-5% higher heating capacity and COP than those of the internal heat exchanger cycle.Zhao et al. "[16]" concluded that the heating capacity and COP of the flash tank cycle were 10.5% and 4.3% higher than those of the internal heat exchanger cycle, respectively. The essential reason is that the superheat of the injected vapour of the flash tank cycle is typically lower than that of the internal heat exchanger cycle, which yields more efficient compression process.

Conclusions

This paper reviews the major researches of refrigerant injection and it has been proven that refrigerant injection in the VCRS shows the improved performance and system reliability. Though most of the research work in the field of refrigerant injection was done by using the Scroll compressor. A little research work is done by using the screw compressor and rotary compressor but very few research works was done by using the hermetically sealed reciprocating compressor. Therefore, from above literature review it is clear that there is large scope to extend the work of refrigerant injection technique in the hermetically sealed reciprocating compressor.

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