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A Review of Vapor Compression-Absorption Integrated Refrigeration Systems

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ABSTRACT

This paper provides a literature review on vapor compression-absorption integrated refrigeration systems. A number of research options are suggested by researchers to integrate vapor compression refrigeration system (VCRS) with vapor absorption refrigeration system (VARs). Each way has its own pros and cons. Present work provides a detailed review on working, parametric study, advantages and disadvantages of various configurations of vapor compression-absorption integrated refrigeration systems.

Keywords: Vapor Compression; Absorption; Integrated Refrigeration Systems.

1.0 Introduction

Vapor compression refrigeration system (VCRS) is widely used refrigeration system (about 80%) and requires a large amount of electrical energy for its operation [1]. The advancement in refrigeration sector has a major impact on energy demand which approximates to 15% of the total energy consumption in the world [2]. Many developing countries like India currently suffer from a major shortage of electricity. Moreover, 56% of the total electrical capacity is generated using coal in India [3]. Not only does it exacerbate the depletion of fossil fuel, but also results in the production of harmful gases due to the burning of fossil fuel, which causes greenhouse effect and deteriorates the environment. But, energy conservation and ecological safety are the indispensable requirement for the sustainable development of any country.

One of the alternatives to reduce the dependence on electrically powered VCRS is the use of vapor absorption refrigeration system (VARs) [4]. VARs which operate on heat energy input are the second most widely used refrigeration systems. Refrigerators which operate on other types of energy input are only used in niche applications [1]. Several researchers have studied the performance of VARs considering H₂O-LiBr as a working pair. This system is generally used for the air conditioning purposes as it can maintain the evaporator temperature up to 5°C [5]. For low temperature applications i.e. below 5°C,

working pair of NH₃-H₂O is used in VARs [6]. But NH₃-H₂O does not form an ideal pair for the absorption system because it produces ammonia mixed with water vapor at the exit of the generator. Water in the refrigerant stream can cause operational problems in the evaporator of the system. Thus H₂O-LiBr fluid pair is suitable from the view point of solubility and boiling point requirements but it cannot be used for low temperature refrigeration [4]. Chakravarthy et al. [1] suggested the use of VCRS for low temperature refrigeration but it requires large amount of electrical energy for its operation.

Engineers and scientists have been constantly engaged in inventing new technologies to provide better alternatives. The idea of combining VCRS with VARs, to innovate an integrated system was looked upon a potential alternative to conventional VCRS and VARs as it economizes the use of energy resources [7]. The appliance of integrated refrigeration system keeps the potentials of both vapor compression and absorption systems, simultaneously eliminates the demerits of both [8]. The main advantage of integrated refrigeration system is that it promises significant electrical energy saving in comparison with equivalent VCRS with small payback period [9]. This system entails the simultaneous usage of electricity and heat energy for refrigeration which can be furnished as waste energy from industrial processes, solar energy, geothermal energy, etc. Even though the space required and initial installation cost for the integrated system is

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high but the shorter payback period (8-9 years) makes them a commercially viable option. Jain et al. [9] concluded that integrated refrigeration systems are promising energy efficient and decarbonizing cooling technology in near future.

There are numerous designs on the compression-absorption integrated refrigeration systems proposed in the literature and can be broadly categorized as follows:

- 1) Vapor compression-absorption refrigeration system [10-22]
- 2) Vapor compression-absorption cascaded refrigeration system [23-39]
 - Series configuration
 - Parallel configuration
- 3) Vapor compression-absorption combined or hybrid refrigeration system [40-42]
- 4) Other vapor compression-absorption integrated refrigeration systems [43-48]

In present paper, an exhaustive literature survey is done to provide insight for the classification, working, thermo-economic performance aspects and comparative advantages and disadvantages of various designs of vapor compression-absorption integrated refrigeration systems.

2.0 Vapour Compression-Absorption Refrigeration System

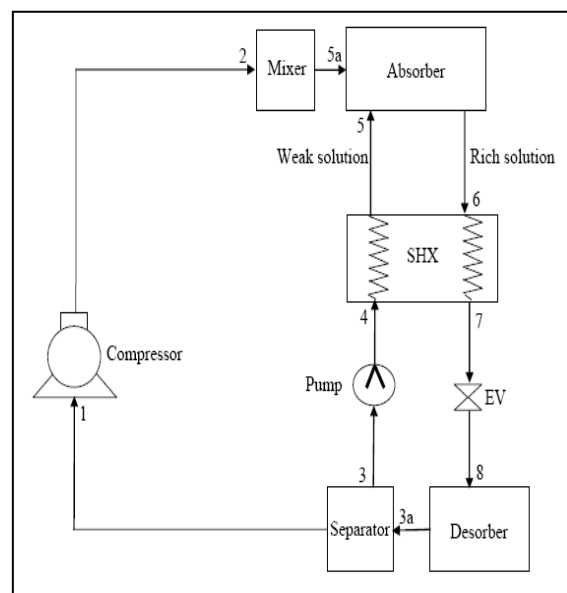
The principle of working of vapor compression-absorption refrigeration system (VCARS) has been given in this section. The compressor draws refrigerant vapor from the desorber and increases its pressure to absorber pressure by consuming electrical energy in compressor as shown in Figure 1 [10]. The refrigerant vapor mixes with weak solution in the absorber and the heat generated in the absorption process is released to the atmosphere. The strong solution is throttled to the desorber pressure and sent to the desorber at low pressure and temperature. This low temperature and low pressure strong solution is deprived of refrigerant vapor by absorbing the heat from source i.e. the medium to be cooled. The refrigerant vapor generated in the desorber is sucked by the compressor and the remaining weak solution is supplied to the absorber by means of a pump. Hence, cooling and heating

effects are produced in the desorber and absorber respectively.

The VCARS offers the following advantages over conventional VCRS [10].

- Non-isothermal heat exchange takes place in the absorber and desorber. Therefore, gliding temperature profile in absorber and desorber is possible which increases the theoretical COP of the cycle.
- The use of mixture allows low pressure levels in the system by changing the concentration of one component in the mixture. This allows low pressure ratio across the compressor which increases the compressor life and requires less electrical energy.
- Better capacity control is possible.
- VCARS offers the advantage of ozone friendly technology due to the use of natural working fluids like NH₃-H₂O and H₂O-LiBr etc.

Fig 1: Schematic Diagram of Vapor Compression-Absorption Refrigeration System [10]



A detailed simulation of 400 kW ammonia-water VCARS has been presented by Pratihari et al. [10] for water chilling application. The results showed that the COP of the system can be increased by maintaining low mass flow rate of weak solution and large relative solution heat exchanger area. Increase in the solution heat exchanger area from 10 to 30% resulted in an increase in COP by 16%.

Usually VCARS are preferred over VCRS for applications where the external temperature gradients are large [11] but Ahlby et al. [12] showed that the VCARS can also be used for applications, where the external temperature gradients are small by optimizing the working conditions. Bourouis et al. [13] evaluated the performance of compression-absorption heat pump using ternary working fluid Trifluoroethanol-Water-Tetraethylglycol-dimethylether for upgrading waste heat. The results showed that the ternary system is more advantageous than the binary working pair. Hulten and Berntsson [14-15] evaluated the performance of compression-absorption heat pump using ammonia/water pair. The COP of system can be improved by allowing a higher absorber pressure (40 bar). Kim et al. [16] presented that the compression-absorption system offers many advantages over conventional vapor compression heat pumps including a large temperature glide, an improved temperature lift, a flexible operating range, and greater capacity control. Other Researchers [17-22] have also analyzed the potential of VCARS for the refrigeration purpose.

3.0 Vapor Compression-Absorption Cascaded Refrigeration System

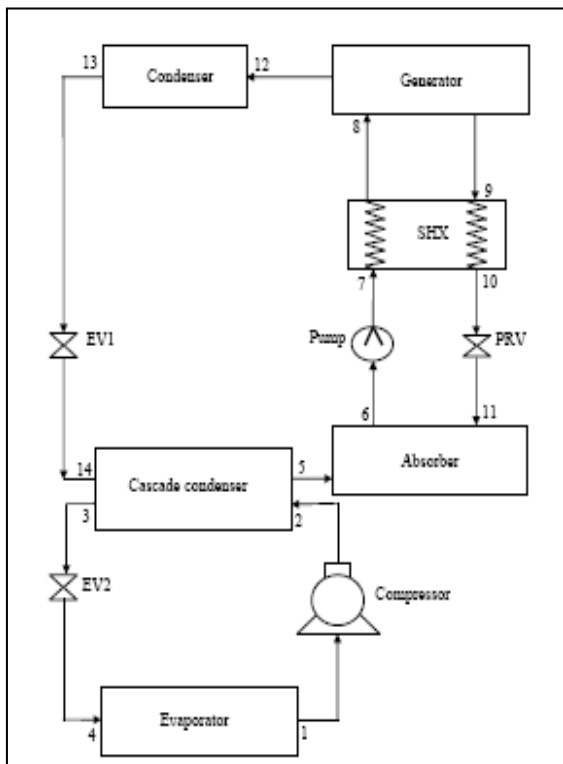
VCRS can be cascaded with VARS either in series or parallel [23] called vapor compression-absorption cascaded refrigeration system (VCACRS). In the series configuration, condenser of VCRS rejects heat to the evaporator of VARS as depicted in Figure 2.

The consumption of electricity in the compressor of the VCRS is reduced as the condensation of the vapor refrigerant occurs at low temperature. The literature reviewed on series configuration is as under:

Cimsit and Ozturk [23] analysed theoretically the performance of VCACRS with H₂O-LiBr and NH₃-H₂O as fluid pair in absorption section and R134a, R410A and NH₃ refrigerants in the compression section of cascaded refrigeration system. It was presented that electrical energy consumption in the cascaded refrigeration cycle was 48-51% lower than conventional VCRS. Chinnappa et al. [24] described a VCACRS consisting of a conventional R22 VCRS cascaded with a solar operated, NH₃-H₂O, VARS for air conditioning application. It was found to yield 49.5% saving in electrical energy consumption by the compression system.

Fernandez-Seara et al. [25] carried out the theoretical study to analyze a VCACRS from the view point of first law of thermodynamics. The system was integrated with a cogeneration system having exhaust gas temperature upto 873 K and it was found that electrical energy consumption was reduced by 133% in one of the configuration. The CO₂ and NH₃ were used as refrigerants in the compression section and NH₃-H₂O as the working pair in absorption section. Kairouani and Nehdi [26] theoretically studied the comparative performance of three refrigerants (R717, R22, R134a) in the compression section with NH₃-H₂O fluid pair in the absorption section of the VCACRS. Geothermal heat was supplied in the generator at the temperature of 335 K for a fixed evaporation temperature of 263 K. The highest performance was obtained by R717. They achieved a refrigeration effect of about 10 MW with the compressor power of 1.65 MW and reported that the same refrigeration effect could be produced by a conventional VCRS by consuming 3.6 MW of electricity which was 54% more than the combined installation consumption. Garimella et al. [27]

Fig 2: Schematic Diagram of Vapor Compression-Absorption Cascaded Refrigeration System in Series Configuration [23]



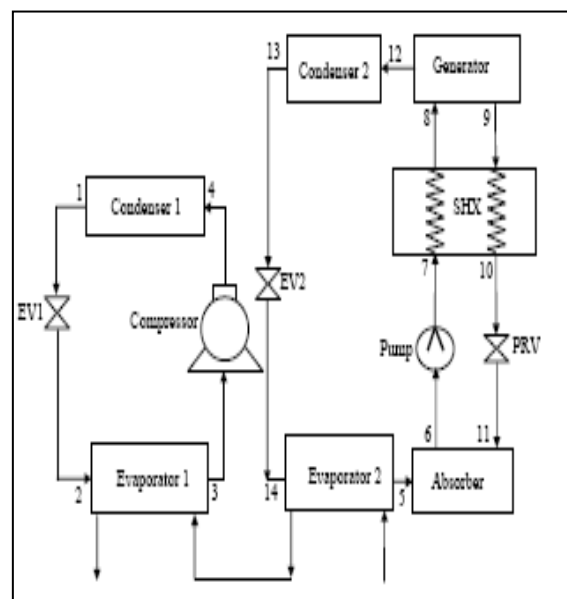
modelled VCACRS for naval ship application where the absorption section was powered by the exhaust heat from the on-board gas turbine power plant. An energy and economic analysis was presented by Marimon et al. [28] where a tri-generation system was integrated with an indirect cascaded refrigeration system for super market application with maximum refrigeration capacity of 100 kW. CO₂ was used as refrigerant in compression section whereas NH₃-H₂O fluid pair was used in the absorption section. Several tri-generation configurations have been studied. They all showed a payback period of less than 6 years and it was concluded that novel tri-generation system is economically feasible and environmentally viable than conventional supermarket systems. Seyfour and Ameri[29] analysed a VCACRS in which the compressor was powered by a microturbine and the waste heat from the turbine was used to drive the absorption section. In this study, H₂O-LiBr pair was considered as the working fluid in the absorption section whereas R22 was considered in compression section. A solar assisted VCACRS was studied by Wang et al. [30].

Goktun and Deha[31] investigated the effect of internal irreversibility on the performance of solar assisted VCACRS. Based on first and second law of thermodynamics, Colorado and Velazquez [32] analyzed a VCACRS with the aim of finding the best pair of working fluid. H₂O-LiBr was used in the absorption section and NH₃, R134a and CO₂ were evaluated in the compression section. The COP values estimated for R134a, NH₃ and CO₂ were 0.5852, 0.5819 and 0.5435 respectively; whereas, the exergetic efficiency of system was 0.2983, 0.2966 and 0.2685 respectively. R134a-H₂O/LiBr fluid pair was reported to be a better alternative in VCACRS. In another study by Colorado and Rivera [33], comparison of the performance of two VCACRS was presented wherein single effect and double effect VARS were cascaded with conventional VCRS. The performance was better with double effect VARS since COP was improved by 36.3% using R134a-H₂O/LiBr fluid pair. Cimsit et al. [34] also performed energy and exergy analyses in order to determine the best suitable working pair in the cascaded refrigeration system. The performance of H₂O-LiBr and NH₃-H₂O fluid pairs was compared while considering R134a in the compression section. In the case of H₂O-LiBr fluid pair, the COP was 27% higher

and total exergy destruction rate was 20% lower as compared to NH₃-H₂O fluid pair. In a study, presented by Jain et al. [35], payback period for series configuration of VCACRS was estimated to be 4.5 years. In another economic study by Jain et al. [36], it has been reported that the cascading of VCRS with VARS becomes attractive for lower rate of interest and increase life span and operational period.

Another way to cascade the VCRS with VARS is the parallel configuration, where the cooling duty is shared by both the refrigeration systems (Figure 3). The product is first cooled in the evaporator of absorption section followed by the evaporator of compression section [37]. The saving in electrical energy is obtained by reducing the cooling load on the VCRS.

Fig 3: Schematic Diagram of Vapor Compression-Absorption Cascaded Refrigeration System in Parallel Configuration [37]



Mohammadi and Ameri [7] theoretically analysed parallel configuration of VCACRS powered by a micro gas turbine based on first and second law of thermodynamics. H₂O-LiBr fluid pair was used in absorption system whereas R22 was used in vapor compression chiller. It was concluded that the cascade configuration of system would increase the efficiency of energy usage upto 50% as compared to the equivalent VCRS.

Sun and Guo[37] set up a prototype parallel configuration of VCACRS for air conditioning

application with the cooling capacity of 589 kW where a gas engine drove directly the screw compressor in a vapor compression chiller and waste heat from the gas engine was used to operate vapor absorption system. R22 and H₂O-LiBr fluid pair were used in compression and absorption systems respectively.

Primary energy rate (*PER*) and comparative primary energy saving were used as the key parameters to evaluate energy utilization efficiency of the cascaded refrigeration system.

The *PER* of 1.81 was obtained with the prototype and it saved more than 25% of primary energy as compared to the conventional electrically driven VCRS.

Sun [38] fabricated the experimental facility and tested prototype VCACRS for central air conditioning which was also driven by a gas engine. R22 and H₂O-LiBr fluid pair was used in compression and absorption systems respectively.

The experimental results showed that the refrigeration capacity of VCACRS reached 596.2 kW when the speed of gas engine was 1800 rpm. *PER* of prototype reached 1.84 at the rated conditions.

The refrigeration capacity of the set up got reduced and energy utilization ratio of the system increased with the decrease of gas engine speed. Jeong et al. [39] constructed a gas engine driven VCACRS for air conditioning application using H₂O-LiBr fluid pair in absorption section and NH₃ in compression section.

The system COP at the design point was about 1.87 and, at 50% partial load operation, the performance increased by 14% because of the simultaneous manipulation of the input gas flow rate and hot water flow rate.

Jain et al. [9] presented the comparative performance study of series and parallel configurations of VCACRS based on combined energy, exergy, economic and environmental (4E) analyses.

The power consumption in the compressor of parallel and series configurations is reduced by 50% and 76.6% respectively as compared to equivalent VCRS [9].

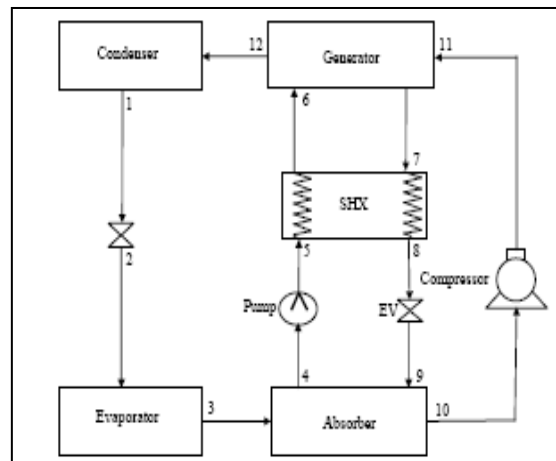
The capital cost of parallel and series configurations is 3.1 and 3.6 times respectively more than equivalent VCRS which is the main drawback in successful implementation of VCACRS. But, the

shorter payback period makes them commercially viable option [9].

4.0 Vapor Compression-Absorption Combined Or Hybrid Refrigeration System

A vapor compression-absorption combined or hybrid refrigeration system (VCAHRS) offers the choice of using high grade energy (electricity) or low grade energy (heat) to produce required refrigeration effect. It is capable of operating in different modes and can be utilized round the clock depending upon the availability of the specific energy sources, i.e. heat energy or electrical energy [40].

Fig.4 Schematic Diagram of Vapor Compression-Absorption Combined or Hybrid Refrigeration System [41]



When the cooling capacity of the absorption system cannot meet the cooling demand of the system, the compression system works to take partial or full cooling load. The operating strategy of the combined refrigeration system ensures the absorption system to work prior to the compression system as depicted in Figure 4. Many researchers [5, 41-42] have analyzed the potential of VCAHRS.

5.0 Other Vapor Compression-Absorption Integrated Refrigeration Systems

In addition to above mentioned systems, there are different possible configurations to integrate VCRS with VARS. Boer et al. [43], Janghorban Esfahani et al. [44] and Meng et al. [45] integrated

the VCRS and VARS in such a way that compressed vapor after superheating in the compressor is absorbed in the absorber by the weak solution coming from the generator. Anand et al. [46] used the compressor in VARS in between the generator and condenser. Han et al. [47] proposed vapor compression-absorption system which is integrated by an absorber and a rectifier. Xu et al. [48] used different concept to cascade VCRS and VARS. The refrigerant in the compression subsystem was condensed by the ambient air or water first. Then, the condensed refrigerant was supercooled by an absorption subsystem. The advantage of the consequence was that the high temperature cooling capacity provided by the absorption subsystem was upgraded to the low temperature cooling capacity of the compression subsystem.

Researchers have used different ways to integrate VCRS with VARS. Each way has its own pros and cons. The application of integrated refrigeration systems maintains the advantages of both VCRS and VARS while minimizing the limitations of both the systems. The compression system of such refrigeration system is generally operated by the shaft work of gas engine or turbine whereas the waste heat from the gas engine or turbine is used as a heat source for the generator of absorption section. By recovering the waste heat from the gas engine or turbine, the primary energy utilization efficiency of integrated system beats the equivalent VCRS. Hence, integrated refrigeration system is having high energy utilization efficiency, which not only saves the running cost but also contributes the additional environmental benefits.

6.0 Conclusions

In consequence of electrical energy shortage and environmental issues related to the global warming and ozone layer depletion attributed to the application of VCRS, the utilization of decarbonizing and energy efficient cooling technology for refrigeration purposes appears to be an appropriate alternative. Researchers have been constantly engaged in inventing new cooling technologies to provide better alternatives. Different configurations of VCRS and VARS are suggested in the literature to Economize the use of energy resources. The integrated system substantially reduces the electrical

energy consumption as compared to an equivalent VCRS as it entails the simultaneous usage of electricity and heat energy for the refrigeration which can be furnished as waste heat from industrial processes. Hence, the operating cost of integrated refrigeration is very less as compared to equivalent VCRS. But, the main hindrance in the practical application of integrated system is their size and initial investment cost. But, shorter payback period makes them commercially viable option.

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