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Thermodynamic performance analysis of a vapor compression–absorption cascaded refrigeration system

Vaibhav Jain [a,*], S.S. Kachhwaha [b], Gulshan Sachdeva [a]

[a] Department of Mechanical Engineering, National Institute of Technology, Kurukshetra, India
[b] Department of Mechanical Engineering, School of Technology, Pt. Deendayal Petroleum University, Gandhinagar, India

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ABSTRACT

In the present study, a thermodynamic model for cascaded vapor compression–absorption system (CVCAS) has been developed which consists of a vapor compression refrigeration system (VCRS) coupled with single effect vapor absorption refrigeration system (VARS). Based on first and second laws, a comparative performance analysis of CVCAS and an independent VCRS has been carried out for a design capacity of 66.67 kW. The results show that the electric power consumption in CVCAS is reduced by 61% and COP of compression section is improved by 155% with respect to the corresponding values pertaining to a conventional VCRS. However there is a trade-off between these parameters and the rational efficiency which is found to decrease to half of that for a VCRS. The effect of various operating parameters, i.e., superheating, subcooling, cooling capacity, inlet temperature and the product of effectiveness and heat capacitance of external fluids are extensively studied on the COP, total irreversibility and rational efficiency of the CVCAS. Besides, the performance of environment friendly refrigerants such as R410A, R407C and R134A is found to be almost at par with that of R22. Hence, all the alternative refrigerants selected herein can serve as potential substitutes for R22. Furthermore, it has been found that reducing the irreversibility rate of the condenser by one unit due to decrease in condenser temperature depicted approximately 3.8 times greater reduction in the total irreversibility rate of the CVCAS, whereas unit reduction in the evaporator's irreversibility rate due to increase in evaporator temperature reduced total irreversibility rate by 3.4 times for the same system. Since the changes in the inlet temperatures of external fluid in the condenser and the evaporator contribute significant changes in system's overall irreversibility, due consideration is required in condenser and evaporator temperatures to improve the system performance.

1. Introduction

Refrigeration is the process of maintaining the system temperature to a value lower than that of surrounding [1] by means of a refrigeration cycle. Vapor compression refrigeration system is widely used in domestic as well as industrial refrigerating and air-conditioning equipments such as in restaurants, hotels, hospitals and theatres. It is also used for manufacturing of ice, dehydration of gases, lubricating oil purification, low temperature reactions, and separation of volatile hydrocarbons, etc. [1].

Many developing countries like India currently suffer from a major shortage of electricity. The demand for electricity in India is very high both in terms of base load energy and peak availability. During the year 2010–2011, base load requirement was 861,591MU against the availability of 788,355 MU – an 8.5% deficit. During peak loads, the demand was for 122 GW against the availability of 110 GW, a 9.8% shortfall. Out of the 1.4 billion people in the whole world with no access to electricity, India accounts for over 300 million [2].

The refrigerating and air conditioning equipment based on VCRS consume a considerable amount of electric power. In India, 56% of the total electrical capacity is generated using coal [2]. Not only does it exacerbate the depletion of fossil fuel, but also results in the production of harmful gases such as CO_2, nitrogen oxides and sulfur oxides etc. It is well known that these gases cause green house effect and deteriorate the environment. In various industrial sectors like liquid milk processing, chilled ready meals, frozen food, cold storage etc. the electricity employed for refrigeration is 25%, 50%, 60% and 85% respectively of their total energy consumption [3]. However, due to poor availability of electric power, the total installed refrigeration capacity is inadequate to meet the refrigeration requirements. Nearly 30% of fresh fruits and vegetables produced in India are wasted due to lack of refrigeration technology [4].

One of the alternatives to reduce the dependence on electrically powered VCRS is the use of VARS in which the compressor is replaced by absorber, pump and generator [1]. VARS demands a

* Corresponding author. Tel.: +91 9868004700.
E-mail address: vaibhavursaathi@gmail.com (V. Jain).

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Nomenclature

BEP	breakeven point (years)
c	concentration of LiBr solution
C	heat capacitance rate of external fluid (kW/K)
c_p	specific heat at constant pressure (kJ/kg K)
CIC	capital investment cost (Rs.)
COP	coefficient of performance
E	exergy (kW)
EC	electric cost (Rs.)
EEUF	electrical energy utilization factor
f	circulation ratio
FESR	fuel energy saving ratio
h	specific enthalpy (kJ/kg)
HUF	heat utilization factor
I	irreversibility rate (kW)
m	mass flow rate (kg/s)
P	pressure (kPa)
PP	payback period (years)
Q	heat transfer (kW)
s	specific entropy (kJ/kg K)
T	temperature (°C)
U	uncertainty
W	power input (kW)

Greek symbol

ε	effectiveness of heat exchanger
η	efficiency
δ	efficiency defect
ψ	specific exergy (kJ/kg)
θ	Carnot factor
σ	coefficient of structural bond
ρ	density of LiBr solution (kg/m^3)

Subscript

a	absorber
cascade	cascaded
comp	compressor
cond	condenser
CVCAS	cascaded vapor compression-absorption system
ef	external fluid
eV	expansion valve
evap	evaporator
g	generator
in	inlet condition
isen	isentropic
liq	liquid line
loss	loss of heat
o	environmental condition
out	outlet condition
p	pump
prv	pressure reducing valve
R	rational
ref	refrigerant
SHX	solution heat exchanger
sub	subcooling in liquid line
suc	suction line
sup	superheat in suction line
t	total
VARS	vapor absorption refrigeration system
VCRS	vapor compression refrigeration system
1, 2, 3, ...	state points

substantial amount of heat energy for the generator; however, heat is low grade energy and its demand can be fulfilled using non-conventional sources such as solar, geothermal and waste heat. The electrical energy consumed by this system is merely 10% of the total energy requirements [5]. Several researchers [6–11] have studied the performance of VARS considering H_2O–LiBr as a working pair. This system is generally used for air conditioning purposes as it can maintain evaporator temperature up to 5 °C [5]. For low temperature applications i.e. below 5 °C, working pair of NH_3–H_2O can be used in vapor absorption system [12]. But NH_3–H_2O does not form an ideal pair for absorption system because the difference in their Normal Boiling Points (N.B.Ps) is not large enough (138 °C). There should be a sufficiently large difference in the N.B.Ps of the two substances (at least 200 °C) [1] so that the absorbent exerts negligible vapor pressure at the generator temperature. This system 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 H_2O–LiBr pair is suitable from the view point of solubility and boiling point requirements but it cannot be used for low temperature refrigeration [1].

The application of cascaded refrigeration system maintains the advantages of both vapor compression and vapor absorption systems while minimizing the limitations of both simultaneously. The main advantage of CVCAS over VCRS is that it saves considerable amount of high grade energy (electrical energy). While the structure of the cascaded system is more complex and bulky, the overall operating cost is relatively lower because of simultaneous usage of electricity and heat energy for refrigeration. Furthermore, the non-conventional sources of energy such as solar, geothermal etc. can be used to supply heat energy for this system. The literature on CVCAS is summarized in Table 1 with key findings.

Many researchers [13,21,22,26] have considered NH_3–H_2O pair of working fluid in absorption system which does not form an ideal pair [1]. Unlike water, ammonia is both toxic and flammable. The previous work [13,21–26] reported on CVCAS is based on first law analysis (energy conservation). In the present study, a CVCAS consisting of VCRS coupled with VARS (H_2O–LiBr as working pair) has been proposed as an alternative to reciprocating vapor compression chiller [27]. Besides comparative energy as well as exergy analysis supported with preliminary economic analysis has also been performed. The concepts of coefficient of structural bond (CSB), heat utilization factor (HUF), electrical energy utilization factor (EEUF), fuel energy saving ratio (FESR) and heat to work ratio have been applied for better understanding of performance of the system with wide range of cooling capacities. The effect of alternative refrigerants (R134A, R410A and R407C), superheating, subcooling, and size of heat exchanger are also investigated in detail.

2. Theoretical formulation of vapor compression–absorption cascaded refrigeration system

2.1. System selection

Fig. 1 shows a simple variable speed VCRS described by Khan and Zubair [27] used for water cooling and the corresponding P-h diagram is plotted in Fig. 2. Saturated refrigerant vapor leaves the evaporator at state 1 and saturated liquid exits the condenser at state 3. The refrigerant then flows through the expansion valve to the evaporator [28].