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Comparative performance study and advanced exergy analysis of novel vapor compression-absorption integrated refrigeration system

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ABSTRACT

In present work, a novel configuration of vapor compression-absorption integrated refrigeration system (VCAIRS) is analyzed. Unlike previous vapor compression-absorption cascaded refrigeration system (VCACRS), proposed configuration works at lower generator temperature of 60 °C. Thus, allowing the use of low grade waste heat for its operation. The performance of VCAIRS is also compared with the equivalent vapor compression refrigeration system (VCRS) and VCACRS for the same cooling capacity of 100 kW. The comparative study result shows that electrical energy requirement in VCAIRS is 21.4% more as compared to VCACRS but it is still 63% less as compared to the equivalent VCRS. Further, the second law efficiency of VCAIRS, VCACRS and VCRS are determined to be 27.9%, 32.7% and 18.8%, respectively. Thus, both the VCAIRS and VCACRS are energy and exergy efficient configurations; but, VCACRS results in more energy efficient cooling technology in the foreseeable future as it utilizes heat at lower generator temperature as compared to VCACRS.

After the comparative performance study, the exergetic performance of VCAIRS is further explored based on the coefficient of structural bonds (CSB) and advanced exergy analysis methods. Highest CSB of 4.39 is obtained for high pressure solution heat exchanger but its overall contribution in total irreversibility rate is merely 0.2%; whereas, the highest contribution of 17.4% in total irreversibility rate is by compressor 1 but CSB value computed for it is merely 1.73. Further, advance exergy analysis results show that 35.2% of total irreversibility rate of VCAIRS can be avoided by improving the efficiency parameter of components of system.

1. Introduction

There are different applications which require refrigeration from near absolute temperature of 4 K to near atmospheric temperature (human comfort) of 300 K [1]. Hence, different refrigeration methods are suggested by the researchers to fulfill this requirement. The selection of refrigeration system also depends on cooling duty across it and its investment and running cost [2]. Around 80% of present day refrigeration systems (300–120 K range) work on electrically powered vapor compression refrigeration cycle; whereas, vapor absorption refrigeration cycle which requires heat energy as input, are the second most widely used refrigeration systems (280–243 K). Refrigerators which operate on other types of energy input are only used in niche applications [1].

Vapor compression refrigeration system (VCRS) is most widely used due to its high COP and smaller size for the same cooling capacity as compared to vapor absorption refrigeration system (VARS). The other advantage of VCRS includes attainment of lower refrigeration temperature as compared to VARS but it consumes large amount of electrical energy for its operation [3].

Researchers are constantly engaged in inventing new technologies to reduce the electricity consumption in VCRS. The proposal of integrating VCRS with VARS is considered as a probable alternative to the conventional VCRS and VARS by the research community since it economizes the usage of energy resources [4]. The integrated 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. Abundant configurations on the combined vapor compression and vapor absorption refrigeration systems have been proposed in the literature which leads to the development of energy efficient and environmental friendly cooling technologies.

Jain et al. [2] compared the performance of series, parallel and combined series-parallel configurations of vapor compression-

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Nomenclature

c_p	specific heat at constant pressure (kJ/kg K)
COP	coefficient of performance
CSB	coefficient of structural bonds
$\dot{E}$	rate of exergy (kW)
f	circulation ratio
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
PR	pressure ratio
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
$\dot{S}_{gen}$	entropy generation rate (kW/K)
T	temperature (K)
$\dot{W}$	rate of power input (kW)
x	mass concentration of absorbent in the solution (%)

Greek symbols

η	efficiency
ε	effectiveness
ρ	density of solution (kg/m^3)

Subscripts

cascade	cascade condenser
comp	compressor
cond	condenser
ef	external fluid
ev	expansion valve
evap	evaporator
EQS	element or subsystem
GH	hot surface
HPA	high pressure absorber
HPC	high pressure circuit
HPG	high pressure generator
HPSHX	high pressure solution heat exchanger
in	inlet condition
ideal	ideal system
isen	isentropic
k	kth element of system
LPA	low pressure absorber
LPC	low pressure circuit
LPG	low pressure generator
LPSHX	low pressure solution heat exchanger
o	environment condition
out	outlet condition
overlap	degree of overlap
p	pump
PRV	pressure reducing valve
R	rational
ref	refrigerant
T	total
VARS	vapor absorption refrigeration system
VCAIRS	vapor compression-absorption integrated refrigeration system
VCACRS	vapor compression-absorption cascaded refrigeration system
VCRS	vapor compression refrigeration system
weak	weak solution
x_i	system efficiency parameter
1, 2, 3, ⋯	state points

Superscripts

AV	avoidable
EN	endogenous
EX	exogenous
UN	unavoidable

absorption cascaded refrigeration system (VCACRS) with an equivalent vapor compression chiller of 170 kW cooling capacity. As compared to equivalent vapor compression chiller, the electricity consumption in the compressor of vapor compression section is reduced by 76.8%, 50%, and 88.3% for series, parallel and combined series-parallel configurations, respectively. It is to be noted here that the heat is supplied in the generator of vapor absorption section at the source temperature of 100 °C for all the three configurations. Bhavesh et al. [5] estimated the energetic and rational efficiencies of VCACRS powered by organic rankine cycle as 79.02% and 46.7%, respectively; with the source temperature, which increases the temperature of the pressurized water upto 151.5 °C. Li et al. [6] estimated exegetic efficiency of 23% for solar absorption-subcooled compression hybrid cooling system, with inlet temperature of hot water as 100 °C. Wang et al. [7] studied absorption-compression hybrid refrigeration system; wherein, all the heat lost in condensation is used for the generation purpose. It was resulted 70–80% reduction in the generation heat and 97.1% improvement in primary energy efficiency of proposed system as compared to conventional VARS. Vasta et al. [8] presented experimental investigation of cascade chiller consisting of an adsorption and vapor compression units. Electrical COP up to 5.7 was recorded for 95 °C driving temperature in adsober. Chen et al. [9] proposed absorption/absorption-compression refrigeration system which consists of a conventional single-effect VARS and an absorption-compression refrigeration system. With the source temperature of 200 °C, the cooling capacity per unit mass of flue gas for the proposed system was 28.2% higher than equivalent VARS; whereas, the exergy efficiency was reported to be 25.9%. Su and Zhang [10] proposed a hybrid compression-absorption refrigeration air-conditioning system combined with liquid desiccant dehumidification. The heat rejected from the condenser of absorption section is used to regenerate the diluted liquid desiccant solution. Besides, the evaporator temperature is increased as the latent heat is handled by diluted liquid desiccant solution. It increases the primary energy efficiency of the system by 34.9% as compared to traditional VARS; whereas, the generator temperature is decreased from 100 °C to 60 °C due to the presence of the compressor at the exit of generator. Ayou et al. [11] improved the performance of VARS by placing a compression booster in between the absorber and the evaporator. The energy and exergy efficiency of the proposed system are reported to be 12.2% and 60.7%, respectively with the generator source temperature of 130 °C. Xu et al. [12] compared the performance of vapor compression-absorption cascaded refrigeration system with an evaporator condenser and with an evaporator-subcooler based on their COP. The COP of vapor compression-absorption cascaded refrigeration system with an evaporator condenser is 7.6% higher as compared to evaporator-subcooler system with generator temperature in the range of 90 to 120 °C.

In addition to the above mentioned systems, researchers [13–15] proposed several other different possible configurations of vapor compression-absorption integrated refrigeration systems. Each configuration has its own pros and cons. In present work, a novel configuration of vapor compression-absorption integrated refrigeration system (VCAIRS) is presented for low temperature application. The proposed integrated system utilizes both the low grade as well as high grade