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Configuration optimization of series flow double-effect water-lithium bromide absorption refrigeration systems by cost minimization

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ABSTRACT

An optimal process configuration for double-effect water-lithium bromide absorption refrigeration systems with series flow – where the solution is first passed through the high-temperature generator – is obtained by minimization of the total annual cost for a required cooling capacity. To this end, a nonlinear mathematical programming approach is used. Compared to the optimized conventional double-effect configuration, the new optimal configuration obtained in this paper allows reducing the total annual cost, the capital expenditures, and the operating expenditures by around 9.5%, 11.1% and 4.9%, respectively. Most importantly, the obtained optimal solution eliminates the low-temperature solution heat exchanger from the conventional configuration, rendering a new process configuration. The energy integration between the weak and strong lithium bromide solutions (cold and hot streams, respectively) takes place entirely at the high-temperature zone, and the sizes and operating conditions of the other process units change accordingly in order to meet the problem specification with the minimal total annual cost. This new configuration was obtained for wide ranges of the cooling capacity (150–450 kW) and the temperature of the cooling water (15–35 °C). The results of this work motivate to apply the simultaneous optimization approach to seek for new multi-effect absorption refrigeration system configurations with parallel and reverse flow as well as other series flow arrangements that minimize the total annual cost.

1. Introduction

Today, many refrigeration systems utilize mechanical compression, which is energy intensive. Nonetheless, there has been an increasing concern over conventional refrigeration system working fluids that contribute to ozone layer depletion, greenhouse effects, and global warming. One alternative to tackle these challenges is the development of more economic and environmentally sustainable refrigeration systems. Over the past decade, there has been an increasing interest in research to develop and improve absorption refrigeration systems (ARSs) [1]. An ARS is a feasible option for harnessing residual heat and renewable sources like solar and geothermal energy. Furthermore, the operating fluids of these processes are environmentally benign [2]. Though the global performance of the absorption cycle is usually poor – in terms of cooling effect per unit of supplied energy −, residual heat like the one rejected from power plants can be harnessed to improve the global energy utilization [3].

Ammonia-water (NH_3-H_2O) based systems are broadly employed where lower temperature levels are required. Nonetheless, water-lithium bromide (H_2O-LiBr) based systems are also extensively used where moderate temperature levels are required (for example, air-conditioning units), the latter system being more efficient than the former. Moreover, the environmental benefit of the ARSs using H_2O-LiBr as the refrigerant-absorbent working pair is already well-known. This advantage of H_2O-LiBr ARSs is not only over other refrigeration technologies such as vapor compression systems, but also over other ARSs using different working pairs such as NH_3-H_2O [4]. That is mainly because (i) ARS uses thermal energy instead of electricity, and (ii) to the best of our knowledge, the LiBr solution has no global warming or ozone depleting potential that has been reported in the open literature, satisfying the environmental criteria defined under both the Montreal and Kyoto Protocols. However, conventional single-effect ARSs show low energy efficiencies and they are limited to using heat sources of low

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Nomenclature

Symbols

A_k	cost parameter for estimating investment for a process unit k (\$/(ft^2)^{Bk}) [Eq. (33)]
B_k	cost parameter for estimating investment for a process unit k (dimensionless) [Eq. (33)]
C_k	cost parameter for estimating investment for a process unit k (\$) [Eq. (33)]
CAPEX	capital expenditures (\$/yr)
CRF	capital recovery factor (dimensionless)
CU	cooling utility (t/yr)
$\mathbf{g}_t$	set of inequality constraints t
$\mathbf{h}_s$	set of equality constraints s
h_i	specific enthalpy of a process stream i (kJ/kg)
H_i	enthalpy flow rate of a process stream i (kW)
HTA_k	heat transfer area of a process unit k (m^2)
HU	heating utility (t/yr)
i	interest rate (dimensionless)
IN	subset of *PS* with the streams i entering a process unit k, except for utility streams (cooling water, chilled water, and hot source)
$LMTD_k$	logarithmic mean temperature difference in a process unit k (°C)
M_i	mass flow rate of a process stream i (kg/s)
n	project lifetime (yr)
OPEX	operating expenditures (\$/yr)
OUT	subset of *PS* with the streams i leaving a process unit k, except for utility streams (cooling water, chilled water, and hot source)
P	pressure (kPa)
PC	set of the system components j
PS	set of the process streams i
PU	set of the process units k
Q_k	heat load in a process unit k; exchanged heat (kW)
T_i	temperature of a stream i (°C, K)
TAC	total annual cost (\$/yr)
THTA	total heat transfer area of the system (m^2)
U_k	overall heat transfer coefficient for process unit k (kW/m^2/°C)
W_k	power in a process unit k (kW)
$\mathbf{x}$	vector of model variables
X_j	mass fraction of component j (% kg/kg)
Z_k	investment for a process unit k (\$)

Greek letters

δ	a small positive value (parameter) used in model constraints Eqs. (13) – (29)
Δ	refers to the difference between two values
ε	effectiveness factor of a solution heat exchanger (dimensionless)

Subscripts

CU	cooling utility
HU	heating utility
i	a process stream
in	inlet
j	a system component
k	a process unit
min	minimum
out	outlet
s	an equality constraint of the mathematical optimization model
t	an inequality constraint of the mathematical optimization model
u	utility (cooling water, chilled water, and hot source)

Superscripts

C	cold side of a heat exchanger
H	hot side of a heat exchanger
L	lower bound

thermal levels [5] such as solar or geothermal energy sources, or low-grade residual heat from industrial processes. In order to enhance the ARS overall efficiency and overcome its limitation to heat source temperature, researchers have proposed improved configurations for ARS, including advanced configurations of multi-effect systems [6]. The double-effect ARS has attracted a lot of interest while being the most commercially applied multi-effect ARS [7].

Many researchers have dealt with the double-effect H_2O-LiBr ARS performing energy analyses, exergy analyses, and exergo-economic analyses. Kaushik and Arora [8] performed model-based parametric energy and exergy analyses of a series flow double-effect H_2O-LiBr ARS, and compared the results with a single-effect ARS. Particularly, they analyzed the effects of varying the generator, absorber, and evaporator temperatures, as well as the pressure drop between the evaporator and the absorber and the heat exchanger effectiveness, on the energetic and exergetic performance, in terms of the coefficient of performance, exergy destruction, efficiency defects, and exergetic efficiency. They also analyzed the effect of the temperature difference between the heat source and the generator, and between the evaporator and the cold room. Kaynakli et al. [9] performed a comparative energy and exergy analysis of a double-effect H_2O-LiBr ARS with series flow considering hot water, steam, and hot air as heat sources in the high-pressure generator. They carried out a parametric analysis of the operating temperatures on the coefficient of performance, exergy destruction in the high-pressure generator, heat capacity, and heat source mass flow rate. Gomri [10] performed a simulation-based comparative analysis based on the first and second law of thermodynamics between single-effect and double-effect H_2O-LiBr ARSs for the same cooling specifications. The author studied the influence of the various operating parameters on the coefficient of performance, heat loads in the system's components, exergetic efficiency (rational efficiency), and the total exergy destruction associated with the two examined cycles. Talukdar and Gogoi [11] performed parametric energy and exergy analyses of a combined vapor power cycle and a double-effect H_2O-LiBr ARS as a bottoming cycle to evaluate its thermodynamic performance. They varied the temperature of the flue gas of the power cycle boiler which is the heat source for the high-temperature generator of the ARS. Also, they compared the energetic and exergetic performance of this process with the performance of a single-effect configuration for the same flue gas temperature. Morosuk and Tsatsaronis [12] proposed an advanced exergy analysis of energy conversion systems, which consists in splitting the total exergy destruction into endogenous/exogenous and unavoidable/avoidable parts. This splitting improves the accuracy of exergy analysis and the understanding of the thermodynamic inefficiencies, and facilitates the improvement of a system. They applied this development to an absorption refrigeration machine as an illustrative case study. An example of how this approach can be used to improve the design is shown in [13]. Garousi Farshi et al. [5] applied the exergo-economic method to analyze three types of double-effect H_2O-LiBr ARSs (series, parallel, and reverse parallel flow) at a broad