Applied Thermal Engineering 141 (2018) 751–761

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental barium chloride-ammonia cooling cycle study at low generation temperatures

F. Martínez-Tejeda[a,*], I. Pilatowsky[b], R. Best[b], O. Meza-Cruz[c], V.H. Gómez[b], E. Cadenas[d], R.J. Romero[e]

[a] Posgrado de Ingeniería, Universidad Nacional Autónoma de México, 62580 Temixco, Morelos, Mexico
[b] Instituto de Energías Renovables, Universidad Nacional Autónoma de México, 62580 Temixco, Morelos, Mexico
[c] Universidad Autónoma del Carmen, 24039 Campeche, Mexico
[d] Posgrado de Ciencias Exactas e Ingeniería, Universidad Autónoma del Estado de Morelos, 62209 Cuernavaca, Morelos, Mexico
[e] Centro de Investigación en Ingeniería y Ciencias Aplicadas, Universidad Autónoma del Estado de Morelos, 62209 Cuernavaca, Morelos, Mexico

HIGHLIGHTS

- An experimental thermochemical cooling system is evaluated.
- An experimental equilibrium equation was obtained.
- Industrial grade barium chloride and ammonia reagents were used.
- Cooling at 3 °C was produced with heat source temperature of 60 °C.

ABSTRACT

Thermally driven cooling systems are becoming increasingly important as an alternative to the conventional mechanical vapour compression cooling systems. Among these technologies, thermochemical cooling offers a large number of chemical reactions in a wide range of operating conditions, which can use low-grade waste heat, as well as solar, biomass or geothermal energy resources. In this work, an intermittent prototype of a single stage thermochemical cooling system, using the reaction: barium chloride and ammonia ($BaCl_2$, $8NH_3$) was designed, constructed and evaluated. In this work industrial grade reagents were utilized without additive compounds to improve the heat transfer. The pressure-temperature equilibrium was similar to that reported in the literature. The generation temperatures ranged between 54 and 69 °C where up to 6.65 L of liquid ammonia was desorbed. Anhydrous $BaCl_2$ was obtained from dehydration of di-hydrate-$BaCl_2$, which it was carried out into the reactor, in order to evaluate the feasibility of these operations under actual conditions. The thermochemical reaction rate in general depended on the working temperatures and constant pressure; in this work the evaporator temperatures ranged from 2 to 5 °C at absorber temperature at 32 °C.

Preliminary results show the feasibility of operating the thermochemical cooling cycle with low temperature sources, with almost constant operating conditions using industrial grade reagents.

1. Introduction

Despite the technological advances in commercial cooling and refrigeration, the use of electricity remains high, and it will increase as the demand for cooling in developing countries increases, especially for air-conditioning [1]. Furthermore, the environmental impact of conventional refrigerants is still affecting the ozone layer and contributing to global warming. Many efforts are being made to mitigate these effects by proposing heat driven cooling technologies operated by renewable energy sources and using refrigerants with minimal environmental impact [2]. Thermal refrigeration is based on the application of different thermodynamic equilibria: liquid-vapour (absorption) and solid-vapour (adsorption, solid-gas absorption or thermochemical), as well as thermo-mechanical cycles (ejector-compression). It is important to develop efficient alternative cooling systems, easy to operate and integration with minimal environmental impacts. Among alternatives for cooling applications, the thermochemical refrigeration is one most promissory technology as it operates

* Corresponding author.
E-mail address: fcmat@ier.unam.mx (F. Martínez-Tejeda).

https://doi.org/10.1016/j.applthermaleng.2018.06.020
Received 9 January 2018; Received in revised form 18 May 2018; Accepted 7 June 2018

Nomenclature

A	absorber
C	condenser
COP	coefficient of performance
CPS	cold production subsystem
CR	condensate recipient
CS	cooling subsystem
D	desorber
E	evaporator
ELM	electronic level meter
FM	flowmeter
G	generator
GNE	expanded graphite
HES	heating electric subsystem
IPS	ice/chilled water production system
LM	level meter
P	pressure
Q	energy
R	reactor
S	solid (salt)
T	temperature
TR	thermochemical reactor
TRS	thermochemical refrigeration system
V	valve
H	efficiency

Subscripts or superscripts

A	absorption
C	condensation
D	desorption/dissociation
E	evaporation
exp	expansion
ext	external
G	generation
g	gas
Hot	heating
i	in
int	internal
L	liquid
O	out
t	thermal
v	vapour

Greek symbols

ΔH°	enthalpy variation

at low generation temperatures.

1.1. Thermochemical refrigeration

The thermochemical cooling cycle based on solid-gas absorption, uses reactions whose products and reagents which desorb and absorb thermally with great refrigerant absorption capacity per mass of absorbent. Among its advantages, a minimal variation in the thermal efficiency for a wide range of operating conditions is observed [3], also the solid absorbent does not volatilize, therefore the rectification process is unnecessary.

The disadvantages include the impossibility of solids to flow into the cycle, which then operates intermittently, where the processes of dissociation-condensation and evaporation-absorption of the refrigerant are performed at different times. Since the thermal conductivity of most solids used is low, extended surfaces and additives for improving heat conduction have been integrated, but affecting mass transfer. Another disadvantage is that the absorbent solid volume increases due to refrigerant absorption [4,5], wherein the solid expands and contracts. Several different solid-gas reactions can be applied to these cycles, usually between salts of halides and alkaline halides with water vapour, ammonia, amines and alcohols. Such is the case of calcium chloride [6–12], strontium chloride [13–16] and barium chloride with ammonia [17–22].

For this work, barium chloride and ammonia were selected, the choice criterion was based on absorption capacity, low desorption temperatures, high absorption values and suitable reaction rates.

There have been several theoretical and experimental studies in recent years on the $BaCl_2$-NH_3 system. Dueñas [17] conducted a single-stage theoretical study where, from the equilibrium relationships of $BaCl_2$-NH_3, the thermal efficiency was calculated from energy balances, for a condensation temperature range between 35 and 40 °C, evaporation temperatures from −5 to −10 °C, dissociation temperatures between 52 and 58 °C and absorption temperatures from 25 to 28 °C, obtaining COP_{int} values from 0.4 to 0.45. Le Pierrès [18] modelled and designed a freezing process at an average temperature of −20 °C. In this study, a cascade process was simulated for freezing, using solar flat plate collectors. Le Pierrès et al. [23] design and construction of an experimental device for a freezing process with the $BaCl_2$-NH_3 mixture, using expanded graphite (GNE) as additive, they carried out a study for a container kept at temperature of −30 °C using low grade heat by flat plate collectors operating at average temperature of 70 °C. The thermochemical experimental prototype was evaluated in summer and autumn. These results showed the potential for application in housing with a solar average coefficient of performance at 0.031 [24]. Rivera et al. [19] conducted an experimental analysis; the reported conditions for the average temperatures: dissociation at 53 °C, condensation at 23 °C, and evaporation from −10 °C to 0 °C. Li et al. [20] performed a study of heat transfer and sorption characteristics for a $BaCl_2$ and expanded graphite mixture for use it in sorption refrigerating systems. The $BaCl_2$-expanded graphite mixture absorbed 0.61 kg of ammonia per kg of this mixture. It was operated with low grade heat at temperatures from 75 to 90 °C, the COP_{int} obtained was between 0.50 and 0.53. In addition, Li et al. [25] proposed and studied a thermochemical refrigeration cycle combining: $BaCl_2$, $MnCl_2$ and expanded graphite mixtures with ammonia as refrigerant, obtaining a theoretical COP of 1.24, using these reagents as sorbents. An innovative methodology was proposed by Li et al. [14] with the aim to reduce the generation temperature using low grade thermal energy. Xu [26] carried out an experimental study concerning the feasibility and performance of operating a two-way, double-effect, thermodynamic refrigeration absorption cycle, using reactions between ammonia and $BaCl_2$, $MnCl_2$ and $NiCl_2$ salts. The results showed that it was feasible to produce four effects of useful refrigerating from a heat supply at a high average temperature of 260 °C with a COP_{int} of 1.0. Stitou [27], carried out an experimental study n to evaluate a solar pilot plant using a solid-gas thermochemical process ($BaCl_2$/expanded graphite-NH_3), to supply air conditioning to a housing, with a refrigerating capacity of 20 kWh, operating at temperatures between 60 and 70 °C, from flat plate collectors. The analysis showed a daily cooling production from 0.8 to 1.2 kWh at 4 °C per m^2 of solar collector, with a COP between 0.15 and 0.23. Meza [28] performed a theoretical and experimental heat transfer study in a solid-gas reactor ($BaCl_2$-NH_3), in order to know the optimum thickness of barium chloride to obtain adequate absorption/desorption of ammonia vapour and apply it to a thermodynamic refrigeration cycle, using renewable energy. In order to analyse the heat transfer in anhydrous barium chloride, an experimental heat conduction study was performed, the main results showed that, the rate of ammonia