INTERNATIONAL JOURNAL OF REFRIGERATION 64 (2016) 176–186

Available online at www.sciencedirect.com

ScienceDirect

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

Compressed-liquid energy storage with an adsorption-based vapor accumulator for solar-driven vapor compression systems in residential cooling

C. Mira-Hernández, J.A. Weibel, E.A. Groll, S.V. Garimella *

School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088, USA

ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form 19 November 2015
Accepted 23 November 2015
Available online 6 January 2016

Keywords:
Cold thermal energy storage
Air conditioning
Vapor compression
Solar cooling
Adsorption

ABSTRACT

A cycle-integrated energy storage strategy for vapor-compression refrigeration is proposed wherein thermo-mechanical energy is stored as compressed liquid. A compressed-liquid tank is integrated into the liquid line of the system by means of an adsorption-based vapor accumulator in the vapor line. Energy is retrieved through expansion of the compressed liquid, which allows for a tunable evaporator temperature. A thermodynamic model is developed to assess the system performance, with storage incorporated, for solar residential cooling in two locations with contrasting ambient temperature profiles. Ammonia, R134a, and propane, all paired with activated carbon as adsorbent, are evaluated. A high cold thermal energy storage density is achieved when operated with ammonia. However, the accumulator suppresses the coefficient of performance of the system because work is required to extract refrigerant from the adsorbent. Practical feasibility of the proposed storage strategy calls for the development of nontoxic refrigerant–adsorbent pairs with more favorable adsorption behavior.

Stockage d'énergie liquide-comprimée avec un accumulateur de vapeur à adsorption pour les systèmes solaires à compression de vapeur utilisés en refroidissement résidentiel

Mots clés : Stockage d'énergie thermique froide ; Conditionnement d'air ; Compression de vapeur ; Refroidissement solaire ; Adsorption

---

* *Corresponding author.* School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907-2088, USA. Tel.: +765 494 5621.

E-mail address: sureshg@purdue.edu (S.V. Garimella).

http://dx.doi.org/10.1016/j.ijrefrig.2015.11.015

Nomenclature

c	refrigerant uptake [kg kg^{-1}]
COP	coefficient of performance
e_s'''	cold thermal energy storage density [kWh m^{-3}] (3600 kJ m^{-3})
h	specific enthalpy [kJ kg^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
M	mass [kg]
p	pressure [kPa]
Q	heat [kJ]
$\dot{Q}$	heat flow rate [kW]
q	heat per unit mass [kJ kg^{-1}]
t	time [s]
v	specific volume [m^3 kg^{-1}]
W	mechanical work [kJ]
$\dot{W}$	mechanical power [W]

Greek

η	efficiency
ρ	density

Subscripts

A	traditional refrigeration subsystem
ads	adsorption
adm	admissible
B	CTES refrigeration subsystem
b	adsorbent in vapor accumulator
c	condenser
e	evaporator
H	high temperature
l	liquid
L	low temperature
S	isentropic
sur	surroundings
v	vapor

1. Introduction

Global concerns about the environmental impact and finite availability of conventional energy sources have motivated efforts to develop technologies that harness clean and renewable energy sources. However, renewable sources are often challenged by their inherently intermittent nature. Energy from renewable sources is not always available in a useful form when demanded, and energy storage strategies are necessary to align supply with demand. In this context, solar cooling technologies appear promising because of the direct relationship between cooling load and solar radiation intensity (Kim and Infante-Ferreira, 2008). Solar radiation intensity strongly correlates with the ambient temperature, and hence, cooling load is considerably higher during insolation hours and generally reaches a maximum value shortly after solar noon. This partial alignment of solar radiation intensity and cooling load thus reduces the required energy storage capacity.

Cold thermal energy storage (CTES), or the process of storing cooling capacity (ASHRAE, 2007), is relevant in a variety of refrigeration applications including solar cooling. Cold thermal energy storage serves to decouple cooling from power consumption. It can be used to shave and/or shift electricity peak demand in conditioned spaces, such as commercial buildings and residences (Chen et al., 2009; Reddy et al., 1991; Saito, 2002). Alternatively, CTES can supply cooling capacity when the energy source is unavailable, as may be the case for refrigeration systems powered by variable renewable energy sources or in the transportation of temperature-sensitive items.

Established CTES technologies include storage systems using chilled water, ice, and other phase change materials (PCM). Water-based storage technologies are mature and commercially available in view of the advantageous thermal properties, chemical stability, wide availability, and low cost of water (Oró et al., 2012; Rismanchi et al., 2012). Sensible cold energy storage in water demands few modifications to conventional refrigeration systems and has a lower initial cost; however, large system volumes are required due to the low energy storage density (Rismanchi et al., 2012). To bring about stratification inside the chilled water storage tank, charging temperatures should exceed the water-density maximum of 4 °C (ASHRAE, 2007; Saito, 2002), restricting the temperature range and reducing the storage density. Ice storage systems, which have much higher storage densities, require charging temperatures below the freezing point of water, between −12 °C and −3 °C (Rismanchi et al., 2012; Wang and Kusumoto, 2001). This temperature range is significantly colder than the typical evaporator temperature in air-conditioning systems (Oró et al., 2012; Saito, 2002), and has an adverse effect on thermal performance. Moreover, ice storage systems have other technological challenges, such as the need for methods to control ice nucleation, processes that prevent adhesion of the ice to the cooling surface, approaches for maintaining the fluidity of ice-water mixtures, and methods to effectively melt the ice, among others (Saito, 2002). Other PCMs, such as eutectic salt solutions and organic compounds, can offer a range of different charging temperatures, but have other limitations. In general, eutectic salt solutions have good thermal properties and low cost, but are chemically unstable and corrosive (Oró et al., 2012). Organic PCMs are chemically stable, but are more expensive and have less favorable thermophysical properties (such as low thermal conductivity, low latent heat of fusion, and large change in density between solid and liquid phases) (Oró et al., 2012).

In air conditioning systems, CTES technologies are beneficial due to the inherently variable nature of the cooling load, which is dominated by daily and seasonal variations in environmental conditions and by user habits. In many areas in the United States, the maximum electrical peak demand occurs during the summer time due to air-conditioning demand. This is especially so in regions where winter demand is met in part by the use of gas or oil for space heating (Reddy et al., 1991).