Applied Thermal Engineering 130 (2018) 515–527

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Variability of absorption heat pump efficiency for domestic water heating and space heating based on time-weighted bin analysis ☆

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HIGHLIGHTS

- AHPs are reexamined in this paper using a time-weighted bin temperature analysis.
- The COP is strongly dictated by the evaporator temperature and the glide of the working fluid.
- The actual AHP performance may vary considerably depending on ammonia purity.
- It is concluded that deployment of AHPs may be restricted geographically.
- In many regions of the U.S, AHPs may significantly underperform baseline technology.

ARTICLE INFO

Article history:
Received 22 June 2017
Revised 29 September 2017
Accepted 27 October 2017

Keywords:
Sorption
Heat pumps
Ammonia
Water heating
HVAC

ABSTRACT

Natural gas-driven absorption heat pumps (AHPs) are under renewed scrutiny as a viable technology for space conditioning and water heating for residential and commercial applications because of natural gas production trends, pricing, and the speculation that it might be a “bridge fuel” in the global transition toward energy sustainability. Since any level of natural gas combustion contributes to atmospheric carbon dioxide accumulation, the merits of natural gas–consuming absorption technology are reexamined in this paper from the point of view of expected efficiency as a driver for AHPs throughout the United States using a time-weighted bin temperature analysis. Such analyses are necessary because equipment standards for rated performance are restricted to one set ambient condition; whereas in actual practice, the AHP must perform over a considerably wider range of external conditions in which its efficiency may be vastly different from that at the rated condition. Quantification of variations in efficiency and system performance is imperative to address how to provide the desired application with the least environmental impact. In this paper, we examine limiting features in AHPs and relate them to systemic performances in 16 cities across all 8 climate zones in the United States, each containing 15 bin temperatures. The results indicate that the true expectation for AHP performance is significantly less than what might be optimized for the rated condition. Statistical measures of the variation in water heating COPs show that for most cities, the COP at the rated conditions is outside the 95% Confidence Interval. It is concluded that deployment of AHP water heaters may be restricted geographically by outdoor temperature constraints.

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1. Introduction

The abundance and low cost of natural gas have sparked renewed interest in developing absorption heat pumps (AHPs) to help the US Department of Energy (DOE) Building Technologies Office (BTO) reach its target goal of reducing building-related primary energy consumption by 50% (relative to 2010 consumption) by the year 2030. BTO’s specific goals for water heating energy reductions are 19% by 2020 and 37% by 2030 [1]. Meanwhile, the European Union (EU) is developing AHP water heaters to satisfy their own metrics and markets. Natural gas may be considered a

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https://doi.org/10.1016/j.applthermaleng.2017.10.142
1359-4311/Published by Elsevier Ltd.

Nomenclature

AHP	absorption heat pump
COP	coefficient of performance, dimensionless
EU	European Union
h	specific enthalpy, kJ kg^{-1}
IEA	international energy agency
m	mass flow rate, kg h^{-1}
q	heat flow rate, kW
P	pressure, bar
s	specific entropy, kJ kg^{-1} K^{-1}
T	temperature, °C or K
TMY	typical meteorological year
v	specific volume, m^{-3} kg^{-1}
x	mass fraction of ammonia in the liquid phase, dimensionless
xv	mass fraction of ammonia in the vapor phase, dimensionless

subscripts

cond.	condenser
boiler	boiler or generator
i	index for the ith state point

short-term "bridge fuel" if it can offset coal consumption and "stabilize" atmospheric CO_2 levels at 450 ppm [2], compared with the April 2017 level of 406.17 ppm reported by NASA [3]. As natural gas is a convenient fuel for gas-fired AHP water heaters, this paper examines the practical impact of the technology in the United States. Since equipment for the residential or commercial markets is not yet fully developed, standards are not yet codified; however, there are established test methods in both the EU and in United States. The current version of EU standard EN 12309-2:2000 defines test methods and conditions for determination of the gas utilization efficiency of gas-driven sorption (adsorption or absorption) equipment with a net heat input lower than 70 kW (19.9 TR) [4]. The ANSI/ASHRAE Standard 182-2008 (RA 2013) [5] is a method-of-test standard for use in factory-performance testing of absorption equipment. This standard is intended for use in conjunction with the rating procedures in ANSI/AHRI Standard 560 [6], which specify the hot water entering and leaving temperature. For space heating applications, we adhere to an outdoor dry bulb (DB) temperature of 8.33 °C (47°F), a return air temperature of 21.1 °C (70°F), and for economy, a supply air temperature of 35 °C (95°F).

Absorption technology is used for chilling, cooling, heating, dehumidification, water heating, evaporation, and distillation in the commercial and industrial sectors and may be driven by fuel, solar, biomass, or waste heat [7–9]. However, its use in residential and light commercial applications is limited because (1) it is difficult to scale down the costs for smaller sizes (5–10 kW); (2) the working fluids are limited by ambient temperature and cost; and (3) the performance is restricted by ambient conditions, hydrated salt precipitation, or chemical separation. A recent extensive study [10,11] of 83 absorption working pairs showed that ammonia–water (NH_3-H_2O), and ammonia–lithium nitrate (NH_3-$LiNO_3$) represent the best choices in terms of performance, cost, and equipment size. The same study examined 81 adsorption pairs, but their performances were significantly below those of the absorption pairs. Although ammonia is a zero global warming potential (GWP) and zero ozone depletion potential (ODP) fluid, its toxicity restricts the absorption unit to outdoor installations, whereas NH_3–$LiNO_3$ is prone to encounter crystallization issues that may lead to operational seizure. Therefore, the leading candidate from the exhaustive screening is NH_3–H_2O, on which this paper is based.

Although many studies—both experimental and analytical—have focused on cooling, refrigeration, innovative cycles, and cogeneration applications [12–23], recent attention has been devoted to hot water systems [22–27], even though these systems have been considered in the past [28]. In response to a worldwide interest in thermally driven heat pumps, the International Energy Agency (IEA) Annex 34 released a detailed report [29] summarizing the research effort to develop sorption systems, several of which contained ammonia as the refrigerant. The work of IEA Annex 34 is augmented by the scope of a subsequent IEA Annex 43 exclusively devoted to fuel-driven sorption heat pumps. Ammonia has favorable thermophysical properties, zero GWP, zero ODP, a long history of use in the commercial and industrial sectors of the economy, and a good safety record in the refrigeration industry [30]. Suggestions for improving the efficiency of ammonia–water heat pumps by utilizing the thermal energy in the products of combustion have been posited recently [31]. Despite the advantages of the ammonia–water system, the requirement for a high degree of rectification and a low reflux ratio in the distillation column impose a design burden because the operating conditions change throughout the year, depending on outdoor conditions. Temperature deviations from the design rating conditions tend to impose a performance penalty on the coefficient of performance (COP).

To quantify the deviation of the actual COP from its rated design point, this paper examines the time-weighted bin temperature COP by simulating the performance of an ammonia–water AHP in 16 cities in the United States, based on Typical Meteorological Year 3 (TMY3) data[1]—and comparing the resulting COP with the rating point COP. This analysis reveals the limitations of thermally driven absorption technology regionally within the United States, governed by the restrictions resulting from the degree of rectification (which depends on the design of the distillation column) and the reflux ratio. The efficiency of this technology varies depending on its environs. The ammonia purity in the evaporator is central in determining the limits of ambient temperature and the regions in the United States where this technology would yield acceptable performance.

In the first section of the paper, we discuss the relationship between evaporator ammonia purity and evaporating temperature. The second section describes the relationship between the reflux ratio and solution flow rates and explains why a low reflux ratio is desirable. The third section simulates the performance of the AHP for water heating under specified standard rating conditions. The fourth and fifth sections discuss the performance of the AHP water heater in various regions of the United States, with the ambient temperatures segmented in bins. Space heating is described in the sixth section. The results are used to draw conclusions regarding the applicability and performance of this technology under the scenario described in the fourth section.

2. Evaporator limitations

Ammonia rectification in ammonia–water AHPs is critical for proper operation of an evaporator because the minimum evaporation temperature is dictated by it, as shown in Fig. 1 for three typical pressures. At lower pressures, the specific volume of ammonia increases, so larger-diameter tubes are required for proper

[1] EnergyPlus Weather Data by Region, https://energyplus.net/weather-region/north_and_central_america_wmo_region_4/USA.