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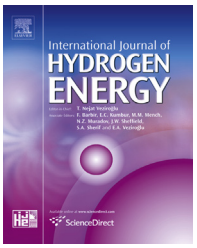

Heat exchanger selection and design analyses for metal hydride heat pump systems

Andrea Mazzucco [a], *Tyler G. Voskuilen* [b], *Essene L. Waters* [c], *Timothée L. Pourpoint* [c,*], *Masoud Rokni* [a]

[a] *Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé 403, DK-2800 Kongens-Lyngby, Denmark*

[b] *Computational Thermal and Fluid Mechanics Department, Sandia National Laboratories, Albuquerque, NM, USA*

[c] *School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, USA*

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ABSTRACT

This study presents a design analysis for the development of highly efficient heat exchangers within stationary metal hydride heat pumps. The design constraints and selected performance criteria are applied to three representative heat exchangers. The proposed thermal model can be applied to select the most efficient heat exchanger design and provides outcomes generally valid in a pre-design stage. Heat transfer effectiveness is the principal performance parameter guiding the selection analysis, the results of which appear to be mildly (up to 13%) affected by the specific Nusselt correlation used. The thermo-physical properties of the heat transfer medium and geometrical parameters are varied in the sensitivity analysis, suggesting that the length of independent tubes is the physical parameter that influences the performance of the heat exchangers the most. The practical operative regions for each heat exchanger are identified by finding the conditions over which the heat removal from the solid bed enables a complete and continuous hydriding reaction. The most efficient solution is a design example that achieves the target effectiveness of 95%.

Introduction

Metal-hydride-based systems have been widely investigated as candidate technologies for hydrogen storage and thermal systems. The first category includes applications in both mobile and stationary systems [1–4] while the second is often applied for hydrogen compression [5], heat recovery and air conditioning [6,7]. Several challenges must be overcome before such solutions provide a commercially valid alternative to existing technologies. Crucial technology gaps cut across disciplines such as material science and mechanical engineering, addressing challenges such as the characterization and the selection of the metal alloys and the design of the heat management system to be integrated in the metal hydride (MH) bed.

In the literature, heat exchanger design has been mostly focused on applications for hydrogen storage rather than

* *Corresponding author.*
E-mail addresses: andmaz@mek.dtu.dk (A. Mazzucco), tvoskui@sandia.gov (T.G. Voskuilen), waters5@purdue.edu (E.L. Waters), timothee@purdue.edu (T.L. Pourpoint), mr@mek.dtu.dk (M. Rokni).

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thermal systems [8–12]. The heat management systems in these two applications must fulfill different functions and therefore typically results in different designs for each. In both cases, the hydriding process dictates the design of the heat exchanger. However, the objective of the heat exchanger for a metal hydride heat pump (MHHP) is to heat the heat transfer fluid (HTF) for as long as possible; while in a hydrogen storage application its primary objective is to cool the hydride bed as rapidly as possible upon loading. Although these are complementary aspects of the same heat transfer problem, they define different performance parameters to be optimized in the heat exchanger system and thus drive the design process to different final configurations.

Various computational models and experimental studies for MHHPs have been proposed to describe the thermal cycle with attention to alloy selection [13], performance [14–16] and heat and mass transfers that take place in the solid bed [17–20]. However, the selection criteria and design approaches for the heat management system are typically not well-documented in the literature or rarely investigated. The selection of a particular heat exchanger, especially for experimental studies, is driven mainly by the availability of the single components rather than the result of an optimization analysis [15,21–23]. Simple and complex computational models have been applied to describe the performance of complete thermal cycles in terms of the coefficient of performance (COP) but often lack general insights into the selection criteria for the heat exchanger [14,20,24,25]. Furthermore, most studies refer to a specific metal hydride pair, making the comparison between MHHPs configurations material dependent.

In this study, we define a set of selection criteria for heat exchanger candidates and outline a general approach that can be used in the initial design stage of a metal hydride thermal system heat exchanger. The heat exchanger effectiveness is computed for each solution and a thermal analysis is performed to study the influence of different Nusselt number correlations on the performance of the various configurations. The results of the thermal model are used to select the most appropriate system among a short list of candidates, independent of the specific metal hydride composition. In addition, a sensitivity study is carried out to investigate the effect of fluid thermo-physical properties and design parameters on the performance of the proposed final configurations. Finally, we present a heat demand analysis to determine the operating points at which the system fulfills performance and design criteria while satisfying the cooling demand of the metal hydride for relevant reaction times.

Motivation

At Purdue University's Hydrogen Systems Laboratory (HSL), investigations on metal hydride systems have focused on material characterization [26–28], hydrogen storage [29–31] and, more recently, thermal applications [32]. One on-going project aims to develop a single-stage heat pump system to recover the waste heat from a high temperature fuel cell and a natural gas reformer in order to heat water for large energy-demanding utilities while increasing the overall efficiency of the system.

Interest in MHHPs has increased due to the potential advantages that such systems can provide when compared to standard compression systems. MHHPs offer the potential to increase the efficiency and operational reliability by tailoring the system to the specific required temperatures; an effect that requires the proper selection of metal hydrides. These systems also have the potential to reduce the number of moving parts required, potentially simplifying the system fabrication, setup, and maintenance. Downsides of current MHHPs include the low thermal power per unit of mass resulting in low COPs, the cyclic nature of their operation, and the high cost of some of the metal hydrides.

This work investigates the heat exchanger integrated in the hydride beds and can be considered as the second stage of a larger study; the first step of which has focused on the material selection of the hydride pairs. This first step was accomplished by Voskuilen et al. and the hydride selection results are discussed in Ref. [32]. The heat exchanger selection analysis in this work is intended to be generally applied to any promising two-hydride pair. The thermal model aims to identify the optimal heat exchanger for a MH heat pump system within the conditions and criteria introduced in the following section.

Methods

In this work, we developed a thermal model of a heat exchanger system and used it to analyze and compare three heat exchanger designs in terms of performance and capability to fulfill the energy demand of the hydride. These three designs, detailed in Section 3.2, are among the most common industrially employed configurations. A general approach must be established for application to these systems regardless of the properties of the particular hydrides chosen. The heat transfer effectiveness is investigated according to the following assumptions:

- The heat transfer process is carried out under steady state conditions.
- The hydrogen absorbing process is modeled as ideal.
- The thermo-physical properties of the heat transfer fluid are kept constant during the simulation.

The design assumes time-independent conditions and the heat exchanger system is modeled to operate at steady state. This design approach is not far from reality as the present study is focused on thermally limited hydride reactions for long-cycle metal hydride heat pumps, and thus, the majority of the operation is, in practice, in a quasi-steady condition. For such an application, it is desirable to maintain the HTF at an elevated temperature during each stage of the cycle and realize sustained HTF heating during hydriding rather than rapid hydride cooling. Therefore, the rapid reaction kinetics that occurs between cycle changes and the design aspects that originate from it are out of the scope of the present study. In our system, the pressure is held constant during hydrogen absorption and the cooling rates are sufficiently high to

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