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Performance tests on a double-stage metal hydride based heat transformer

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ABSTRACT

In this manuscript, the performance tests on a double-stage metal hydride based heat transformer (DS-MHHT) are presented. A prototype of DS-MHHT has been built and tested for upgrading the waste heat available from 393 to 413 K to about 463 K using $La_{0.35}Ce_{0.45}Ca_{0.2}Ni_{4.95}Al_{0.05}/LaNi_5/LaNi_{4.35}Al_{0.65}$ alloy combination. The hydrogen transfer between the paired metal hydride reactors of DS-MHHT has been studied experimentally. The effects of operating temperatures such as heat source temperature and heat reject temperature on the performance of DS-MHHT in terms of coefficient of performance (COP_{HT}), specific heating power (*SHP*) and second-law efficiency (η_E) were investigated. For the given operating temperatures of 463/403/303 K, the experimentally determined COP_{HT}, *SHP* and η_E were 0.2, 17.1 W/kg of total alloy mass and 0.29, respectively. The maximum engineering temperature lift achieved was about 80.5 K at the operating conditions of heat output temperature 463 K, heat input temperature 393 K and heat sink temperature 298 K.

1. Introduction

The global energy consumption has been increasing steadily due to the rapid industrialization and improvement in the living standard of the mankind. The major contribution to this global energy consumption is by fossil fuels. In addition, the predominant part of electric power is also produced from fossil fuels. Nevertheless, these fuel resources are limited and thus the mankind is forced to find the alternatives for resolving the critical issues associated with the use of fossil fuels such as environmental pollution and global warming. On the other side, most of the energy consuming industries release thousands of MW of low grade heat into atmosphere in the form of sensible heat in gaseous and liquid effluents, latent heat in vapor effluents, radiation and convection from the hot objects. The renewable energy sources like solar energy, geothermal energy, etc. are not used directly because of their relatively low grade. If these low grade heat sources are upgraded to high temperature, it can be again used as inputs for thermal machines and several industrial applications. Usually heat will be upgraded by using conventional liquid–gas absorption heat pumps or transformers (H_2O–LiBr and NH_3–H_2O). But the operating temperatures of these systems are limited to about 150 °C because of properties of working solution. Metal hydride based heat transformer (MHHT) falls under the category of dry sorption system and it can upgrade the heat from medium temperature (100–150 °C) to high temperature (170–200 °C). The simplest MHHT consists of two reactors; one is a high temperature reactor and other is a low temperature reactor with hydrogen gas as the working fluid. The single-stage heat transformer is restricted to a temperature lift of about <40 K. For high temperature lift (>50 K) multi (two)-stage system is required. The MHHT systems are more advantageous over the conventional systems

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Nomenclature

C_p	specific heat, J/kg K
$\dot{m}_f$	mass flow rate of the heat transfer fluid, kg/s
m	mass, kg
Q	heat, W
T	temperature, K
t	time, s
η_E	second-law efficiency

Subscripts

A,B,C	reactors/alloys
cy	cycle time
f	fluid, final
fi	heat transfer fluid inlet
fo	heat transfer fluid outlet
i	initial
H	heat output
M	heat source
L	heat sink

Abbreviations

COP	coefficient of performance
HTF	heat transfer fluid
MHHT	metal hydride based heat transformer
PCT	pressure–concentration–temperature
SHP	specific heating power
V	valve

in terms of providing high temperature lift, higher heat storage capacity, compactness, noise free and vibration less operation, environment friendly, etc.

Tuscher et al. [1] tested a metal hydride based heat pump in heat upgrading mode and showed a maximum temperature lift of about 17.6 K at the heat source temperature of 353 K and heat sink temperature of 286 K. Suda et al. [2] developed a prototype of double-stage heat pump to generate steam in the temperature range of 393–423 K using the waste heat available at 353 K and ambient air as the cooling medium. It was found that the dynamic pressure difference regulates the rate of hydrogen transfer between the paired reactors. Subsequently, a series of experimental studies on MHHT have been carried out at IKE, University of Stuttgart, Germany [3–5]. Werner and Groll [3] built and tested a double-stage metal hydride based heat transformer (DS-MHHT) lab-scale model to upgrade heat from 358 K to 408 K with a specific power output of 30 W/kg. Absorption and desorption experiments were carried out to investigate the dynamic behavior of reaction beds under various operating pressures and temperatures. Isselhorst and Groll [4] built a prototype of DS-MHHT for upgrading the heat input of 403–413 K to about 463–473 K using $LmNi_{4.85}Sn_{0.15}$/$LmNi_{4.49}CO_{0.1}Mn_{0.205}Al_{0.205}$/ $LmNi_{4.08}Co_{0.2}Mn_{0.62}Al_{0.1}$. The employed six reactors were connected in star scheme to get quasi-continuous power output of 7 kW. The design data for COP and specific power output were about 0.27 and 38 W/kg hydride at the operating conditions of heat output temperature 463 K, heat source temperature 403 K and heat sink temperature 313 K. Willers and Groll [5] tested a prototype DS-MHHT for upgrading the heat from 408 to 465.5 K employing $LmNi_{4.85}Sn_{0.15}$/$LmNi_{4.49}CO_{0.1}Mn_{0.205}Al_{0.205}$/ $LmNi_{4.08}Co_{0.2}Mn_{0.62}Al_{0.1}$. They achieved a specific power output of 30 W/kg and a COP of about 0.1.

Sun et al. [6] introduced three different evaluation criteria viz. coefficient of performance, alloy output and temperature output to compare the performance of heat transformers with different alloy combinations. It was reported that the alloy output was increased by enhancing the heat transfer in the reactors. Kang and Yabe [7] investigated the effects of various operating conditions, as well as the design parameters, on the performance of the MHHT. Gambini [8] presented a procedure for the evaluating the performance of MHHT under dynamic operation. It was reported that the heat output and COP always increase by increasing the cycle time in consequence of the increase of hydrogen transfer. Gopal and Murthy [9] predicted the performance of the MHHT system based on the reaction kinetics and heat transfer rates of the coupled reactors. Yang et al. [10] developed a 2-D mathematical model to simulate the performance of the MHHT system. They analyzed the dynamic behavior of the MHHT in three subsequent cycles. Furthermore, Yang et al. [11] also presented the parametric studies on the single-stage MHHT employing $LaNi_5$/$LaNi_{4.7}Al_{0.3}$ pair. It was reported that COP was mainly dependent on the amount of hydrogen exchanged between the coupled reactors. Kumar et al. [12] presented a thermodynamic analysis of the MHHT for different alloy pairs. They reported that with single-stage MHHT, the temperature boost of about 30–50 K could be achievable. Muthukumar and Groll [13] presented a review on metal hydride based thermal machines and also discussed the possible ways of improving the system performance. They have also summarized the state of art status of metal hydride based heat pump systems. In a recent publication by Sekhar et al. [14], the numerical and experimental investigations of a single-stage MHHT using $LaNi_5$/$LaNi_{4.7}Al_{0.3}$ alloy pair were presented. It was observed that the numerically predicted temperature profiles were in good agreement with experimentally measured temperature profiles over a complete cycle.

It is observed from the above literature survey that many researchers have presented the numerical modeling of the

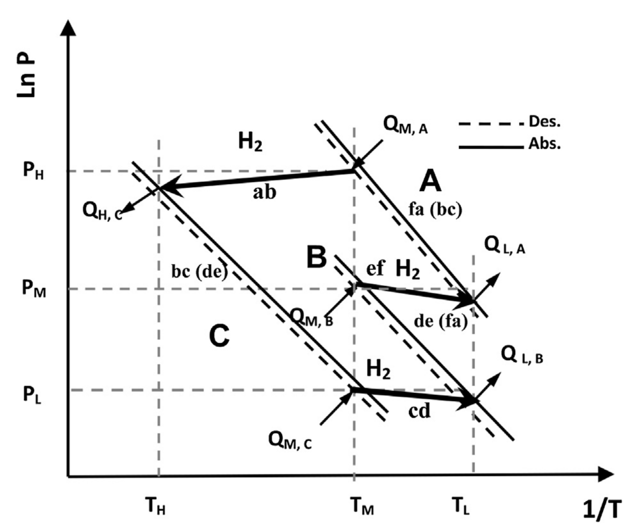

Fig. 1 – Operation of a DS-MHHT on van't Hoff plot.