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Pressurised-cell test stand with oscillating heating for investigation heat transfer phenomena in metal hydride beds

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ABSTRACT

In this paper we present the apparatus and methodology for investigating the thermal diffusivity (TD) of metal hydride (MH) beds when exposed to a range of temperatures and pressures. For this purpose a pressurised-cell test stand has been designed, manufactured and assembled. The system is based on a cylindrical pressure vessel, with Peltier elements on both bases of the cylinder, to provide symmetrical heat delivery along the axis. The pressure cell design allows both thermophysical property measurements and studies of heat transfer phenomena accompanying hydrogen absorption and desorption in metal hydrides. The effective TD is measured using a modified Ångström method, i.e. a modified temperature oscillation method. The first of introduced modifications accounts for a finite longitudinal specimen dimension. The second alteration enables the measurements to be performed in temperature scanning mode. TD can be calculated both from the amplitude and from the phase change of the temperature response signal.

The system and the developed methodology have been tested by measuring the effective thermal conductivity of the powdered $LaNi_5$ bed. Investigations have been performed under inert gas, with pressure ranging from medium vacuum conditions up to about 0.45 MPa of nitrogen and helium. In the paper we present obtained results and compare them against the results from similar investigations performed in open cell apparatus under atmospheric gas conditions. Both the very good accuracy and the effectiveness of the developed procedure was demonstrated.

Introduction

Understanding the thermal properties of MH packed beds is critical for accurate analysis of the heat and mass transfer phenomena in hydrogen storage applications. However, this poses a challenge for routine measuring methods due to the complex interrelation of different heat and mass transfer mechanisms in MH beds regarding the fact that the bed effective TD depends on the system temperature, pressure

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Nomenclature

a	thermal diffusivity, $m^2\ s^{-1}$
A, B, C, D	coefficients of the approximation function
b	temperature change rate, $K\ s^{-1}$
c_p	specific heat, $J\ kg^{-1}\ K^{-1}$
f	frequency, s^{-1}
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
j	imaginary unit
k	reciprocal dimension constant, m^{-1}
L	linear dimension, m
p	pressure, Pa
r	radial coordinate, m
T	temperature, K/°C
x	space linear coordinate, m
φ	phase lag (shift), rad
ε	initial phase shift, rad
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
θ	temperature changes, K
ρ	density, $kg\ m^{-3}$
τ	time, s
τ_Ω	oscillation period, s
ψ	amplitude attenuation, n.d.

Subscripts

eff	effective
lin	linear i.e. constant heating rate component
s	signal
x, L	at x, at $x = L$
Ω	period
φ	phase
ψ	amplitude

Abbreviations

RT	room temperature
TC	thermocouple
TD	thermal diffusivity
TM	temperature modulation (modulation at steady offset)
TP	thermophysical property
TSM	temperature scan modulation (modulation of linearly changed temperature)
MH	metal hydride

and the hydrogen concentration in solid. Therefore, determining the effective thermophysical properties of hydrides requires a modified, reliable and easy to implement approach. This concerns both parameters characterising the conductive heat transfer: the TD and the thermal conductivity.

The primary issue to be considered when discussing the thermophysical parameters (TP) of a typical MHs and MH beds is the complexity of combined and coupled conductive, convective and radiative heat transfer phenomena. The complications of determining the resulting effective thermal conductivity have been widely discussed in the literature, both for loosely packed beds, treated as porous structures ([1,2]), and compacted hydride absorber – composites with highly conductive matrices ([3–11]). Two important considerations steam from this research. Firstly, the effective thermal conductivity of regarded structures depends on the filling gas pressure ([1,2,12,13]), so this factor needs to be taken under account when planning MH investigations. In particular the sought method should allow for measurements under a range of pressure conditions. Secondly, the MH bed properties are strongly dependent on the powder particle size distribution which defines the pore size distribution. This is due to the fact that the MH bed topology shapes the filling gas thermal conductivity component and the thermal contact resistances ([1], [13–16]). The particle and pore size distributions are MH powder preparation method dependent (usually ball milling is utilized [7,17]). A robust method of investigation of thermophysical properties of MH beds should be able to result in definition of effective parameters. Thus the experimental data can be compared with the data predicted by applying any of the homogenisation method ([2,12,16,18]).

Discussing the heat transfer phenomena in MH beds at least two more effects need to be noted: the hydrogen absorption/desorption and diffusion. The absorption or desorption is accompanied by a huge heat release or consumption, respectively. In fact heat effects of hydrogen sorption are so substantial that these phenomena are being considered to utilize in thermal energy storage applications [7]. Such strong volumetric heat sources substantially affect the heat transfer. In turn, because the sorption reaction kinetics strongly depends on the system temperature and the gas pressure, the heat transfer drastically influences hydrogen sorption or release rate. This problem has widely been treated in the literature where results of both analytical and numerical analyses have been reported ([19–23]).

Such a complication of heat and mass transfer phenomena limits the applicability of traditional TP investigation methods in MHs. Primarily, it is difficult to implement any complex TP investigation method ([24–27]) because the appropriate inverse procedures frequently reveal to be ineffective. The inverse approach has been limited to special single parameter identification only ([14,22,28]). In result, different phenomena and different parameters are usually investigated in separate experiments with the use of different test stands. When the effective thermal conductivity is concerned, two types of approaches are possible: thermal conductivity of the MH structures can be measured directly in stationary experiments or calculated from the TD data obtained by transient method ([24,25]). Speaking of the first type experiments, the comparative method should be pointed out as one of the most popular ([9,15]). Other methods that can be employed for this purpose include constant heat flux ([4,5]), direct heating [3] or calorimetric studies ([29,30]). However, application of any of these methods is hindered due to the demand for specially controlled test conditions imposed by the particular specimen properties. These requirements are difficult to accommodate on corresponding test stands, such as guarded hot plate or a laser flash [16,31]. Considering the effective TD measurements, a range of transient methods is available: monotonic heating [28], transient hot wire [1], transient hot plane [13,27], or oscillating heating [2].

In view of a possible facilitation of MH beds studies, the oscillating heating method seems to be the most promising to be implemented [32]. There are several relevant advantages to this approach: different specimen geometries may be used