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An installation for water cooling based on a metal hydride heat pump

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Abstract

Results of investigations on the creation of an installation on the basis of a metal hydride heat pump for cold water production at temperatures <4°C are presented.

Keywords: Metal hydride; Heat pump; Hydrogen; Refrigeration

1. Introduction

Metal hydride heat pumps (MHHPs) have not yet found any practical applications although it is possible to expect their perspective use. There exists at the present time much practical experience and knowledge of metal hydride synthesis, their properties, kinetics and thermodynamic processes in MHHPs, the choice of metal hydride couples, and the creation of experimental devices mainly for cooling applications [1,2]. As an application for the use of MHHP we developed a demonstration system for water cooling down to <4°C. Simultaneous to the production of cold water, the installation allows us to obtain water heated to 50°C for technical or household needs.

2. Experimental

MHHP development is based on the modular principle to obtain cold water from an installation using a set of modules. The installation includes a MHHP, a tank of cooled water and a pump for cool water supply. There are two water circuits: (1) one for pumping of water coolant and for the removal of the released heat; and (2) one for supplying cooled water, removal of the generated cold and accumulation of cooled water in a tank with heat insulation. There is a manual control unit and a computer for automatic control. A schematic diagram of the installation is presented in Fig. 1. The MHHP consists of two units, each containing four modules assembled in a square group with a center-to-center distance of 55 mm. The individual module (Fig. 2) is a stainless steel tubular element 1200 mm in length and 32 mm in diameter with a collector filter for hydrogen transfer placed inside the tube along its length. The filter separates the high-temperature and low-temperature parts of the module. The space between the collector and the outside shell is filled with metal hydride powder.

The effective thermal conductivity of the metal hydride beds is low and is in the range 0.1–0.5 W/(m K) [3]. Numerous studies devoted to MHHP development have paid attention to the necessity of improving this characteristic. For example, in Ref. [1] it was shown, for metal hydride $LaNi_{4.7}Al_{0.3}$–H_x, that increasing the thickness of such a powder layer by >2 mm considerably reduces the effectiveness of hydrogen absorption. Methods for increasing the thermal conductivity of metal hydride powder are [4–6]: introducing cross or longitudinal fins, the creation of a continuous metal matrix with good thermal conductivity using foam metal, the addition of metal powders and the deposition of a metal coating with high thermal conductivity on the metal hydride particles with further compaction.

In the present installation, the longitudinal finning of corrugated aluminum foil was used as the most inexpensive and adaptable method for a production version. It increases the thermal conductivity of the metal hydride filling to 8 W/(m K). For measurement of this parameter, we used the technique described in Refs. [7,8].

The high-temperature part of the module has an electric heater. Water at a temperature of 10–15°C is used as a coolant. The volume of the tank with heat insulation for the collection of cooled water is 20 l. The initial temperature of the cooled water is 15–25°C. The high-temperature part of the modules is filled with $LaNi_{4.6}Al_{0.4}$ metal hydride powder, and the low-temperature part is filled with

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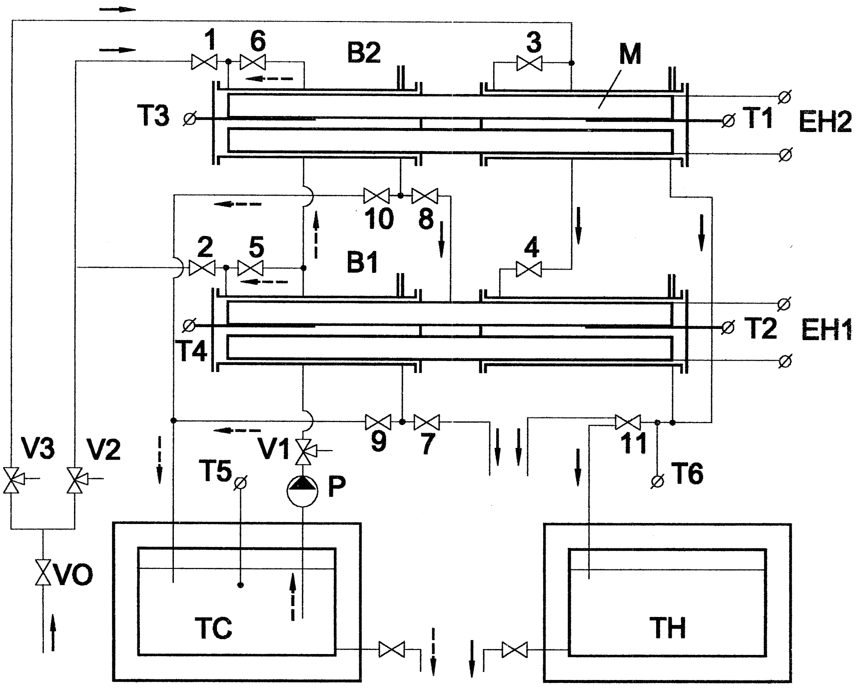

Fig. 1. Scheme of the experimental installation for the production of cold water. 1–11, Electric valves; V0–V3, valves regulating the water flow; B1, B2, units 1, 2; M, module; T1–T6, temperature sensors; EH1, EH2, electric heaters; TC, tank of cooled water (0–4°C); TH, tank of heated water ($T > 45$°C); P, pump. Arrows show the movement of water in the open hydraulic circuit; dashed arrows show the movement of cold water in the closed circuit.

$MmNi_{4.15}Fe_{0.85}$. The approaches proposed in Refs. [2,9,10] were suitable for metal hydride pair selection. The calculated temperatures for the selected couple, taking into account hysteresis, were (in °C): $T_{\text{hmin}} = 148–135$; $T_{\text{m}} = 32–25$; $T_{\text{lmin}} = (-51–58)$, and the coefficient of performance (COP) was 0.33. The $P–T–C$ relationships for the metal hydrides were investigated using a Sieverts' apparatus. The obtained isotherms are shown in Fig. 3.

Each module was filled with 1.5 kg of the appropriate metal hydride powder. Each module was checked for tightness before assembly, evacuated for 100 h and filled

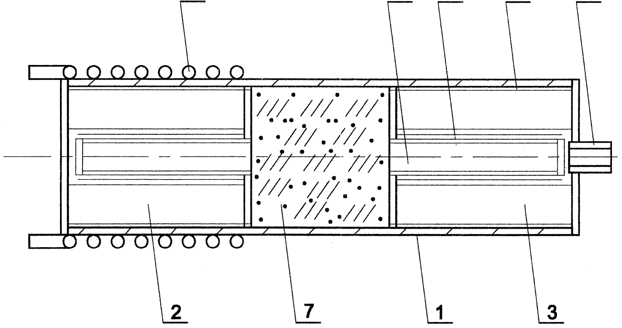

Fig. 2. Scheme of a MHHP module with a heater. 1, Stainless steel shell; 2, high-temperature metal hydride; 3, low-temperature metal hydride; 4, corrugated aluminum foil; 5, internal punched tube; 6, nickel grid; 7, kaolin cotton wool; 8, pipe for evacuation and intake of hydrogen; 9, electric heater.

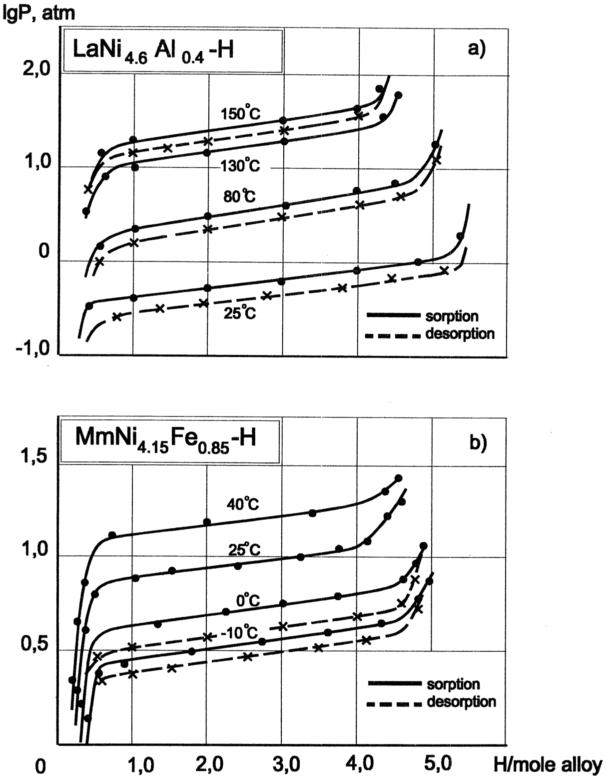

Fig. 3. Temperature dependence of the dissociation pressure of $LaNi_{4.6}Al_{0.4}H$ (a) and $MmNi_{4.15}Fe_{0.85}H$ (b) on composition.

with purified hydrogen from calibrated volumes. The high-temperature metal hydride was saturated with hydrogen up to a content of 120 cm^3/g, which corresponded to the composition $LaNi_{4.6}Al_{0.4}H_{4.55}$. In addition, each module passed an initial performance test reproducing a nominal operation cycle, i.e. heating of the high-temperature part to 200°C, cooling with water with simultaneous measurement of the temperature of the cooled part of the low-temperature module. The installation is shown in Fig. 4.

The installation operates in a cyclic mode. Desorption of hydrogen from the high-temperature metal hydride takes place in the first half-cycle for the high-temperature part of the module, which is heated by an electric heater to 200°C. Hydrogen flows into the low-temperature part of the module, where it is absorbed by the low-temperature metal hydride. Since the hydrogen sorption reaction is exothermic, the released heat is removed by circulating cooling water. Operation is by a regeneration cycle. After the electric heating has been turned off and cooling of the high-temperature part of the module has occurred using water (which, during this initial period of time, is heated to 50°C and can be used for technical application), absorption of hydrogen by the high-temperature metal hydride takes place, resulting in intensive hydrogen desorption from the low-temperature metal hydride (which is an endothermic reaction). Heat is removed from this portion of the module as a result of this reaction, and circulating water is cooled. The cooled water passes to a tank with heat insulation. To support continuous cold generation, MHHP units work in a half-cycle shift, i.e. when one MHHP unit generates cold, the low-temperature metal hydride in the other unit is ‘charging’ with hydrogen. The control system provides operation of the installation in two modes — manual and automatic.

3. Results

Tests performed on the installation produced the following results (example of a series of tests).

3.1. Initial data

Volume of cooled water	18 l
Reference temperature of cooled water	21.1°C
Temperature of cooling water	10.1°C
Half-cycle time	20 min

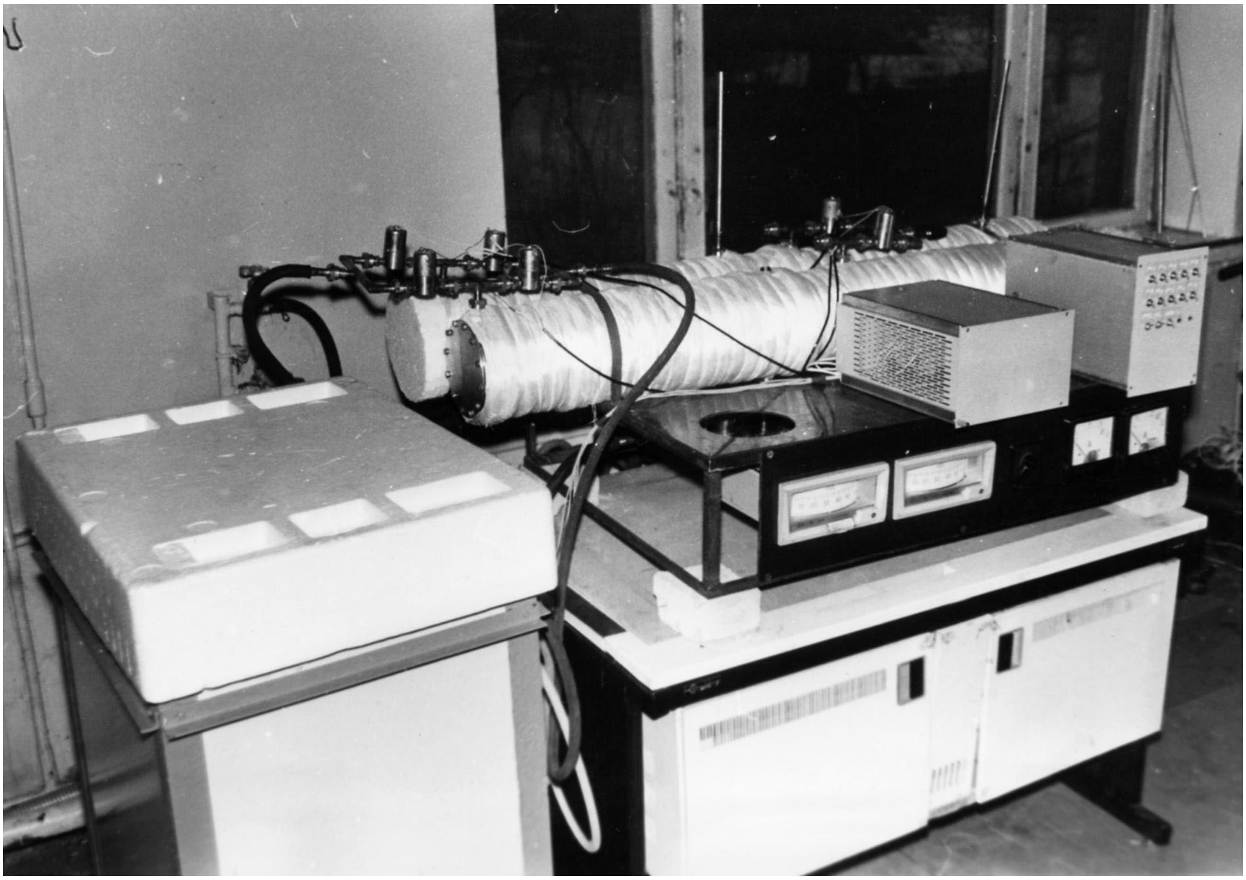

Fig. 4. The experimental installation for cold water production.

3.2. Output data

Operating time of installation	Eight half-cycles, 160 min
Output temperature of cooled water	1.5°C
Quantity of produced cold	1.48×10^{6} J
Average cold productivity	154 W
Quantity of supplied energy	12.9×10^{6} J
Average power consumption	1.34×10^{6} W

A series of tests of the installation were conducted in manual and automatic control mode. Cold productivity of the installation was a little below the designed value, probably due to the insufficient thermal conductivity of the metal hydride filling. The duration of the hydrogen sorption and desorption processes (half-cycle time) also depends on the thermal conductivity of the filling, which in turn determines the MHHP cold productivity.

4. Conclusion

Investigations have shown the expediency of the modular principle for MHHPs, which can provide the desired productivity at lower temperature by using a set of modules, as well as continuity of the cold generation process. During the development of MHHP, an important criterion is the choice of effectively working metal hydride pairs and providing a high thermal conductivity metal hydride filling. For the choice of the metal hydride pairs it is necessary to use real dependencies taking into consideration the plateau slope and the hysteresis of the sorption–desorption process.

Increasing the thermal conductivity of the metal hydride filling by using longitudinal finning was insufficiently effective. Foam metal will be used in future for the creation of a continuous metal matrix, and design decisions concerning recapturing the sensible heat of the hydride beds following each half-cycle will be considered.

The economic efficiency of MHHP-based refrigeration devices can be considerably increased by using the heat of secondary power sources as an energy source, for example heat of the exhaust gases of internal combustion engines, wastewater heat of technological works, etc.

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