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Experimental study of heat transfer enhancement in a liquid piston compressor/expander using porous media inserts

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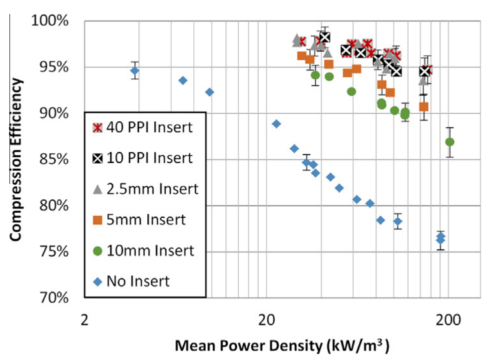
HIGHLIGHTS

- Porous medias role to improve compressor/expander performance shown experimentally.
- Significant increase in efficiency increase (up to 18%) at fixed power density.
- Significant increase in power density (up to 39 folds) at fixed efficiency.
- Surface area is the predominant contribution to improvements.

GRAPHICAL ABSTRACT



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ABSTRACT

The efficiency and power density of gas compression and expansion are strongly dependent on heat transfer during the process. Since porous media inserts can significantly increase heat transfer surface area, their addition to a liquid piston compressor/expander has been hypothesized to reduce the time to complete the compression or expansion process and hence the power density for a given thermodynamic efficiency; or to increase the thermodynamic efficiency at a fixed power density. This paper presents an experimental investigation on heat transfer with porous inserts during compression for a pressure ratio of 10 and during expansion for a pressure ratio of 6. A baseline case without inserts and five cases with different porous inserts are tested in a compression experiment: 3 interrupted ABS inserts with plate spacing of 2.5, 5, and 10 mm and 2 aluminum foam inserts sized with 10 and 40 pores per inch. The 2.5 mm and 5 mm interrupted plate inserts were also tested in expansion experiments. Porous inserts are found, in compression, to increase power-density by 39-fold at 95% efficiency and to increase efficiency by 18% at 100 kW/m^3 power density; in expansion, power density is increased three fold at 89% efficiency, and efficiency is increased by 7% at 150 kW/m^3. Surface area increase is found to be the predominant cause in the improvement in performance. Thus, a liquid piston compressor/expander together with a porous medium may be used in applications requiring high compression ratios, high efficiencies, and high power density such as in an open-accumulator compressed air energy storage (CAES) system or a compressor for compressed natural gas (CNG).

1. Introduction

Compressed air is a potential cost effective, power-dense, reliable and scalable means for storing energy at the utility scale compared to electric batteries, pumped-hydro and closed hydraulic accumulators [1–4]. In a conventional compressed air

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energy storage (CAES) system, compressed air is produced using excess electricity and stored in underground caverns. It is then combined with natural gas in a gas turbine to boost combustion efficiency. As a storage device, its efficiency is typically less than 50% [5]. In recent years, isothermal CAES have been proposed both by industry and academia as an energy storage approach that does not require fuel [6,7]. Here, mechanical work is consumed in the compressor to compress air during the storage phase, and recuperated in the expander as the compressed air expands during the regeneration phase.

For isothermal CAES to be viable, a high pressure (e.g. 200–300 bar), powerful and efficient compressor/expander is critical. Such a compressor is also needed for compressing natural gas as fuel for vehicles. Conventionally a high pressure gas compressor consists of multiple stages with inter-cooling. This creates a zig-zag pressure–volume curve consisting of successive adiabatic and constant volume cooling segments. A compressor with multiple adiabatic stages and ideal inter-cooling is the most efficient if all stages have the same compression ratio [8]. As the number of stages increases, compression approaches the most efficient isothermal compression. Whereas efficiency of the compressor/expander is governed by the pressure–volume (*P*–*V*) curve, the time it takes to trace the curve and hence the power (work/time) depends on the heat transfer rate in the compressor/expander or in the inter-cooling. If less time is allowed for heat transfer, the *P*–*V* curve deviates more and more from isothermal and becomes less and less efficient. Hence, there is an inherent trade-off between efficiency and power of a compressor/expander.

This trade-off can be mitigated by optimizing the compression and expansion trajectories, or by improving the heat transfer capability. In [9–11], trajectories are optimized for three cases: when $h \cdot A$ (the product between the heat transfer coefficient, h, and the heat transfer surface area, A) is a constant, when $h \cdot A$ is volume dependent, and when $h \cdot A$ is an arbitrary function. By matching power and availability of heat transfer capability, several-fold improvement in power densities over ad hoc (sinusoidal or linear compression/expansion) profiles at the same efficiency can be achieved. Optimal volume-time trajectories at low pressure ratios (1 bar to 7 bar) have been validated experimentally in [12,13]. The effectiveness of using tuned compression trajectories is also shown in simulation in [14].

Heat transfer capability can be enhanced by actively spraying very small liquid droplets with high heat capacity and large total heat transfer surface area [15–18]. The approach pursued in this paper is the use of a liquid piston in a compression/expansion chamber filled with porous material, as proposed in [19]. The liquid piston freely flows through the porous material which greatly increases the heat transfer area. Compared with a rigid piston, a liquid piston also forms an effective low friction seal for the air being compressed. In addition to the CAES application, liquid piston is also being pursued as a cost-effective and efficient means to compress natural gas for vehicle use [20], as well as for hydrogen [21] and supercritical CO_2 [22]. Numerical simulations of fluid flow and heat transfer were conducted for various geometries (tiny tubes, metal foams and interrupted-plate heat exchangers) in [19,23–25]. Preliminary experimental studies of enhanced heat transfer with the use of inserts are reported in [26]. However, since the instrumentation was limited, only limited qualitative inferences could be made. Recently, a liquid piston compressor was also demonstrated in a benchtop ocean compressed air energy storage (OCAES) system [27].

The objective of this paper is to test experimentally the effectiveness of various porous media to increase the efficiency or power density of a liquid piston compression/expansion process. A series of compression and expansion experiments using different types of porous inserts in a low-pressure (12 bar maximum pressure) compression/expansion chamber are presented. The porous inserts under study are ABS plastic interrupted-plates with 2.5 mm, 5 mm and 10 mm spacing between plates and aluminum foams with 10 and 40 pores per inch (PPI). These were chosen to span a range of surface area augmentation types, to utilize commercially available materials (foams), and based on demonstrated advantages from previous computational studies (interrupted plates) [24]. The input/output work, heat transfer and change in internal energy of the air, and compression/expansion efficiencies are calculated during compression/expansion for cases with porous inserts and compared with a benchmark case without porous inserts. This is the first experimental study of a compressor/expander with heat transfer inserts and a liquid piston that has been conducted with precise documentation of the volume, pressure and bulk temperature of the air during compression and expansion. The results show, indeed, that porous media inserts can significantly improve the trade off between efficiency and power density in a liquid piston compressor/expander.

The remainder of the paper is structured as follows. Section 2 provides an overview of the liquid piston compressor/expander and the governing equations that describe it. Section 3 presents the test facilities and describes the porous materials that are used. Section 4 describes the testing, data analysis and uncertainty analysis. Section 5 presents the results for the compression and expansion tests. Sections 6 and 7 contain discussion and conclusions.

2. Liquid piston compression/expansion processes

In a liquid piston air compressor/expander, air enters and exits a compression/expansion chamber from the top, and liquid (water in our case) from the bottom. The volume of the liquid in the chamber is controlled by a hydraulic pump/motor. In compression mode, the compression/expansion chamber is initially filled with air at ambient pressure. As liquid is pumped into the chamber, the volume of the air above it is reduced and the pressure is increased. In expansion mode, the chamber is initially filled with mostly liquid and a small volume of compressed air above the liquid. As liquid is allowed to exit the chamber, the volume of the compressed air increases and pressure is reduced. As such, the liquid column acts as a piston and mechanical work is applied and extracted via the hydraulic pump/motor for the liquid piston. The compression/expansion cycles can be repeated (frequently, if high power is desired) with the intake of ambient air or the exhaust of expanded air. With the liquid piston, the chamber can be filled with a porous medium since both liquid and air can flow through it. This can significantly increase the surface area for heat transfer for a given amount of initial/expanded air volume.

In this paper, air is treated as an ideal gas since pressures are relatively low (1–12 bar under compression) and temperatures are modest (200–450 K). This assumption allows a mass-average bulk temperature to be derived from a measured pressure and volume. An additional assumption is that the chamber and water lines are rigid and the water is incompressible. This permits the volume of air in the chamber to be determined by the difference between the initial air volume and the amount of liquid introduced.

Let P_0 and T_0 be the ambient pressure and temperature. We assume that the compressed air is to be stored in a tank at the constant pressure of rP_0 (r is the compression ratio) and that there is sufficient dwell time for the compressed air in the storage vessel to cool down to T_0 before reusing. The work input for the compression process and work output from the expansion process are illustrated as the horizontally-shaded areas under the *P*–*V* curves in Fig. 1. The work input to compress V_0 volume of ambient air at $(P_0,\ T_0)$ to be stored in the tank consists of the compression work to rP_0 along a certain compression trajectory (ζ_c) defined by the *P*–*V* (or *T*–*V*) profile, and the isobaric ejection of the compressed air into the tank: