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Research Paper

Design analysis of a liquid-piston compression chamber with application to compressed air energy storage

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HIGHLIGHTS

- A design of a high-efficiency gas compressor using porous media in the compression chamber is presented.
- Compression is with a liquid piston, allowing a porous heat exchanger to be integral to the compression space.
- A shaped compression chamber allows control of the piston speed and skewness through the matrix during the compression and expansion processes.
- The shaped chamber is shown to lead to enhanced heat transfer and improved compression efficiency.

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ABSTRACT

The present study focuses on a design analysis of a shaped liquid piston compression chamber based on CFD. The liquid piston compression chamber is for application to Compressed Air Energy Storage (CAES), which can be used to even the mismatch between power generation and power demand, and, thus, the objective of the design exploration is to maximize the compression efficiency. Within the compression chamber is an open-cell metal foam medium for enhancement of heat transfer. Traditionally, the chamber has a cylindrical shape. The present study explores the effects on compression efficiency of varying the profile of cross-sectional diameter along the axis of the chamber. This leads to a compression chamber with curved walls that assume a gourd-like shape. A set of exploratory design cases is completed using the orthogonal array concept based on the Taguchi method, hence reducing the number of realizations. CFD simulations provide insight into how the chamber shape affects the flow physics during compression. A quantitative design analysis shows that, in general, a large aspect ratio and a steep radius change of the chamber is preferred, which is in line with a visualization of the CFD flow fields. The relative importance of each different shape parameter is analyzed.

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1. Introduction

A design analysis for a shaped liquid piston compression chamber for application to Compressed Air Energy Storage (CAES) is presented. The CAES stores energy (e.g. from wind turbines) by compressing air during low power demand periods, liberating it by expanding compressed air during high power demand periods [1]. The benefit is that it evens the mismatch between power generation and power demand, such as experienced with wind generation. Analyses based on CFD simulations have shown that compression efficiency is higher when the compression process is more isothermal, for the same pressure compression ratio [2]. Typically, compression results in a temperature rise of the compressed air. This temperature rise occurs as a result of part of the compression work being converted into an increase in internal energy of the air. This internal energy rise is wasted, however, during the storage period as the compressed air cools to ambient temperature. Therefore, cooling the air during compression is important for lowering input work and maintaining high compression efficiency. Avoiding high temperatures is important also for materials and durability reasons.

A liquid piston approach can be used for the CAES compression. The sealing effectiveness of a liquid piston gives an advantage over a traditional solid piston in terms of power consumption [3]. A more important advantage of the liquid piston to CAES is that it offers the possibility of inserting porous media into the chamber to enhance heat transfer, as liquid can flow through the pores of porous medium. Detailed modeling and CFD simulations have been conducted on liquid piston compressors with open-cell metal foam inserts for application to lower pressure compression ratios. Although the porous medium introduces resistance to the flow, which causes pressure drop, the power loss due to this is minuscule relative to the power needed to compress the air. The results show that

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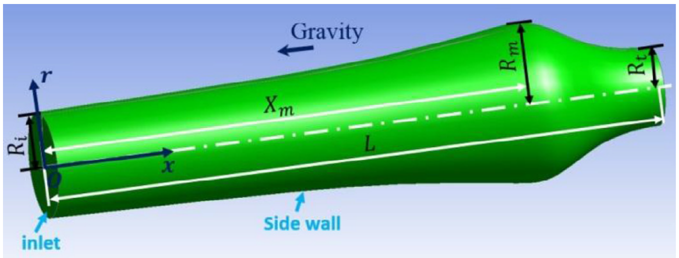

Fig. 1. Schematic of liquid piston chamber and shape parameters.

such compressors benefit from the cooling effect afforded by a liquid piston and the accompanying heat absorbing media for improving compression efficiency [4].

Numerical modeling of the liquid piston compressor with the inserts of porous media is done with volume-averaging techniques [5,6]. The continuity, momentum and energy equations are volume-averaged on the scale of a Representative Elementary Volume (REV) of the porous medium. Instead of resolving the flow through the exact shape of the porous medium, these volume-averaged equations are solved. As a result, flow through a porous medium is solved in a continuum domain without the need for resolving the pore-scale activities directly; a negative momentum source term arises in the momentum equation that represents the pore-scale activities and satisfies closure. This effect is often modeled by Darcian and inertial terms [7]. Two volume-averaged energy equations, one each for the solid and fluid, are solved, coupled by an interfacial heat transfer term. Since the liquid piston chamber involves two phases, water and air, the Volume of Fluid (VOF) method [8] is used in conjunction with the porous media model.

Traditionally, the compression chamber has a cylindrical shape. The present study explores the compression efficiency change that is derived by varying profiles of cross-sectional diameter along the axis of the chamber. This leads to a compression chamber with curved walls that make it assume a gourd-like shape. The advantage of such shape is that it offers an opportunity for more complex flow features in the chamber during compression that enhance mixing and heat transfer. To analyze the wall shape effect, the shape is parameterized and a series of design exploration cases based on orthogonal arrays is created. The orthogonal arrays of experiments have been often used with the Taguchi optimization method [9], and shown to be capable of reducing the number of realizations, whether experimental or numerical [10,11]. In the present study, four shape parameters are recognized, each having four different values of parameters of interest. Based on the orthogonal array method, sixteen orthogonal arrays of the design are created, each analyzed by a CFD run. The results give insight into the fluid flow and heat transfer characteristics in the compression chamber and lead to an optimized chamber shape within the chosen parameter domain.

2. Orthogonal arrays of exploratory designs

The present study investigates the effects of the shape of a liquid piston compression chamber. A schematic of a shaped chamber is shown in Fig. 1. Within the chamber is inserted an open-cell metal foam porous medium of 10 pores per inch (PPI) and 93% porosity. As water is pumped into the left end of the chamber (note that gravity is from right to left in Fig. 1), a rising water-air interface acts as a piston surface that compresses the air in the chamber. The compression process starts with pre-compressed air at 7 bars and 293 K and ends at 210 bars after 3 seconds. The chamber volume is fixed at $2.19\times10^{-3} m^3$ in this study. The chamber's main shape is governed by four parameters, as labeled in Fig. 1: the length, the inlet radius, the maximum radius, the top cap radius and the location of the maximum radius with respect to the inlet.

Table 1
Levels of investigation for different parameters.

	$\mathcal{L}_1$	$\mathcal{L}_2$	$\mathcal{L}_3$	$\mathcal{L}_4$
$\mathcal{P}_1$	1	2	4	8
$\mathcal{P}_2$	1.5	2	4	6
$\mathcal{P}_3$	0.333	0.5	0.65	0.8
$\mathcal{P}_4$	1.5	2	4	6

Of interest to the design is analysis with the different ratios of these five shape parameters, since the chamber volume is fixed. Four dimensionless shape parameters based on these five length scales are created:

$$\mathcal{P}_1 = \frac{L}{R_m} \tag{1}$$

$$\mathcal{P}_2 = \frac{R_m}{R_i} \tag{2}$$

$$\mathcal{P}_3 = \frac{X_m}{L} \tag{3}$$

$$\mathcal{P}_4 = \frac{R_m}{R_t} \tag{4}$$

The domains of interest for these parameters are: $1 \le \mathcal{P}_1 \le 8$, $1.5 \le \mathcal{P}_2 \le 6$, $0.333 \le \mathcal{P}_3 \le 0.8$, $1.5 \le \mathcal{P}_4 \le 6$. Four levels (values) for each parameter within its own domain are chosen for investigation. They are given in Table 1. Using the "L′ 16 Array," based on the Taguchi design method [9], sixteen orthogonal exploratory shape designs are created, and given in Table 2. A design is an array of shape parameter values, and it is orthogonal to other arrays of parameter values. The orthogonal array method can be proven mathematically. A practical perspective is that (1) each design is most different from the others, and (2) in all 16 designs, each level of each parameter has been combined with all other levels of other parameters. CFD simulations are done for different designs.

3. CFD modeling

Each of the designs in Table 2 is analyzed by CFD. The compression chamber is studied in cylindrical coordinates. As shown in Fig. 1,

Table 2
Exploratory designs based on orthogonal arrays.

	$\mathcal{P}_1$	$\mathcal{P}_2$	$\mathcal{P}_3$	$\mathcal{P}_4$
Design 1	1 ($\mathcal{L}_1$)	1.5 ($\mathcal{L}_1$)	0.333 ($\mathcal{L}_1$)	1.5 ($\mathcal{L}_1$)
Design 2	1 ($\mathcal{L}_1$)	2 ($\mathcal{L}_2$)	0.5 ($\mathcal{L}_2$)	2 ($\mathcal{L}_2$)
Design 3	1 ($\mathcal{L}_1$)	4 ($\mathcal{L}_3$)	0.65 ($\mathcal{L}_3$)	4 ($\mathcal{L}_3$)
Design 4	1 ($\mathcal{L}_1$)	6 ($\mathcal{L}_4$)	0.8 ($\mathcal{L}_4$)	6 ($\mathcal{L}_4$)
Design 5	2 ($\mathcal{L}_2$)	1.5 ($\mathcal{L}_1$)	0.5 ($\mathcal{L}_2$)	4 ($\mathcal{L}_3$)
Design 6	2 ($\mathcal{L}_2$)	2 ($\mathcal{L}_2$)	0.333 ($\mathcal{L}_1$)	6 ($\mathcal{L}_4$)
Design 7	2 ($\mathcal{L}_2$)	4 ($\mathcal{L}_3$)	0.8 ($\mathcal{L}_4$)	1.5 ($\mathcal{L}_1$)
Design 8	2 ($\mathcal{L}_2$)	6 ($\mathcal{L}_4$)	0.65 ($\mathcal{L}_3$)	2 ($\mathcal{L}_2$)
Design 9	4 ($\mathcal{L}_3$)	1.5 ($\mathcal{L}_1$)	0.65 ($\mathcal{L}_3$)	6 ($\mathcal{L}_4$)
Design 10	4 ($\mathcal{L}_3$)	2 ($\mathcal{L}_2$)	0.8 ($\mathcal{L}_4$)	4 ($\mathcal{L}_3$)
Design 11	4 ($\mathcal{L}_3$)	4 ($\mathcal{L}_3$)	0.333 ($\mathcal{L}_1$)	2 ($\mathcal{L}_2$)
Design 12	4 ($\mathcal{L}_3$)	6 ($\mathcal{L}_4$)	0.5 ($\mathcal{L}_2$)	1.5 ($\mathcal{L}_1$)
Design 13	8 ($\mathcal{L}_4$)	1.5 ($\mathcal{L}_1$)	0.8 ($\mathcal{L}_4$)	2 ($\mathcal{L}_2$)
Design 14	8 ($\mathcal{L}_4$)	2 ($\mathcal{L}_2$)	0.65 ($\mathcal{L}_3$)	1.5 ($\mathcal{L}_1$)
Design 15	8 ($\mathcal{L}_4$)	4 ($\mathcal{L}_3$)	0.5 ($\mathcal{L}_2$)	6 ($\mathcal{L}_4$)
Design 16	8 ($\mathcal{L}_4$)	6 ($\mathcal{L}_4$)	0.333 ($\mathcal{L}_1$)	4 ($\mathcal{L}_3$)

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