



Research Paper

Experimental investigation of heat transfer in liquid piston compressor

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HIGHLIGHTS

- Thermal analysis of a liquid piston compressor presented using thermal resistances.
- Heat transfer rate and compression work evaluated during the compression process.
- Convective thermal resistance of air has a major contribution in total resistance.
- Overall heat transfer coefficient reaches a steady value towards the end of compression.
- Improving heat transfer in the chamber can further increase compression efficiency.

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ABSTRACT

The use of liquid pistons is a promising approach for attaining efficient near-isothermal compression. One of the key factors affecting the efficiency of a liquid piston compressor is heat transfer. Understanding the heat transfer mechanism during compression is crucial for the design and development of an efficient liquid piston compressor. In this paper, heat transfer in the liquid piston compressor is studied experimentally for air compression. An analytical model is presented based on a thermal resistance circuit. Experiments are performed using compression chambers of different materials for a compression ratio of 2.05–2.35 with various stroke times of compression. It is observed that the rate of heat transfer increases with faster stroke time of compression. However, a faster compression process requires a higher compression work and results in a higher air temperature. The convective heat transfer coefficient of air decreases rapidly as compression proceeds and approaches a steady value towards the end of compression. Thermal resistance analysis for compression with different chamber materials indicates that convective thermal resistance of air has a significant contribution in the total thermal resistance. During the initial phase of compression, the high conductivity of the chamber material helps improve the overall heat transfer coefficient; however, it has a marginal effect during the later phase of compression. An isothermal compression efficiency of 84–86% is observed with the liquid piston.

1. Introduction

Compressed air consumes a great share of total energy consumption in the industrial applications. For a typical industrial facility in the USA, approximately 10% of the electricity consumed is for generating compressed air. For some facilities, compressed air accounts for more than 30% of the electricity consumed [1]. Energy costs during the utilization period of the compressor may contribute more than 75% of the overall cost over the life cycle. Improvements in the energy efficiency of compressed air systems can result in energy saving of 20–50% [2]. Another major application of compressors is for the compressed air energy storage. Efficient energy storage systems facilitate effective utilization of intermittent renewable energy sources. Compressed air energy storage systems have a great potential to serve as large-scale

energy storage systems. The compressor and expander are the key components in a compressed air energy storage plant. Development of an efficient compressor and expander would make compressed air energy storage systems economical and competent [3].

The liquid piston concept shows a significant improvement in the efficiency of gas compression and expansion in comparison to the conventional reciprocating compressor. In a liquid piston, a column of liquid is used to compress gas in a fixed volume chamber. As liquids conform to irregular volumes, the surface area to volume ratio in the compression chamber can be maximized using a liquid piston. The high surface area to volume ratio helps in attaining a higher rate of heat transfer during gas compression. This results in a compressor with a near-isothermal operation, leading to an efficient compression with minimal compression work [4].

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Nomenclature

a_0, a_1, a_2	model constants
A	area (m^2)
A_{inner}	area of the inner surface of the chamber (m^2)
C_v	specific heat of air at constant volume (J/kg K)
$h_{\text{conv,air}}$	convective heat transfer coefficient of air ($\text{W/m}^2 \text{K}$)
$h_{\text{conv,amb}}$	convective heat transfer coefficient of ambient ($\text{W/m}^2 \text{K}$)
$h_{\text{conv,gas}}$	convective heat transfer coefficient of gas ($\text{W/m}^2 \text{K}$)
$h_{\text{conv,water}}$	convective heat transfer coefficient of water ($\text{W/m}^2 \text{K}$)
k_{solid}	thermal conductivity of the chamber material (W/m K)
m	mass of the gas (kg)
n	polytropic index of compression process
P	pressure (Pa)
P_0	pressure at the start of compression (Pa)
P_f	pressure at the end of compression (Pa)
P_r	compression pressure ratio
\dot{Q}	rate of heat transfer (J/s)
r_{inner}	inner radius of the chamber (m)
r_{outer}	outer radius of the chamber (m)
R	gas constant (J/kg K)
$R_{\text{cond,solid}}$	conductive thermal resistance of chamber material (K/W)
$R_{\text{conv,air}}$	convective thermal resistance of air (K/W)
$R_{\text{conv,amb}}$	convective thermal resistance of ambient (K/W)
$R_{\text{conv,gas}}$	convective thermal resistance of gas (K/W)

$R_{\text{conv,water}}$	convective thermal resistance of water (K/W)
t	time (s)
t_{solid}	thickness of the chamber (m)
T	temperature of gas (K)
T_{∞}	temperature of ambient (K)
\dot{U}	rate of change of internal energy of gas (J/s)
U_h	overall heat transfer coefficient ($\text{W/m}^2 \text{K}$)
V	volume (m^3)
V_0	volume at the start of compression (m^3)
V_f	volume at the end of compression (m^3)
W_{comp}	compression work (J/s)

Greek symbols

η_{iso}	isothermal efficiency of compression
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Subscripts

0	start of compression
conv	convective
cond	conductive
comp	compression
f	end of compression
∞	ambient

Heat transfer plays an important role in improving the efficiency of compression in the liquid piston. For an isothermal compression, the instantaneous rate of heat transfer should be equal to the instantaneous mechanical power from to the compressor [5]. Piya et al. [6] presented a numerical modeling of liquid piston gas compression based on thermal-fluids and heat transfer mechanisms. Their results indicated that heat transfer processes actively contribute towards extraction of heat energy from the working gas during compression. Also, their simulation shows that liquid piston compression maintained a lower gas temperature than observed during adiabatic compression. Kermani et al. [7] performed heat transfer analysis of liquid piston compressor for hydrogen applications. They presented a thermodynamic model of liquid piston compressor to investigate the heat transfer phenomenon inside the compression chamber. Increasing the total heat transfer coefficients at the interface and the wall, together with the compression time, played key roles in reducing the hydrogen temperature.

Various heat transfer enhancement techniques have been tried in liquid piston compressor. Porous media inserts for heat transfer enhancement in liquid piston compressor have been analyzed by Zhang et al. [8] using Computational Fluid Dynamics (CFD) simulations. It was observed that heat exchangers can effectively suppress temperature rise and secondary flows in liquid piston compressor. Further, Yan et al. [9] performed an experimental study using porous media inserts in a liquid piston compressor/expander. Porous media inserts have shown a significant increase in efficiency (upto 18%) at a fixed power and a significant increase in power density (up to 39 folds) at a fixed efficiency. The increase of surface area was the predominant cause of the performance improvement with the use of porous media. Another experimental study of a high pressure (210 bar) liquid piston air compression has shown performance improvement with the use of porous media inserts [10]. The use of porous media could achieve $10\times$ increase in power density at a constant efficiency for the high-pressure air compression. Design analysis of shaped compression chamber using porous media in liquid piston compressor is presented by Zhang et al. [11]. It was observed that shaped compression chamber leads to enhanced heat transfer and improvement in compression efficiency. Highly efficient isothermal air compression and expansion can lead to an efficient large-scale compressed air energy storage system [12].

Various other heat transfer enhancement techniques like trajectory optimization [13], the use of hollow spheres [14] and spray cooling [15] have shown better performance in the liquid piston compressor. Liquid piston compressor with heat transfer enhancement has the potential to develop a highly efficient energy storage system [16].

A review of heat transfer in reciprocating compressors indicates that very little attention was paid to heat transfer modeling and assessment of its effect. This is attributed partly to the lack of consensus about the seriousness of its impact and partly to its complexity [17]. However, there is a good agreement in the literature that heat transfer inside the cylinder is one of the main factors affecting the efficiency of the reciprocating compressors. Recently, Tuhovcak et al. [18] presented a comparative analysis of heat transfer models for the reciprocating compressors. Their analysis indicated that the isentropic efficiency of the compressor is significantly influenced by the type of heat transfer model. They also presented heat transfer analysis in the cylinder of the reciprocating compressor using complex CFD simulations. Results showed a large deviation between integral correlations and numerical model for heat transfer prediction [19]. This illustrates the importance and complexity of heat transfer models in reciprocating compressors.

The optimal design of a liquid piston compressor demands a thorough understanding of the heat transfer process during compression/expansion. However, there are very limited studies investigating heat transfer in liquid piston compressor experimentally. Majority of earlier studies on liquid piston compressor have used heat transfer models for flow through the pipe. However, there exists a considerable difference in fluid flow conditions and heat transfer characteristics between the liquid piston and pipe flow. Also, the validity of a fully developed pipe flow model for liquid piston compressor has not been confirmed with experimental investigations. In this paper, heat transfer in the liquid piston compressor is studied experimentally. The rate of heat transfer during the compression process is investigated thoroughly. The effect of stroke time of compression on the rate of heat transfer is studied by experimentally varying stroke time of compression. A detailed analysis of the liquid piston compressor using a thermal resistance circuit is presented. Experiments with compression chambers of different materials are also performed to investigate the influence of the material of the compression chamber on heat transfer characteristics. Finally, the

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