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Enhancing Energy Efficiency in Chilean Cryogenic Gas Plants with Liquid Piston Systems: A Dynamic Modelling and Simulation Study

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ABSTRACT

Liquid piston systems (LP) are an efficient, simple, and environmentally friendly way to harvest energy from relief pressurised gas flows. In this paper, we study an LP system that operates by constantly introducing gas into a piston chamber containing water. The expansion of the gas propels the water, resulting in an isothermal expansion process due to their interaction. The discharged water is used to generate electricity. A dynamic model was developed using gPROMS and the numerical results were validated against previously published experimental data. The power output predictions show a maximum relative error of 6.4% from the experimental results. The performance of the LP system was evaluated employing waste gas data obtained from a liquefaction plant utilised to supply oxygen to a metallurgical furnace located in Chile. The predicted thermal efficiencies for the case study were as high as 80%, and the produced power output was 90 kW. The cost analysis demonstrated a decrease of 5.9% in electricity consumption attributed to the LP recovery system. Furthermore, the economic analysis illustrated a payback period for the investment ranging from 1.7 to 3.8 years, followed by an annual savings generation spanning from 24 to 47 kUSD depending on the electricity cost.

Keywords: Liquid Piston (LP), Hydro-Pneumatic Energy Storage (HYPES), Energy Systems, Modelling and Simulation

NONMENCLATURE

Abbreviations	
LP	Liquid Piston
Latin Letters	
A	Surface area [m^2]
C_d	Coefficient of discharge [-]
c_p	Constant-pressure spec. heat [J/kgK]
c_v	Constant-volume spec. heat [J/kgK]
D	Diameter [m]
H	Piston height [m]
h	Liquid level [m]
h_c	Convective heat transfer coefficient [W/m^2 K]
k	Thermal Conductivity [W/mK]
m	Mass [kg]
P	Pressure [Pa]
R	Ideal gas constant [J/kgK]
T	Temperature [K]
t	Time [s]
V	Volume [m^3]
W	Work [kJ]
Greek Letters	
η	Efficiency [%]
μ	Molecular Viscosity [Pas]
ρ	Mass density [kg/m^3]

1. INTRODUCTION

Liquid piston (LP) expansion systems function by using gas pressure to move a liquid contained within a vessel, thereby generating mechanical work [1]. This process involves releasing the liquid from the container, during which the gas's potential energy is converted into boundary work on the interface between the liquid and

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gas [1]. This action propels the liquid with increasing momentum as it exits the container. The main benefits of LP technology for energy storage and energy generation are a high energy conversion efficiency (60-80 %) (energy generated vs. energy input), scalability, and maturity of components [1, 2]. LP systems can be found in several energy applications including Stirling engines [3, 4], compressors [1, 5], and energy storage [1, 6, 7]. The focus of LP research by using numerical tools is related to increase of efficiency by using heat transfer enhancement methods such as spray cooling [8, 9], and optimisation of surface area [5]. This allows isothermal regimes which yield higher specific powers. Moreover, other topics of LP research are also related to tanks configurations [10, 11] and LP cycle variations [12, 13].

Chile currently accounts for 28.3% of the global copper production and holds approximately 23.0% of the world's copper reserves [14]. It is projected that Chile's annual copper production will increase from the current 5.8 million tonnes per year to 6.2 million tonnes per year by 2027 [14]. However, mining activities in Chile face environmental challenges, particularly concerning air and water pollution [15]. Chile faces a significant challenge in modernizing and upgrading its smelting operations, which are among the oldest and least sustainable among the world's largest copper producers [14, 16]. Some of the necessary improvements include enhancing sulfur capture, treating exhaust gases, improving slag treatment, and implementing emission monitoring systems [14, 16]. Another factor that makes the Chilean smelting process less competitive compared to countries like China is its high operational costs, primarily driven by energy consumption, which accounts for up to 35% of the overall costs due to energy inefficiencies [17]. Smelting costs in Chile average around 135 US dollars per ton of concentrate, while in China, these costs are approximately 50 US dollars per ton [14]. Over the years, China has maintained low costs and improved energy efficiency [14].

The smelting process involves the utilisation of oxygen for the burners within the furnace hearth. This is done to enhance the efficiency and overall productivity of the process. Such burners allow for better control of combustion and higher temperatures, resulting in improved processing of ores and metal [18, 19]. The oxygen is provided by on-site liquefaction plants to ensure a continuous gas supply to the furnace process. During liquefaction, the air is treated and separated mostly into oxygen and nitrogen. The nitrogen gas is vented into the atmosphere without utilising the exergy available. In this work, we study an LP system to recover energy from the nitrogen produced in the liquefaction plant of the smelting furnace. To the best of our knowledge, this work introduces a novel approach as it is the first attempt to simulate an energy recovery system employing an LP system. We employed real input data from a cryogenic plant in Chile. A numerical model of the LP was developed in gPROMS [20] and the performance predictions are used to assess the economic feasibility and cost savings yielded by the proposed system for energy recovery.

The structure of this paper is as follows: In Section 2, the operation of the LP is explained. Section 3 elaborates on the development of the LP model, while Section 4 focuses on the validation of the model using experimental data. Moving on, Section 5 delves into the simulation work's study case. The outcomes of the LP simulation, as well as the cost and economic analysis for the case study, are presented in Section 6. Finally, Section 7 provides a summary of the study's accomplishments and findings.

2. THE LP SYSTEM

Fig. 1 illustrates the liquid piston (LP) system under study, building upon prior research that adopted a two-tank LP setup to recirculate water for energy storage purposes, thus minimising system size [10,11]. The LP presented here can run with presurised exhaust gases from any process. The system works as follows. Piston I is filled with water, and Piston II is empty. Then, Gas-line 1 fills with gas the inner cavity of Piston I. Subsequently, V1 and V2 are opened. Piston I is pressurised by Gas-Line 1 while discharging water through turbine T towards Piston II. In this process, power is generated. Thereafter, the remaining gas in Piston I is released via Gas-Vent 1 toward the environment. While Piston II is pre-charged using Gas-Line 2 in preparation for its discharge. Then, a similar discharge process to Piston I is applied to Piston II. Valves V3 and V4 are opened, and gas from Gas-Line 2 is introduced to Piston II, recirculating the water through turbine T towards Piston I. Thereafter, Gas Vent 2 is opened to decompress Piston II, and while Piston II is pre-compressed. The entire sequence is repeated iteratively. More details of the LP system are presented by Aliaga et al. [21].

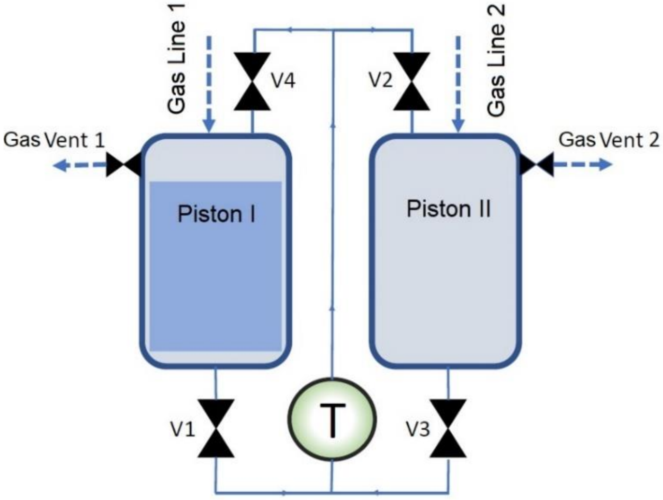

Fig. 1. LP system to evaluate an energy recovery case study [21]

3. LP MODEL DEVELOPMENT

In this section, we introduce the mathematical model developed for the LP system. The software used was gPROMS Model Builder which solves for differential/algebraic equations using the Finite Difference Method. The solver runs with a variable time-step and Backward Differentiation Method for temporal derivatives approximation. Fig. 2 shows a simplified model of the LP, where only one piston is simulated assuming that both pistons work with the same operating conditions.

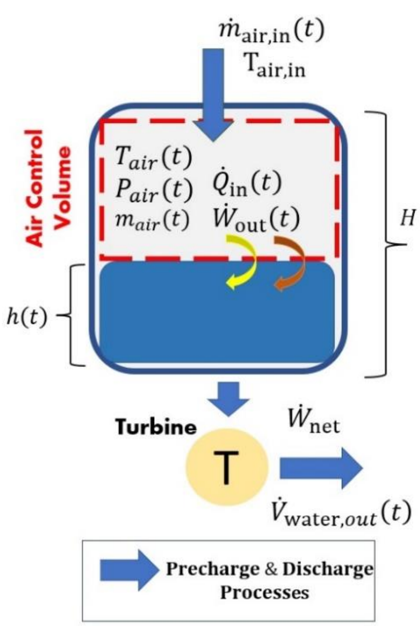

Fig. 2. Main variables of the LP system

The control volume is placed in the gas chamber above the liquid. The physical properties of water are considered constant, and the water temperature is regarded as constant and unaffected by any heat transfer process. The nitrogen gas was modelled using the ideal gas law and the physical properties such as molecular viscosity, thermal conductivity, and specific heats were obtained and implemented in gPROMS using the NIST database [22].

The mass and energy conservation equations for the presurisation of an LP chamber were developed by Wisniak et al. [23], and are written as follows:

$$\frac{dm}{dt} = \dot{m}_{in} \quad (1)$$

$$m\, c_v \frac{dT}{dt} = \dot{m}_{in}\left(c_p T_{in} - c_v T\right) - \dot{W} - \dot{Q} \quad (2)$$

Where the sub-index *in* is related to inlet variables. The heat transfer $\dot{Q}$ is calculated as follows:

$$\dot{Q} = h_c A_{wall}(T_{wall} - T) + h_{gas} A_{piston}(T_{water} - T) \quad (3)$$

Where h_c is the convective term for a fluid in a circular channel and is calculated using Petukhov, Kirillov, and Popov correlations detailed in [24]. And h_{gas} is a convective heat transfer coefficient of impinging gas jet [24]. Moreover, the liquid level of the LP can be tracked using the following equation derived in literature [25]:

$$\frac{dh}{dt} = Cd\,\frac{D_t}{D}\sqrt{\frac{2P + \rho g h}{\rho}} \quad (4)$$

The flowrate and hydraulic power can be calculated as follows:

$$\dot{V} = Cd\,\frac{\pi {D_t}^2}{4}\sqrt{\frac{2P}{\rho} + 2gh} \quad (5)$$

The hydraulic power is calculated with the following equation $\dot{W} = \dot{V}\, P\, \eta_{turbine}$.

4. LP MODEL VALIDATION

In this section, we present the validation of the LP model. We used a pilot plant of the constant-pressure LP system introduced by Camargos et al. [26]. This prototype involves the utilisation of a reciprocating compressor operating at 10 bar. The system incorporates a 0.2 m^3 air reservoir and an LP setup consisting of a 0.18 m^3 tank for air and water. Compressed air is directed into the air/water tank and is regulated by a pressure control valve. When discharging, the water is directed towards a compact Pelton turbine with a maximum capacity of 300 W. Table 1 shows the main parameters and variables set for the validation of the model.

Table 1. Simulation parameters for the model validation from experimental data [26]

Parameters	Value [unit]
LP height	0.8 [m]
Discharge Coefficient	0.23 [-]
LP diameter	0.5 [m]
Turbine efficiencies	29-43 [%]

Fig. 3 and 4 show the results for several working pressures of the LP system. The relative errors in the predicted flow rate of discharge and power output are less than 4.8% and 6.4%, respectively. This serves as confirmation that our simulation methodology is capable of accurately predicting a real system implementation.

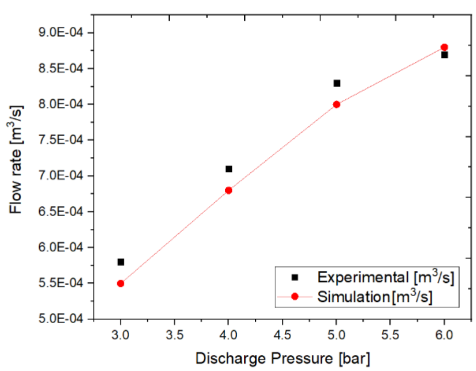

Fig. 3. Validation of the flow rate predicted by the LP model using experimental data [26]

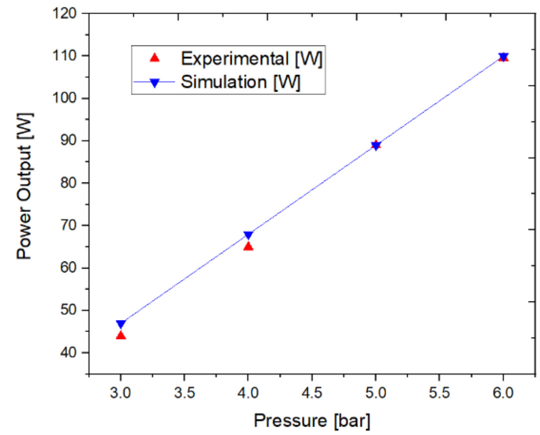

Fig. 4. Validation of the power output predicted by the LP model using experimental data [26]

5. SIMULATION OF THE LP SYSTEM FOR THE CASE STUDY

In this section, we discuss the design and simulation setup of the LP system for the case study. Section 5.1 defines and explains the case study, Section 5.2 presents the data of the case study that will be used for the simulations, Section 5.3 shows the simulation parameters and outlines the geometric design of the LP system for the case study.

5.1 Case Study: Energy Recovery in Liquefaction Plants for Metallurgical Furnaces in Chile

Metallurgical furnaces in Chile utilise oxygen-enriched burners that consume a substantial amount of oxygen, of about 10,000 Nm^3 per hour [27]. To supply this oxygen demand, especially when the mining site is located far from a readily available gas supply network, oxygen gas is produced directly on-site through liquefaction units. This production method ensures a constant and sufficient oxygen supply for the furnaces.

The process of producing oxygen gas through liquefaction also generates nitrogen as a byproduct. Unfortunately, in some cases, this nitrogen is released into the environment without fully utilising its potential exergy (useful energy). The proposed LP system has potential for effectively harnessing the exergy contained in the nitrogen byproduct. Instead of releasing nitrogen into the environment, the LP system can potentially utilise its energy for power generation purposes, thereby enhancing overall energy efficiency and minimising wastage. In the following section we provide flow date from a real oxygen-production plant [27].

5.2 Parameters of the Liquefaction Plant

Table 2 shows the parameters of the nitrogen vented for a liquefaction plant. These parameters correspond to the flow characteristics when the gas is vented into the atmosphere.

Table 2. Nitrogen gas resource available for energy recovery [27]

Parameters	Value [unit]
N_2 available	38,000 [Nm^3/hr]
N_2 mass flow	1.2 [kg/s]
Temperature	300 [K]
Working pressure	6-8 [bar]

5.3 LP Design and Simulation Parameters

Table 3 shows the design and main parameters for the simulation of the LP system customised to generate power by utilising the exhaust nitrogen gas conditions in Table 2.

Table 3. LP design to extract the energy from the nitrogen waste gas flow

LP Design	Value [unit]
Diameter	3 [m]
Height	7 [m]
Volume	50 [m^3]
Discharge Pipe	7 [inch]
Coefficient of discharge	0.9 [-]
Turbine-gen. Eff.	0.85[-]
Turbine Nominal Power	100 [kW]
Water Flow Rate	0.5 [m^3/s]
Pressure head	2 [bar]

6. RESULTS AND DISCUSSIONS

In this section, we present the simulation results and economic assessment for the case study. Section 6.1 shows the predicted variables and performance indicators of the LP system. Section 6.2 details the economic and cost analysis performed for the case study.

6.1 LP performance

Fig. 5 illustrates the key variables simulated for the case study. The graph represents the consecutive performance of two cycles, depicting the continuous operational mode in which the system employs a pair of pistons. During the initial phase (t < 6s), the LP pre-compression occurs, involving a flow of 1.2 kg/s at a temperature of 300 K. As the inflation process advances, the gas temperature rises to 420 K, resulting in a pressure of 2 bar. During this stage, the piston does not generate power, and the water volume capacity is 47 m^3. Between 6s < t < 98s, the LP discharges water, producing a power output of 90kW at a steady pressure of 2 bar. Maintaining this operational regime necessitates a nitrogen gas consumption rate of 1.16 kg/s, having an efficiency (energy output vs. energy input) up to 80%. From 99s < t < 102s, while the first piston releases surplus gas to return to ambient pressure, the second piston undergoes pre-compression. Subsequently, between 102s < t < 196s, the second piston discharges, repeating the cycle.

6.2 Cost Savings and Economic Analysis

In this section, we present an economic scenario to evaluate the feasibility and economic benefits of implementing an LP to recover energy from the liquefaction plant. To estimate the energy consumption of the liquefaction plant we can consider a typical value for a specific work of liquefaction (power consumed vs. kg liquid air produced) of 0.27 kWh/kg [28]. Moreover, the LP system recovered energy and produced power at 0.02 kWh/kg. Additionally, for calculating the gas production in kg, we assume a 12-hour daily operation and an effective oxygen consumption rate of 10,000 Nm^3 per hour for the furnace. Table 4 details the results of the energy cost assessments for the liquefaction plant. The cost of energy ranges from 1,092 to 2,184 USD per day. These costs vary based on the prevailing electricity rate, which ranges from 60 to 120 USD per MWh in Chile (denoted by the super index in Table 4). The LP system recovers 5.9% of the consumed input of energy, equivalent to 130 USD per day. The economic analysis, shown in Table 5, reveals a conservative scenario where the payback period for the investment in the LP energy recovery system spans from 1.7 to 3.4 years under different electricity price conditions.

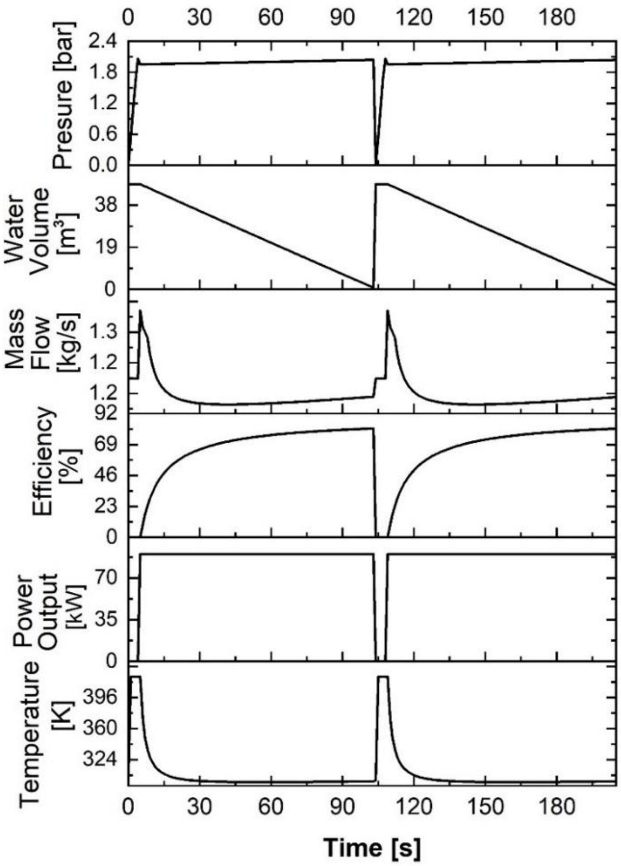

Fig. 5. Dynamic variables of the LP simulated using the available nitrogen flowrate

Additionally, the capital cost was taken to fluctuate between 900 and 2,000 USD per kW. This capital cost scenario represents a worst-case estimation compared to Yao et al. [13] estimates, which suggested costs ranging from 400 to 800 USD per kW. In which case the payback is better.

Table 4. Energy consumption and savings

Item	Amount [unit]
Air Produced	67,392 [kg]
N_2 Recovered	51,840 [kg]
Energy Consumed	18,196 [kWh]
Energy Produced	1,080 [kWh]
Cost of Energy per Day[1]	2,184 [USD/day]
Value of Energy Production[1]	130 [USD/day]
Cost of Energy per Day[2]	1,092 [USD/day]
Value of Energy Production[2]	65 [USD/day]
Cost Reduction	**5.9 [%]**

electricity cost in Chile: 120USD/MWh [1], 60 USD/MWh [2]

Table 5. Economic analysis

Item	Amount [Unit]
Capital Cost	900-2,000 [USD/kW]
Investment	81-180 [kUSD]
Payback [1]	3.4-7.6 [years]
Payback [2]	1.7-3.8 [years]

electricity cost in Chile: 120USD/MWh [1], 60 USD/MWh [2]

7. CONCLUSIONS AND COMMENTS

In this work, we used data from an air liquefaction facility in Chile that employs its oxygen output for smelting furnaces, and we successfully designed an LP system to recover energy from the waste nitrogen gas flow delivered by the cryogenic gas plant. The dynamic model developed for the LP system was validated using experimental data and used to design the LP system. The main findings and final remarks are as follows:

- The LP system is well-suited for energy recovery applications in cryogenic gas plants. The results showed 90 kW of LP power output with 80% energy conversion efficiency. This system performance yields a cost reduction of 5.9% on the electricity consumed by the process.
- Under a conservative estimation, the return on investment for the LP energy recovery system is projected to be within 1.7-3.8 years, following which the recovery unit would generate annual savings ranging from 24-47 kUSD.
- The system operates with only 2 bars of pressure, which provides cost benefits in pressure vessel construction.
- In future work, the integration of an air preheating system for the LP using the fumes of the furnace will be studied to increase the power output and thus energy savings.

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