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Energy Consumption Analysis of Ionic Liquid Compressors via Lumped Parameter Model#

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ABSTRACT

Ionic liquid compressor is a type of compressors applied in hydrogen refueling stations. It uses ionic liquid (IL) for piston sealing and is driven by a hydraulic system. Previous literature mainly focused on piston motion and pressure variation. However, few studies referred to the influence of IL supplement on energy consumption and capacity. In this study, a lumped parameter model (LPM) of ionic liquid compressors is established. Power proportions of all parts are presented. Moreover, specific power and capacity are obtained under different amounts of IL supplement. Results show that the gas indicated power accounts for the main portion of the shaft power. The powers used for IL flow and hydraulic transmission will increase as the IL supplement amount increases, resulting in a rise in the shaft power. Insufficient and excessive IL supplement can both decrease capacity of compressors. Decreasing IL supplement amount can decrease the shaft power but specific power will rise if there is too little supplement amount.

Keywords: ionic liquid compressor, specific energy, liquid supplement, capacity, liquid fraction

NOMENCLATURE

Abbreviations	
BDC	Bottom Dead Center
IL	Ionic Liquid
LPM	Lumped Parameter Model
TDC	Top Dead Center
Symbols	
E	Specific power, kWh/kg
p	Pressure, MPa
q	Flow rate, Nm3/h
T	Temperature, K
V	Volume, m3
P	Power, kW

1. INTRODUCTION

Ionic liquid compressors are a type of positive displacement compressors. They are promising in the field of hydrogen energy due to their lower energy consumption, fewer moving parts, and high reliability [1]. Ionic liquid (IL), a type of molten salt with a melting point below 100 °C, is applied to cover the moving piston for lubrication and sealing [2]. IL has good thermal stability and low gas solubility [3]. A hydraulic system is used to drive the piston instead of a crank-rod mechanism. The piston motion is subject to both the pneumatic and hydraulic systems.

Previous research explored mathematical modeling for calculating piston motion of compressors or engines. Guo et al. [4] presented a model incorporating valve dynamics for simulating the thermodynamic process of ionic liquid compressors. The piston trajectory is approximated as a route derived from a crank-rod mechanism. Zhou et al. [5] designed a liquid piston compressor with a column spool to buffer the piston at the cylinder bottom. The numerical results verified that the buffer structure greatly reduces the piston shock on the cylinder wall. Kang et al. [6] proposed a novel liquid piston compressor with a double buffer structure. The influence of piston mass on the pulsation of piston velocity was discussed. Jin et al. [7] presented an investigation of dynamic characteristics of the free piston of ionic liquid compressors through a fluid-structure interaction modeling. Hu et al. [8] built an engine simulation model considering hydraulic valve dynamics. The predicted engine performance was verified by experiments.

Some studies focused on the analysis of energy consumption and capacity of positive displacement compressors. Zhou et al. [9] built a mathematical model considering heat transfer and damping effect of the porous media. The results show that both heat transfer

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efficiency and hydraulic overflow losses are the key parameters governing the energy efficiency. Specklin et al. [10] proposed an innovative solution to achieve quasi-isothermal compression. An internal forced convection was mounted at the top part of the compression chamber to enhance heat transfer and reduce energy consumption. Ren et al. [11] discussed the influence of hydraulic oil compressibility on volumetric efficiency of diaphragm compressors by theoretical analysis and experimental investigation.

However, former studies rarely presented a theoretical reference of IL supplement from the perspective of saving energy and increasing capacity. IL supplement determines dynamic IL proportion inside cylinders, which can further affect volumetric efficiency by changing clearance volume of cylinders [12]. Thus, it is significant to investigate the influence of IL supplement on energy consumption and capacity.

This paper performs an energy consumption analysis of ionic liquid compressors based on the lumped parameter model (LPM). Power proportions of all parts are presented, including gas compression, IL flow, friction, and hydraulic transmission. Moreover, specific power and capacity are obtained under different amounts of IL supplement. This study can provide a reference for saving energy and increasing capacity of ionic liquid compressors.

2. WORKING PRINCIPLE

Fig. 1 illustrates the schematic diagram of the system. A set of cylinder assembly is mainly composed of a gas cylinder, hydraulic cylinder, piston, suction valve, and discharge valve. The IL inside the gas cylinder flows out through the discharge valve. Subsequently, the IL is filtered out and collected by a separator. The free piston reciprocates between the top dead center (TDC) and bottom dead center (BDC), driven by a hydraulic system. The suction and discharge valves are used to control hydrogen inflow and outflow, respectively. The pressure

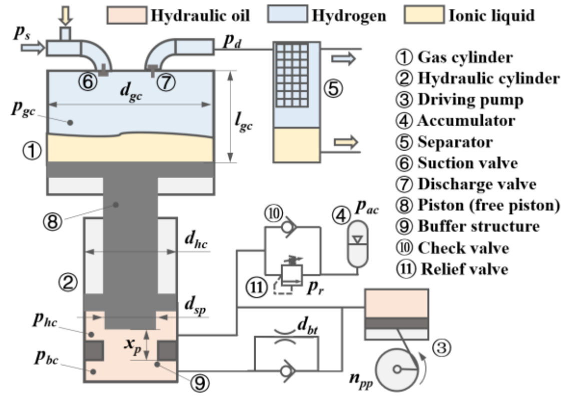

Fig. 1 Schematic diagram of the system

in the inlet and outlet pipes are suction pressure p_s and discharge pressure p_d, respectively.

As to the hydraulic system, a relief valve is used to avoid excessive pressure, while a check valve is applied to supplement hydraulic oil to the hydraulic cylinder. An accumulator is used to offer stable back pressure of the system. A buffer structure is designed to prevent the piston from severe collision on the hydraulic bottom. A throttle valve and check valve are connected to the buffer chamber. A driving pump is used to provide power to the system.

3. LUMPED PARAMETER MODEL

3.1 Model assumption

The LPM model is underpinned by the following assumptions:

(1) The gas cylinder and hydraulic cylinder are considered control units. Unified state variables (such as pressure and temperature) are used, ignoring the uneven distribution of physical properties caused by flow within the control unit.

(2) The heat exchange between the hydraulic system and the ambient environment is ignored.

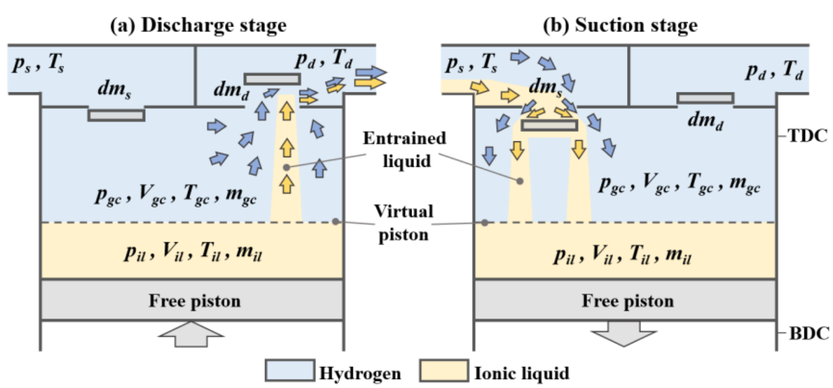

Fig. 2 Schematic diagram of the gas cylinder and the valves

(3) Leakage from hydraulic components or structures is not considered in the LPM except for the flow through the aperture of the buffer structure.

3.2 Conservation equations

The schematic diagram of the gas cylinder and the valves is displayed in Fig. 2. IL is entrained into the cylinder at the suction stage and out of the cylinder at the discharge stage. Assume that there is a virtual piston between the IL and hydrogen in the LPM, thereby dividing the gas and liquid into two control volumes. Their pressure variations can be calculated according to their volume changes and the flow rate into them. Additionally, their pressures are equivalent due to their direct contact. The inertial force between the two phases is ignored to ensure their equal pressures.

According to the first law of thermodynamics, the energy conservation equation of the hydrogen in the cylinder is derived as Eq. (1) [13].

$$\frac{dQ}{dt}+\frac{dm_s}{dt}h_s+\frac{dm_d}{dt}h_d=p_{gc}\frac{dV_{gc}}{dt}+\frac{d\left(m_{gc}u_{gc}\right)}{dt} \tag{1}$$

where m_s, m_d, and m_{gc} are the hydrogen mass through the suction valve, discharge valve, and in the gas cylinder, respectively. Q is the heat transfer, V_{gc} and p_{gc} represent the volume and pressure of the gas cylinder, respectively. h is the enthalpy, and u is the internal energy of the hydrogen.

The hydrogen mass variation is caused by the flow through the valves. The flow equation of the valves is written as Eq. (2).

$$q_m=K_vA_v\sqrt{2\rho\Delta p} \tag{2}$$

where q_m is the mass flow rate through the valve. K_v is the valve flow coefficient. A_v is the equivalent flow area of the valve aperture. ρ is the hydrogen density.

The inflow mass is defined as positive while the outflow is defined as negative. There is one suction valve and one discharge valve in the pneumatic part. Hence, the continuity equation is obtained as Eq. (3) [14].

$$\frac{dm_{gc}}{dt}=\frac{dm_s}{dt}+\frac{dm_d}{dt} \tag{3}$$

RKS equations are adopted for calculating hydrogen pressure. The variation of u_{gc} can be derived from Eq. (4).

$$\frac{du_{gc}}{dt}=\left(\frac{\partial u_{gc}}{\partial T_{gc}}\right)_v\frac{dT_{gc}}{dt}+\left[T_{gc}\left(\frac{\partial p_{gc}}{\partial T_{gc}}\right)_v-p_{gc}\right]\frac{dv_{gc}}{dt} \tag{4}$$

where T_{gc} is the hydrogen temperature in the cylinder. v is the specific volume of the hydrogen.

As to the control volume of ionic liquid, its pressure can be derived from Eq. (5).

$$\frac{dp_{il}}{dt}=\frac{B_{il}q_{il}}{V_{il}} \tag{5}$$

where p_{il}, B_{il}, and V_{il} are the pressure, bulk modulus and volume of the IL, respectively. q_{il} is the overflow rate of the control volume.

3.3 Model structure and main parameters

Fig. 3 illustrates the LPM of ionic liquid compressors. The pneumatic and hydraulic systems are modeled separately and then connected by the free piston. Customized components are built for calculating gas-liquid heat transfer, flow rates through the buffer structure and discharge valve. The main parameters are listed in Table 1.

Table 1. Main parameters

Parameter	Value
Diameter of the gas cylinder d_c (m)	0.100
Length of the gas cylinder l_c (m)	0.150
Suction pressure p_s (MPa)	0.5
Discharge pressure p_d (MPa)	1.0
Rotary speed of the pump n_{pp} (rpm)	300
Stroke length l_{stk} (m)	0.105

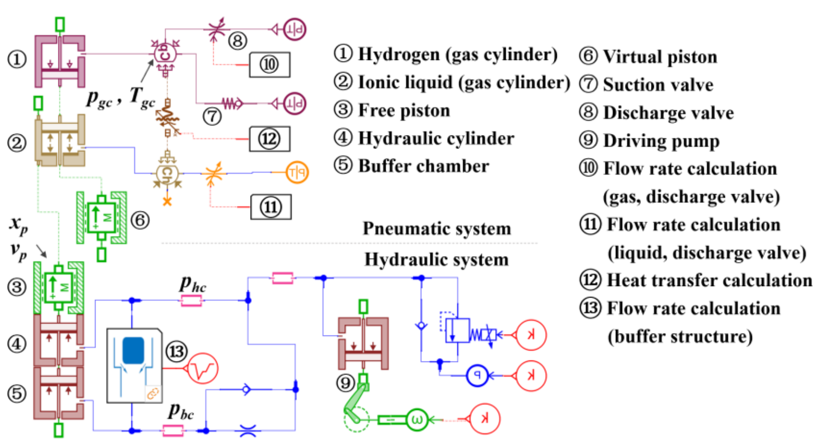

Fig. 3 Lumped parameter model of ionic liquid compressors

4. RESULTS AND DISCUSSION

$V_{s,il}$ is defined as the amount of IL supplement per working cycle. Multi-cycle simulations are performed under different $V_{s,il}$. Fig. 4 displays the variation of the liquid fraction inside the cylinder at the BDC $\alpha_{liq,BDC}$. Shown as the purple line ($V_{s,il}$ = 0.85 mL), $\alpha_{liq,BDC}$ will constantly decrease if there is little $V_{s,il}$ due to IL overflow

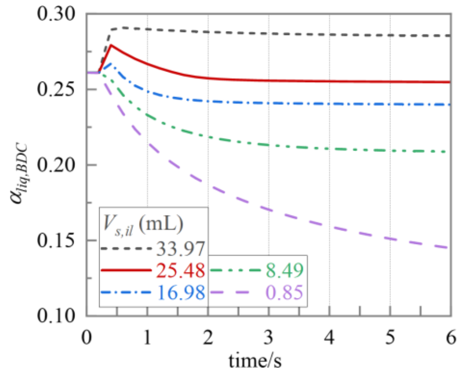

Fig. 4 Variation of liquid fraction at the BDC

through the discharge valve. IL is prone to flow out if its fraction increases. $\alpha_{liq,BDC}$ will finally become stable after a period of time, which means IL inflow and outflow reach equilibrium gradually. The power and capacity under steady states are recorded to further analyze the energy consumption of compressors.

The shaft power P_{sft} is defined as the power provided by the motor of the driving pump. It can be divided into four parts, shown as Eq. (6).

$$P_{sft} = P_g + P_{il} + P_{fri} + P_{hyd} \tag{6}$$

where P_g is the indicated power used for gas compression. P_{il} is the power used for IL flow. P_{fri} is the friction power. P_{hyd} is the power consumed for hydraulic transmission.

Fig. 5 illustrates the proportion of each part of P_{sft} under different $V_{s,il}$. Generally, P_g accounts for 62%~72%, which occupies the main portion of P_{sft}. P_{il} and P_{hyd} will increase as $V_{s,il}$ increases, resulting in a rise in P_{sft}. The efficiency of compressors is subject to the proportion of P_g since other parts belong to unnecessary energy loss. However, high P_g proportion does not strictly mean low energy efficiency since the capacity is not taken into consideration.

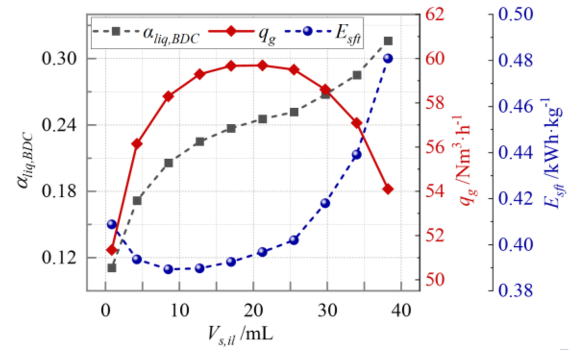

Fig. 6 Variations of specific power and capacity

To better analyze the energy efficiency, Fig. 6 shows specific power E_{sft} and capacity q_g under different $V_{s,il}$. E_{sft} is the ratio of P_{sft} over the gas mass flow rate. q_g is the gas volumetric flow rate under the standard condition. Illustrated as the red line in Fig. 6, q_g first increases and then decreases as $V_{s,il}$ increases. Small $V_{s,il}$ causes a large clearance volume at the BDC, leading to low q_g. Large $V_{s,il}$ results in high $\alpha_{liq,BDC}$, and then IL occupies more space at the suction stage, which is adverse to gas inflow. Displayed as the blue line in Fig. 6, E_{sft} is not minimal when there is little $V_{s,il}$ since the corresponding q_g is also low. Thus, decreasing $V_{s,il}$ can decrease P_{sft} but E_{sft} will rise if there is too little $V_{s,il}$. To balance energy consumption and capacity, the range of 10~20 mL for $V_{s,il}$ is optimal in this case.

5. CONCLUSIONS

In this paper, an energy consumption analysis of ionic liquid compressors is performed based on the lumped parameter model (LPM). Power proportions of all parts are presented, including gas compression, ionic

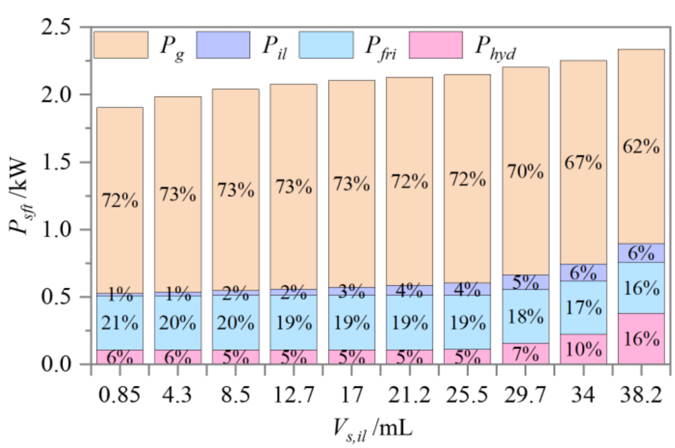

Fig. 5 Proportion of each part of the shaft power

liquid (IL) flow, friction, and hydraulic transmission. Moreover, specific power and capacity are obtained under different amounts of IL supplement. The main conclusions of this paper are as follows.

The liquid fraction inside the cylinder at the bottom dead center will finally become stable after a period of time, which means IL inflow and outflow reach equilibrium gradually.

The indicated power used for gas compression accounts for the main portion of the shaft power. The powers used for IL flow and hydraulic transmission will increase as the IL supplement amount increases, resulting in a rise in the shaft power.

Insufficient and excessive IL supplement can both decrease capacity of compressors. Decreasing IL supplement amount can decrease the shaft power but specific power will rise if there is too little supplement amount.

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