A Comparison of LVDT and RC Methods to Characterize the Performance of a Linear Compressor

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ABSTRACT

A recently employed approach for characterizing the PV power of a linear compressor using a resistive-capacitive (RC) type acoustic circuit is compared to the more conventional approach that utilizes linear variable displacement transducers (LVDT) mounted on the compressor pistons. Experiments using the two methods have been carried out and results show that both approaches agree well with calculations of the PV power at the piston face. In terms of absolute numbers, the PV power at the compressor outlet (that is the inlet of a regenerator) obtained by the RC approach is 5%~20% lower than the PV power on piston face obtained by the LVDT method. The RC load approach provides advantages such as simple assembly, non-contact, and the ability to simulate the impedance conditions of cold heads. In addition, it may provide a new method to investigate linear compressors losses.

INTRODUCTION

The linear compressor is the key component to ensure the long-life and high reliability operation of Stirling-type cryocoolers. It delivers an amount of PV power to a cold head. Typically this PV power is stated as the power at the face of the piston of the compressor rather than what is actually delivered to the cold head. Due to blow-by, irreversible heat transfer losses within the compressor, and pressure drops through transfer line and intrinsic flow channels in the compressor, the actual PV power delivered to the cold head is less than that measured at the face of the piston. In 2006, Bradley et al. measured the PV power difference between these two places in a linear compressor with a 4.3 cc swept volume[1]. They employed a hot wire anemometer and a lock-in amplifier to measure the losses and pointed that the magnitude of the losses was significant.

The RC load approach from thermo-acoustic field is introduced which is able to obtain the PV power at the outlet of the compressor directly. It was proved to be a feasible method to test the performance of linear compressors[2]. In this paper, experiments between LVDT and

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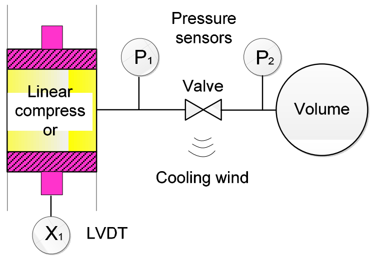

Figure 1. Schematic diagram of a RC load driven by a linear compressor

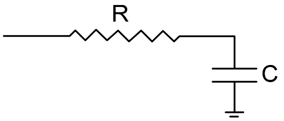

Figure 2. The equivalent circuit

RC load methods are carried with a linear compressor. Influences of impedance conditions, frequencies and charging pressures are investigated.

THEORETICAL ANALYSIS

RC Method

RC load is known as a resistive-capacitive (RC) type acoustic circuit which is widely employed to measure the PV power delivered in the thermo-acoustic field[3-5]. Recently it's also been proved to be a feasible method to test the performance of a linear compressor[2]. Figure 1 shows the schematic diagram of a RC load driven by a linear compressor. Its equivalent electrical circuit is shown in Figure 2.

When the system is operating, PV power delivered to the RC load is transformed into heat and taken away by cooling water. P1 and P2 are pressure sensors mounted before and after the valve. The capacitance of the load can be obtained by:

$$Z_c = \frac{1}{\mathrm{j}\omega C} = -\mathrm{j}\frac{\gamma P_0}{2\pi fV} \tag{1}$$

The volume flow rate of this in series system can be obtained as follow:

$$\vec{\dot{\boldsymbol{V}}}_c = \frac{\vec{\boldsymbol{P}}_2 - 0}{Z_c} = \frac{\mathrm{j}2\pi fV\,\vec{\boldsymbol{P}}_2}{\gamma P_0} \tag{2}$$

The resistance of RC load is:

$$R = \frac{\vec{\boldsymbol{P}}_1 - \vec{\boldsymbol{P}}_2}{\vec{\dot{\boldsymbol{V}}}_c} = \frac{\gamma P_0 |P_1|}{2\pi fV|P_2|}\sin\theta_{P_1-P_2} \tag{3}$$

So the PV power at the compressor outlet can be expressed as:

$$W_{pv} = \frac{1}{2}\mathrm{Re}\left[\vec{\boldsymbol{P}}_1 \vec{\dot{\boldsymbol{V}}}_c^{\,*}\right] = \frac{2\pi fV}{2\gamma P_o}\mathrm{Im}\left[\vec{\boldsymbol{P}}_1 \vec{\boldsymbol{P}}_2^{\,*}\right] = \frac{\pi fV}{\gamma P_0}|P_1||P_2|\sin\theta_{P_1-P_2} \tag{4}$$

where f is the frequency, P_0 is the mean pressure, V is the buffer volume, γ is the specific heat ratio, $\theta_{P_1-x_1}$ is the included angle between P_1 and P_2, the arrow and bold indicates vector, and * denotes complex conjugation. During the experiment, f, V and P_0 are known. The PV power can be obtained only by measuring the amplitude of P_1 and P_2 as well as their included angle. Hence, this is a non-contact approach which is easy to assemble. Besides, various load conditions can be obtained with this method.

LVDT Method

LVDT (linear variable displacement transducer) is one of the frequently-used piston position sensors. It's mounted directly on the piston(s) to obtain the displacement. With this more conventional approach, the PV power at the face of piston(s) can be expressed as:

$$W_{pv} = 2\times\frac{1}{2}\mathrm{Re}\left[\vec{\boldsymbol{P}}_{\boldsymbol{1}}\vec{V}^{*}\right] = 2\pi f A|P_1||x_1|\cos\theta_{P_1-x_1} \quad (5)$$

where x_1 is the piston displacement amplitude, $\theta_{P_1-x_1}$ is the included angle between P_1 and x_1,2 indicates that this is a dual opposite linear compressor.

The PV power obtained from the RC load method is the PV power delivered at the compressor outlet. While the PV power obtained from the LVDT method is that at the piston face. There are blow-by[6], irreversible heat transfer losses within the compressor[7], and pressure drops through transfer line and intrinsic flow channels in the compressor between these two places[8]. These losses are difficult to calculate or even measure. Bradley, et al. divided these losses into pressure losses and flow losses, measured each of them and indicated that the PV power delivered is about 60%-80% of the PV power at the piston face due to their measurement[1]. In this paper, RC load method is used to obtain the PV power delivered directly which is a more convenient when compared with their method.

EXPERIMENTAL RESULTS

Frequency Dependency

In this experiment, an opposed linear compressor with a swept volume of 1.8 cc is employed. There is a LVDT sensor mounted at each end of the pistons, and two pressure sensors P1 and P2 are used. Generated heat is taken away by the cooling wind. Our RC loads are consisted by PISTON needle valves and different reservoir volume (50 cc, 100 cc and 250 cc).

Figure 3 shows the comparison results of frequency and load impedance (R) dependency of efficiency between the two methods. The calculation results are also shown here. The charging pressure is 2.5 MPa, and a 250 cc volume is used here. The load impedance is adjusted through regulating the valve. It's shown that the trends of both experimental approaches agree well with calculations of the efficiency at the piston face. For these three kinds of curves, the efficiencies increase first and then decrease as R increases. For each frequency, there is an optimum R to obtain the highest efficiency. This optimum R shifts to a higher value as the frequency increases. The best efficiency occurs at 40 Hz with the R of about 3.5×108 Pa·s/m^3. This should be the operation frequency and impedance of a cold head designed in order to match well with this linear compressor. On the other hand, it's also shown that the highest efficiency at the compressor outlet and the piston face are only 51% and 65% respectively, although the best efficiency designed is as high as 82%.

Figure 4 shows the measured efficiency difference of these two approaches. In our experimental range, these differences are between 5%-20% of the total input electrical power. The difference increases as R increases. Figure 5 shows the efficiency ratio of these two approaches. In our experimental range, these ratios are between 60%-80%, which agree well with the results by Bradley[1].

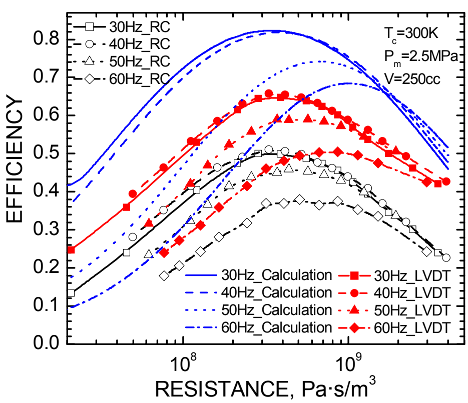

Figure 3. Comparison of frequency dependency between two methods

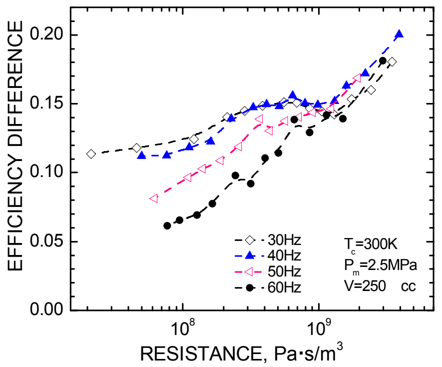

Figure 4. Efficiency difference of two approaches

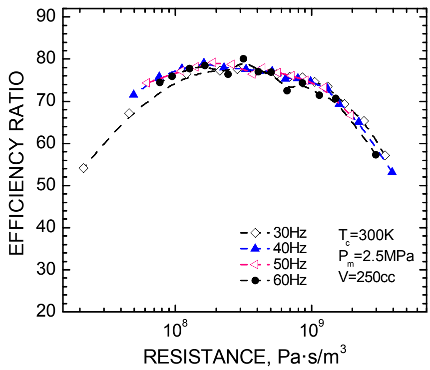

Figure 5. Efficiency ratio of two approaches

It's also shown that there is difference between the LVDT measurement results and the calculations of the PV power at the piston face because some losses are not taken into account in our calculation model, such as the iron loss (including hysteresis loss and eddy current loss) and the windage loss. On the other hand, the pressure sensor P_1 is located at the compressor outlet and not the piston face: there is a pressure drop between these two places which induces related difference.

What should be pointed out was that in Bradley's experiment, not only pressure sensors were needed, but also a hot wire anemometer was employed to measure the mass flow delivered to the cold head, and a lock-in amplifier was applied to measure the phase angle between the pressure and volume velocity. In our experiment, only two pressure sensors are needed with RC load method to obtain the absolute PV power delivered from the compressor, which is more convenient and simple. Besides, impedance dependency can be investigated with RC approach.

Pressure Dependency

Figure 6 shows the comparisons between charging pressures from 1.5 MPa to 2.5 MPa. It's indicated that for three kinds of efficiency, the charging pressure has weak influence on the results. For each approach, the curves are almost overlapped.

Volume Dependency

The effect of different volumes is shown in Figure 7. With different volumes, the imaginary part of the load impedance Z_c is different. For calculations, the result of a 50 cc volume is better. For LVDT results, the curves of three volumes are overlapped. As for RC measurements, the results of 100 cc is better while 50 cc is worse. That's because a smaller volume can't guarantee

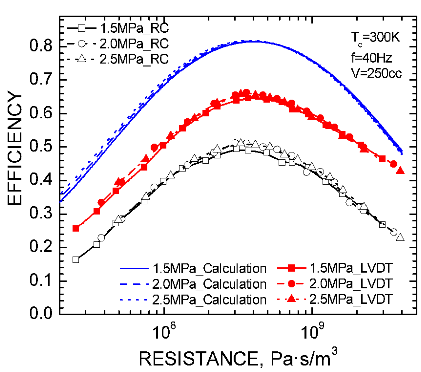

Figure 6. Comparison of pressure dependency

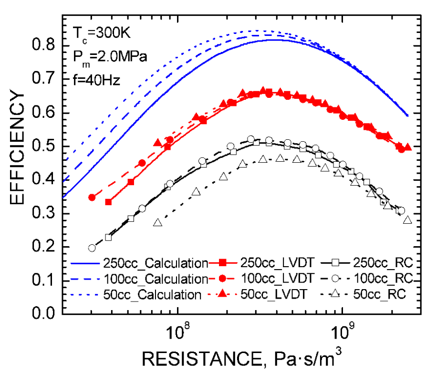

Figure 7. Comparison of volume dependency

an adiabatic process of the working gas inside, which leads to a smaller γ value that will influence the PV power value from equation (4). On the other hand for a smaller volume, the dead volume of the system can no longer be ignored and will induce a larger deviation.

CONCLUSION

RC load method is a feasible method to test the performance of a linear compressor. It's simple and more convenient compared with LVDT and hot wire anemometer methods. Various impedance conditions can also be simulated which is important for designing a cold head. Comparisons are made between RC and LVDT approaches, and dependency of results on frequency, R, charging pressure and volume are investigated. In our experimental range, results from two methods agree well with calculations. What's more, PV power at the compressor outlet (obtained by RC method) is 5%-20% lower than that of the PV power on piston face (obtained by LVDT method).

ACKNOWLEDGMENT

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