Evaluation of Total Pressure Oscillator Losses

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ABSTRACT

The ratio of piston PV power to the electrical input power typically has been used to define compressor efficiency for regenerative cryocoolers. This definition ignores blowby, irreversible heat transfer, and flow losses within the compressor. A new total loss method redefines compressor efficiency by subtracting the mechanical losses from the PV power at the piston face. The total loss method consists of a set of simple measurements. One measurement accounts for pressure losses within the compressor by measuring the electrical and PV power required for a blanked-off compressor for a given pressure ratio. The second accounts for flow losses by measuring the electrical and PV power for a given stroke with the compressor connected to a large reservoir. The sum of these mechanical losses subtracted from the PV power measured at the piston face gives the estimated PV power delivered to an attached load. In this work we evaluate the total loss method for a moderate size pressure oscillator with a swept volume of 4.3 cm^3. We compare these estimates with system measurements using hot wire anemometry at the compressor outlet to determine the PV power delivered by the compressor to a load. We also determine the significance of these losses as they relate to compressor charge pressure and operating frequency. We report on measurements for mean pressures from 1.5 to 2.5 MPa, pressure ratios from 1.0 to 1.3, frequencies of 30, 40, 50, 60, and 70 Hz, and the corresponding mass flows.

INTRODUCTION

Stirling and pulse tube cryocoolers utilize pressure oscillators (compressors) to produce oscillating pressure and mass flow to deliver PV power to the cold head. Typically, this PV power is referred to as the power generated at the face of the piston(s) of the compressor. This differs from what is actually delivered to the cold head. In the past this has lead to inconsistencies about what defines the efficiency of the compressor and/or system leading to misunderstanding about improving overall cryocooler efficiency. Mechanical losses arise from blow-by and irreversible heat transfer within the compressor along with pressure drops through transfer lines and intrinsic flow channels in the compressor. PV power at the piston face(s) neglects these mechanical losses, thereby leading to

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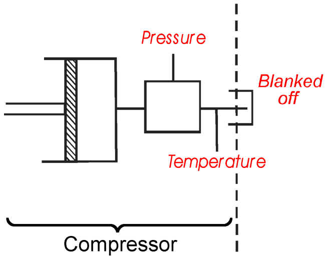

Figure 1. Experimental setup for pressure loss measurement.

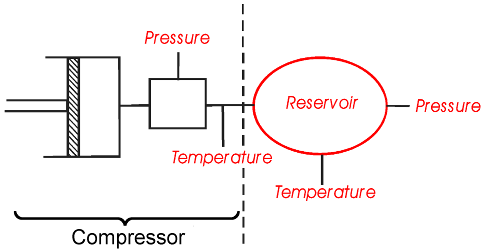

Figure 2. Experimental setup for flow loss measurement.

a poor definition of compressor efficiency as solely the ratio of PV power at the piston(s) face divided by the electrical input power. Subtracting these losses from the power at the piston face arrives at a much better definition of the true power delivered to the cold head. Thus, a more accurate definition for the efficiency is the ratio of delivered PV power divided by the electrical input power accounting for the mechanical losses.

PRESSURE OSCILLATOR LOSSES

Loss Measurement Technique

Previously, we discussed preliminary work on a simple set of measurements to more accurately evaluate the total loss within a compressor using simple instrumentation consisting of pressure transducers, temperature sensors, and an available method to determine instantaneous piston position (or volume variation)[1]. In this work we further demonstrate this technique through more extensive measurements over a wider range of frequency and charge pressure.

When discussing delivered PV power, both pressure and flow losses must be considered. The pressure losses arise from the irreversible heat transfer between the gas and walls in void spaces within the compressor and the blow-by at the piston seals. Flow losses result from pressure drops through transfer lines and intrinsic flow channels within the compressor. While a measurement of the total for these losses would suffice, we are unable to simply measure the total, so we must separate them to an appropriate extent. Thus, we first consider only the pressure losses, measuring the lost PV power accordingly. Next, we consider the flow losses and measure the lost PV power as well. Although this second measurement will include a small pressure loss component, we account for it by subtracting it from the initial flow loss measurement.

Mechanical losses may be characterized for any compressor and are independent for a system with a cold head attached. Thus, for any combination of compressor and cold head the PV power delivered to the load is expressed as

$$\dot{W}_{delivered} = \dot{W}_{PV,piston} - \dot{W}_{PV,p} - \dot{W}_{PV,m}, \tag{1}$$

where $\dot{W}_{PV,\,piston}$ is PV power at the piston with a load, $\dot{W}_{PV,\,p}$ is the lost PV power due to pressure losses, and $\dot{W}_{PV,\,m}$ is lost PV power due to flow losses.

Pressure losses can be evaluated by establishing pressure amplitude without introducing flow, as depicted in Figure 1 by capping off the compressor and measuring the PV power at the piston face as a function of pressure amplitude. As there is little or no volume for flow there are no flow losses incurred in this measurement. Flow losses can be evaluated by establishing flow without introducing pressure amplitude in the compressor, as shown in Figure 2 by adding a sufficiently large reservoir volume onto the compressor outlet. A small pressure loss component is embedded in this measurement. We account for this by evaluating the pressure amplitude as a function of mass flow. For a given mass flow the pressure amplitude correlates to a PV power loss of the pressure loss measurement. This is then subtracted to arrive at the final flow loss.

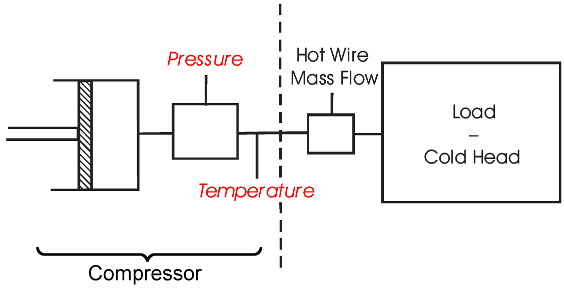

Figure 3. Measurement setup and instrumentation for load and measurement validation.

PV Power

PV power measured at the piston is determined from

$$\dot{W}_{PV,piston} = \frac{1}{2} P_1 \dot{V}_1 \cos\phi, \tag{2}$$

where P_1 is the dynamic pressure amplitude, $\dot{V}_1$ is the amplitude of the volume velocity, and ϕ is the phase angle between the pressure and the volume velocity. For this work the pressure amplitude is measured using piezoresistive pressure transducers, the instantaneous volume velocity is measured directly by linear variable displacement transducers (can be done indirectly employing the electrical analogy[2]), and the phase angle between pressure and volume velocity is found by using either an oscilloscope or lock-in amplifier. Employing Eqs. (1) and (2) with the measurements described leads to simple calculations for the PV power at the piston thereby arriving at the important delivered power.

Measured PV Power – Method Validation

We now validate this total loss method by measuring the PV power delivered to a load (cold head in this instance previously optimized for a similarly sized compressor[3]) as shown in Figure 3. We accomplish this by using a hot wire anemometer to measure the mass flow delivered to the load, a pressure transducer to measure the pressure amplitude at the compressor, and a temperature sensor placed between the compressor and cold head to measure the gas temperature. From these simple measurements we may then calculate the delivered PV power to the cold head from

$$\dot{W}_{measured} = \frac{1}{2} RT \frac{P_1}{P_0} \dot{m}_1 \cos\phi, \tag{3}$$

where R is the gas constant for helium, T is the temperature of the gas, P_1 is the pressure amplitude, P_0 is the mean pressure, $\dot{m}_1$ is the mass flow amplitude, and ϕ is the phase angle between the pressure and the mass flow. Calibration of the hot wire was accomplished in accordance with the method described by Lewis et al.[4]

MEASUREMENTS AND DISCUSSION

Losses – Pressure and Flow

Measurements for the flow ('with reservoir' setup) and pressure ('blanked off' setup) losses were made as shown in Figures 1 and 2 with a moderate sized 4.3 cm^3 pressure oscillator (maximum swept volume). The mean charge pressures were 1.5, 2.0, and 2.5 MPa and the frequencies were 30, 40, 50, 60, and 70 Hz. For the flow loss measurements the volume of the reservoir was 578 cm^3. Plots of the flow losses for pressures of 2.5, 2.0, and 1.5 MPa for all 30-70 Hz frequencies are presented in Figures 4, 5, and 6. As expected, flow losses decrease slightly as the mean pressure is

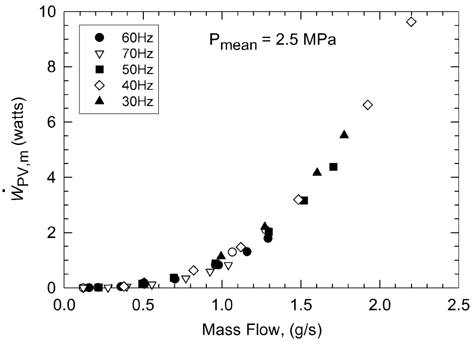

Figure 4. Flow losses for 2.5 MPa P_{mean}.

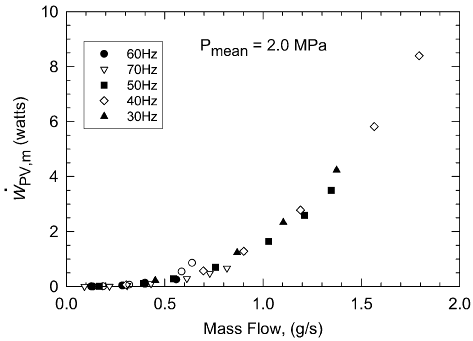

Figure 5. Flow losses for 2.0 MPa P_{mean}.

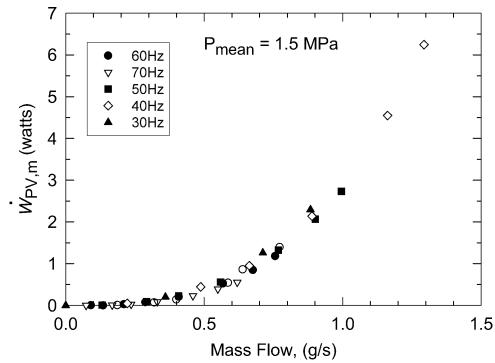

Figure 6. Flow losses for 1.5 MPa P_{mean}.

lowered. The flow losses shown appear to be rather large until one realizes that for normal operation with pressure ratios of 1.0 to 1.3 the corresponding mass flows are not high at all As such the highest flows experienced for operation with the cold head were around 1 g/s or less. Thus the real flow losses were quite low—on the order of 1% or less of the electrical input power. These losses are significantly lower than the pressure losses—an order of magnitude lower or more. Figures 4, 5, and 6 also show that, for a given mean pressure, these losses are rather independent of frequency as well.

The pressure losses on the other hand are fairly large as shown in Figures 7, 8, and 9. In fact, these losses grow to be quite sizeable as the mean charge pressure drops from 2.5 MPa down to 1.5 MPa. For this setup at 2.5 MPa, the losses grow from about 2.5% of the electrical input power at 30 Hz to over 25% at 70 Hz. A similar trend occurs for both 2.0 MPa and 1.5 MPa, as well as with greater increase in the losses occurring for the lower charge pressures. Thus, for a given pressure amplitude, the pressure losses increase with increasing operating frequency. This suggests that the overall efficiency for the compressor is highest at the lower frequencies of 30 to 40 Hz, as the losses are fairly low. This is certainly expected for a compressor of this type originally designed for 30 to 40 Hz nominal operation.

We observe here that the pressure losses certainly dominate the mechanical losses investigated here. They are at least an order of magnitude greater than the flow losses at any given operating mean pressure which might encourage the reader to disregard them altogether. We suggest that while this may not contribute to a reduction of more than a few percent in the accuracy for the total loss method it is an unwise practice nonetheless, particularly as this may not always be the case for every compressor and/or system. One particular advantage for conducting the flow loss measurements is they may be used to correlate the mass flow at the piston. From these measurements we find that the

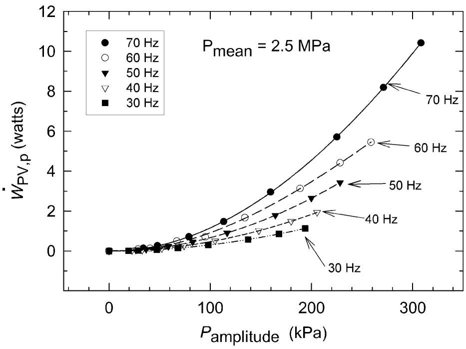

Figure 7. Pressure losses for 2.5 MPa P_{mean}.

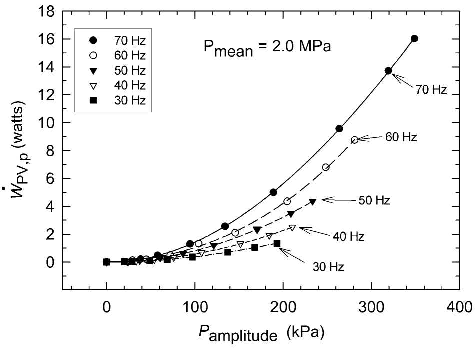

Figure 8. Pressure losses for 2.0 MPa P_{mean}.

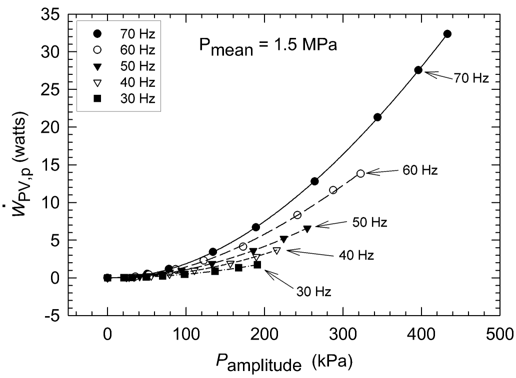

Figure 9. Pressure losses for 1.5 MPa P_{mean}.

flow at the piston only deviates from the reservoir by about 10%. As such, a sizable error in the mass flow at the piston results in an error of only 5% for the total loss calculated using Eq. 1 for the representative load. Again this may not always be the case for other compressors and/or systems, so it is wise to consider this during the flow loss measurements.

Delivered PV Power – Calculated vs. Measured

Having completed the loss measurements, we now arrive at a calculated value for the delivered power using Eq. 1 for the representative load (cold head). We now wish to consider the value of this method by comparing these results with the measured PV power derived from the hot wire anemometer. For an ideal case, there would be no mechanical losses, so the PV power calculated at the piston would be equal to the measured power at the hot wire (cold head). Thus, if we consider a ratio of the "delivered" power divided by the "piston" power for and ideal case, the efficiency of transmitting power at the piston to the load would be 100%. In reality, we find there are mechanical losses, so the best way to evaluate this method is to take the ratio of the delivered power (whether by calculating using Eq. 1 or by the measured value with the hot wire anemometer) divided by the idealized power calculated at the piston.

Figures 10 to 14 show the ratio of the delivered PV power divided by the piston PV power plotted as a function of the piston PV power for frequencies from 70 to 30 Hz, respectively. For each frequency we observe that there is no apparent dependence upon mean charge pressure. So for a given mean charge pressure, the ratio of delivered to piston PV power is not affected by operating frequency, as Figures 10-14 clearly show. The total loss calculation discussed here predicts values that are within 15% of the measured value for 70 Hz and improves dramatically to within only a few

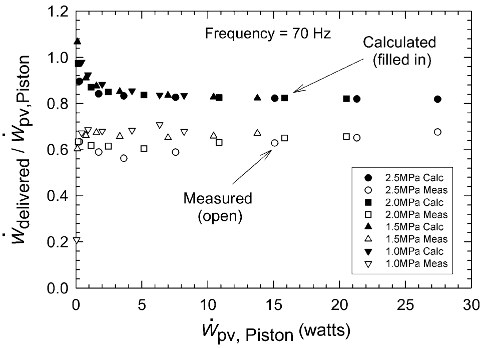

Figure 10. Total loss Calc'd. vs Meas'd. @ 70 Hz.

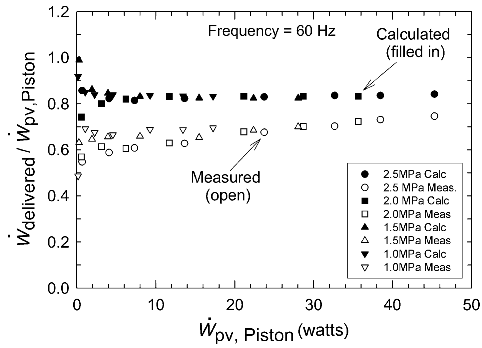

Figure 11. Total loss Calc'd. vs Meas'd. @ 60 Hz.

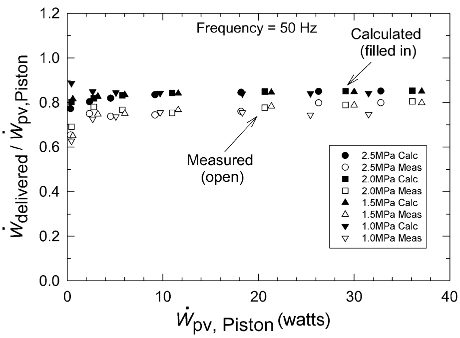

Figure 12. Total loss Calc'd. vs Meas'd. @ 50 Hz.

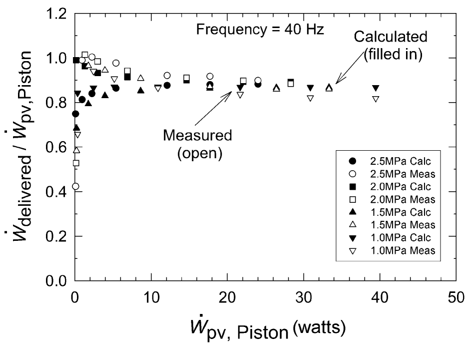

Figure 13. Total loss Calc'd. vs Meas'd. @ 40 Hz

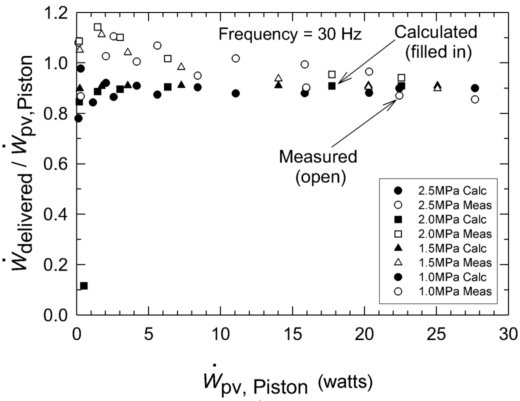

Figure 14. Total loss Calc'd. vs Meas'd. @ 30 Hz.

percent at lower frequencies such as 30 and 40 Hz. The calculated and measured values are fairly constant over a fairly large range of PV power at the piston. However, for values below about 10 watts, there is considerably more inaccuracy in the values that correspond with higher inaccuracies in the mass flow and phase angle between mass flow or pressure and volume velocity. We show these values to clearly demonstrate the range over which this method may be accurately employed. At 30 and 40 Hz, the calculated and measured ratio of delivered to PV power nearly agree within just a few percent. This correlates with the lower pressure losses experienced at lower frequencies as expected, as the efficiency for the compressor increases at these frequencies for which it was designed. This trend is apparent when reviewing the relative pressure losses at all frequencies and correlating them with the corresponding ratio of delivered to piston PV powers. We observe then that the measured PV power validates the total loss method, as it is only about 15% less accurate than the direct cold head load measurements at 70 Hz and within just a few percent at 30 and 40 Hz. This then gives us a better estimate and definition for compressor efficiency as the ratio of the delivered power divided by the electrical input power.

CONCLUSION

We have demonstrated a method using simple measurements that can evaluate important pressure and flow losses within Stirling-type compressors. This method leads to a more accurate estimate for delivered PV power and a better more accurate definition for the efficiency of such compressors. The measurements needed to provide meaningful information about the PV power that can be delivered to a load require little instrumentation (pressure sensors, temperature sensors, a reservoir volume, and instrumentation to measure the instantaneous voltage and current of the compressor) and minimal modification to existing compressor components or systems. With this information we can better understand compressor losses and the real power transmitted to cold heads, thereby understanding to a greater extent the losses and inefficiencies for the overall system.

The total loss method demonstrated here shows that the PV power delivered to the cold head is less than the PV power at the piston, which is routinely referenced to define compressor efficiency. For the moderate-size 4.3 cm^3 compressor evaluated here this simple calculation for the delivered PV power is about 70 percent of the piston PV power and is only a few percent (at 30 Hz) to 15 percent (at 70 Hz) larger than that of the direct measurements of the delivered power. This total loss method eliminates the complexity and expense for special instrumentation to measure the delivered power. This feature alone can aid in evaluating and troubleshooting systems/components at an early development state without significant investment of time and expense. This method should be used consistently in reporting experimental results, thereby unifying the wide range of cryocooler efficiency data reported in the literature.

ACKNOWLEDGMENT

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