CFD Simulation and Experimental Validation of a Diaphragm Pressure Wave Generator

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ABSTRACT

Industrial Research Ltd has been developing a low-cost diaphragm pressure wave generator for cryocoolers since 2004. Thermodynamic losses in the pressure wave generator can have a significant impact on the overall efficiency of a cryocooler. To help characterize the thermodynamic losses, a two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in the diaphragm pressure wave generator. The ANSYS-CFX commercial code was utilized for the 2-D model. A series of validation experiments were conducted on an apparatus consisting of a diaphragm pressure wave generator connected to four cylindrical spaces with the same volume but different diameters (40mm, 60mm, 80mm and 100mm). Volume and pressures at different locations were measured for both helium and nitrogen gas over a range of frequencies. The pressure and volume measurements were used to calculate hysteresis loss. Good agreement was achieved between the CFD simulations and the validation experiments. The model will be used to increase the efficiency and optimize the design parameters. Results obtained from CFD simulations and validation experiments are presented and discussed in this paper.

INTRODUCTION

Industrial Research Ltd has been developing a low-cost diaphragm pressure wave generator for cryocoolers since 2004.[1] Thermodynamic losses in the pressure wave generator can have a significant impact on the overall efficiency of a cryocooler. Understanding of these losses is essential to accurate prediction of the performance of many reciprocating machines.

Heat transfer related hysteresis loss is one of the most important losses for reciprocating machines. It has been studied analytically and experimentally since the 1980s[2], and good correlations have been made for the losses in a simple piston-cylinder system like a gas spring.[3, 4] For a diaphragm pressure wave generator, the ratio of bore diameter to stroke is normally larger than for other types of pressure wave generators. This causes the fluid flow in it to experience more abrupt changes in cross-section while integrating with the cold head. As a result, there is a lack of conclusive understanding of the hysteresis losses in this complex geometry. Thus, the hysteresis loss in a diaphragm pressure wave generator is difficult to predict.

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Computational Fluid Dynamics (CFD) is a powerful tool for investigating complex fluid flow and heat transfer. It also can greatly reduce the extent and number of experiments required for the development of a product. To help characterize the thermodynamic losses, a two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in a diaphragm pressure wave generator. A series of validation experiments was conducted on an apparatus consisting of a diaphragm pressure wave generator connected to four cylindrical spaces with the same volume, but different diameters.

BACKGROUND AND PRELIMINARY VALIDATION

Gas Spring Hysteresis Losses

Lee[2] developed an analytical model for the hysteresis loss based on the solution of the one-dimensional transient conduction equation. The cyclic lost work can be expressed as

$$Loss = \frac{\pi}{2} P_0 V_0 \left(\frac{P_a}{P_0}\right)^2 \frac{\gamma - 1}{\gamma} \left(\frac{1}{y}\right) \frac{\cosh y \sinh y - \sin y \cos y}{\cosh^2 y - \sin^2 y} \tag{1}$$

where P_0 is the pressure at mid-stroke, V_0 is the volume at mid-stroke, P_a is the amplitude of pressure, γ is the ratio of specific heats of gas, ω is the angular velocity, D_h is the hydraulic diameter, and α is the thermal diffusivity of gas at mid-stroke. The symbol y is defined by

$$y = (Pe_{\varpi}/8)^{1/2} \tag{2}$$

where Pe_{ω} the oscillating Peclet number

$$Pe_{\omega} = \frac{\omega D_h^{\ 2}}{4\alpha} \tag{3}$$

To improve the correlation with experimental data, Kornhauser and Smith[4] suggested y, as defined by Equation (2), be replaced by

$$y = 0.49 Pe_{\varpi}^{\ 0.43} \tag{4}$$

Following Lee's analysis, Kornhauser[4] proposed a non-dimensional cyclic lost work as a function of oscillating Peclet number

$$Loss_{nd} = \frac{\oint PdV}{P_0 V_0 \left(\frac{P_a}{P_0}\right)^2 \left(\frac{\gamma - 1}{\gamma}\right)} \tag{5}$$

Preliminary Validation

ANSYS CFX is the commercial CFD package used in this study. When integrated with the ANSYS workbench platform, it provides geometry and mesh tools, pre- and post processors and an advanced solver using coupled algebraic multigrid. It is capable of modeling compressible flows in a closed volume with a moving boundary using 2D or 3D geometries.

Preliminary validation was performed using ANSYS CFX to simulate single compression space experiments by Kornhauser.[3] Kornhauser's test rig consisted of a cylindrical space mounted on a compressor base, which had a piston diameter of 50.8mm and a piston stroke of 76.2mm. A 2D axisymmetric approximation of the rig is represented by a 5^{o} portion of the cylinder with a one-layer mesh in ANSYS CFX. The geometry is meshed by 14520 elements, and 200 to 400 time-steps were used. Isothermal boundary conditions and a laminar model were applied in the simulations. Seven cases were calculated with a range of oscillating Peclet numbers from 0.62 to 952. All the cases simulated were at a compression ratio of 2.0, with helium as the working gas.

Figure 1 shows the non-dimensional loss plotted versus the oscillating Peclet number for the CFX simulations together with Kornhauser's data. The solid line is calculated using Equation (1). It appears that the CFX results agree quite well with the experimental data and with the predictions from Equation (1). It is suggested by analytical, numerical, and experimental results that at higher

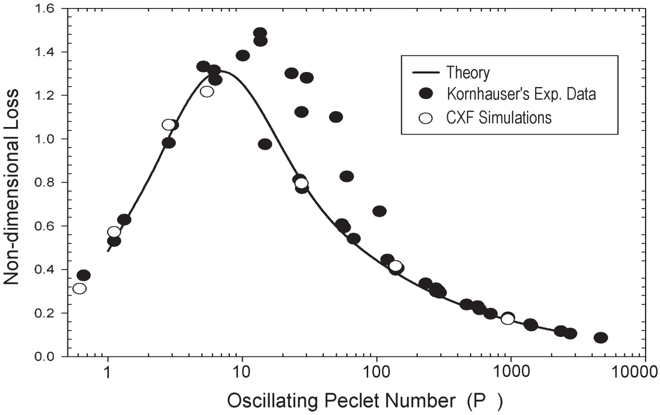

Figure 1 Comparison CFX results with Kornhauser's experimental data

Peclet number, hysteresis loss is less where the process is nearly adiabatic. It is surprising that when using a laminar model, the CFX results at higher Peclet numbers in Fig. 1 still fit very well with the experimental data. This may be attributable to the fine mesh and small time-steps used.

EXPERIMENTAL SETUP

Figures 2(a) and 2(b) show a cross-section and photograph of the experimental setup, respectively. The apparatus used in these experiments consists of a diaphragm pressure wave generator connected to four cylindrical spaces with the same volume but different diameters (40mm, 60mm, 80mm and 100mm). The volume of the cylindrical spaces is 490ml. The diaphragm pressure wave generator used in this work is a model CHC200, which has a swept volume of 200ml, a nominal bore diameter of 320mm, and piston stroke of 2.5mm. The detailed specifications have been described previusly by Caughley.[1]

Pressures were measured with three high frequency pressure sensors with a range of 500 psia. They are flush-mounted at three different locations as shown in Figure 2(a). Sensor P2 is installed on the top of the buffer volume, while the other two (P1 and P3) are installed on the top plate of the compression volume. P1 is approximately 150 mm from the centerline of the piston, and P3 is 80 mm from the centerline of piston. The volume was calculated from the displacement of the piston as measured by an eddy current displacement sensor based on the assumption that the volume

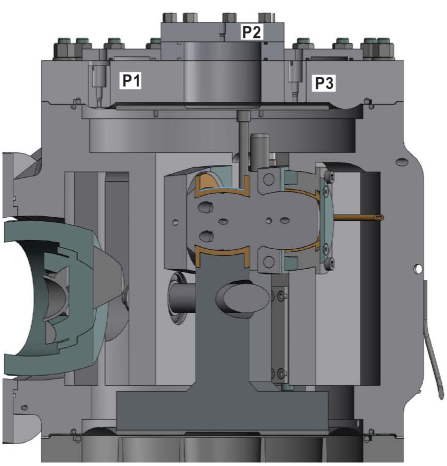

Figure 2(a) Cross-section of experimental setup

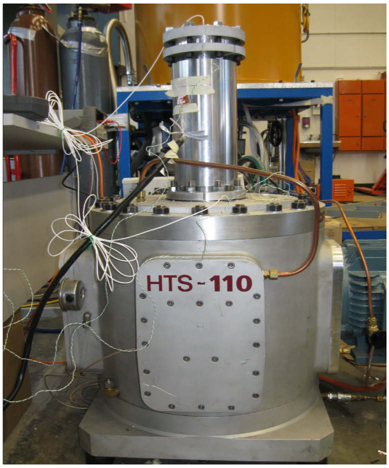

Figure 2(b) Photo of experimental setup

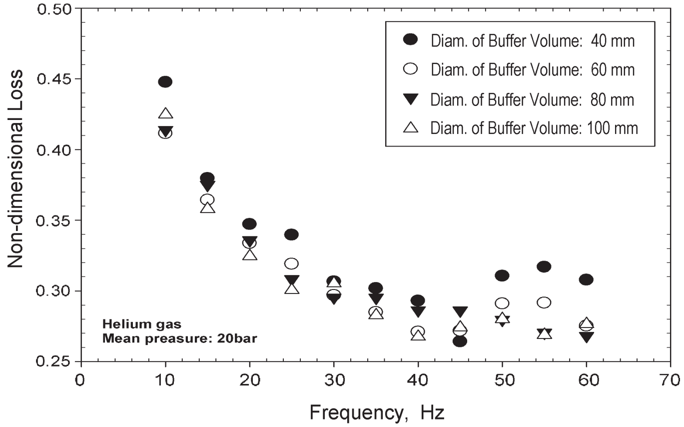

Figure 3. Non-dimensional losses versus frequency (Helium)

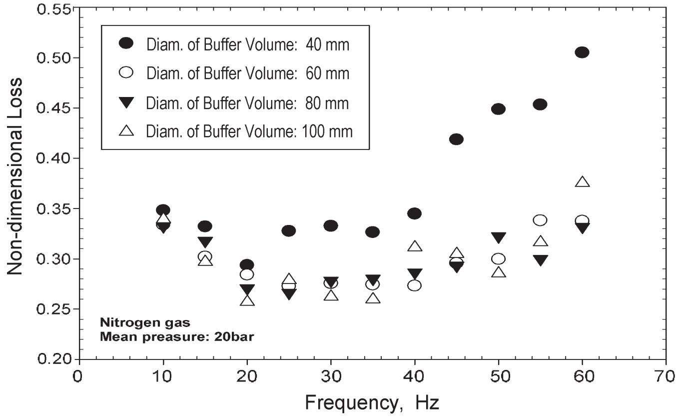

Figure 4 Non-dimensional loss versus frequency (Nitrogen)

varies linearly with the displacement of the piston. Instantaneous measurements were recorded by a DPO3000 oscilloscope with four channels. During each cycle, more than 200 pressure volume data points were collected. Static pressure was measured with an RS461 pressure transducer.

Volume and pressures at different locations were measured for both helium and nitrogen gases from 10 Hz to 60 Hz at a charging pressure of 20 bar. The cyclic loss was calculated by integrating *PdV* over the cycle. The non-dimensional cyclic loss was calculated using Equation (5).

EXPERIMENTAL RESULTS

Non-dimensional cyclic losses plotted against frequency for different buffer volumes are compared in Figure 3. The results shown in Figure 3 were measured for helium at point P3. For all buffer volumes, the non-dimensional loss decreases with increasing operating frequency for frequencies less than 50 Hz. Figure 3 also shows that the non-dimensional loss decreases as the buffer volume diameter increases.

Figure 4 shows the non-dimension loss plotted versus frequency for nitrogen. For all buffer volumes, the non-dimensional loss drops gradually with increasing frequency for frequencies less than 20 Hz. After that, the non-dimensional loss rises with increasing frequency for buffer volumes with a diameter from 60mm to 100mm. At the same time, the non-dimensional loss increases significantly with increasing frequency for the smallest diameter volume. Figure 4 also shows that the non-dimensional loss is largest for the smallest buffer volume diameter.

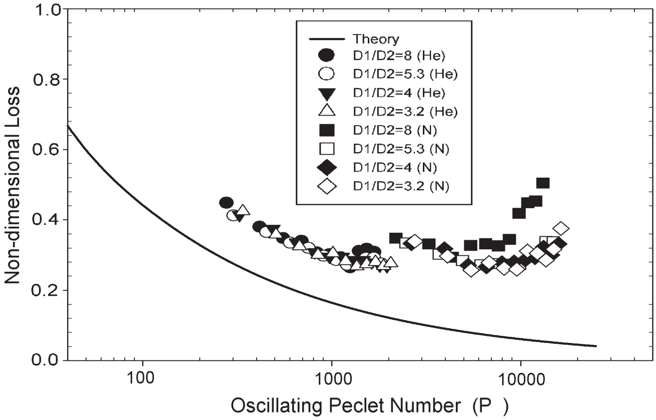

Figure 5 Non-dimensional losses versus oscillating Peclet number (Helium and Nitrogen)

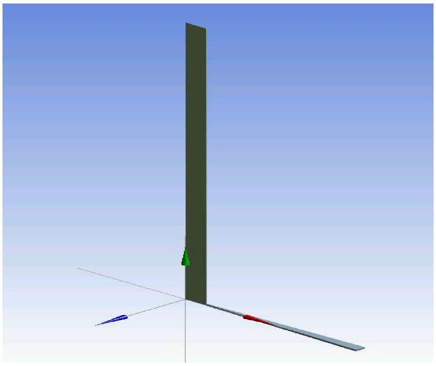

Figure 6 2D axisymmetric model of the experiment

Figure 5 shows that the non-dimensional loss plotted against the oscillating Peclet number for Helium and Nitrogen. In Figure 5, D1 is the diameter of the compression volume, and D2 is the diameter of the buffer volume. The solid line is calculated using Equation (1). The results show that the non-dimensional loss measured for a complex geometry with an abrupt cross-section change is larger than that predicted by Equation (1). At an oscillating number less than 10000, the results still follow the trend predicted by Lee. However, at an oscillating Peclet number larger than 10000, the non-dimensional loss rises significantly with an increase of the Peclet number.

COMPARISSION WITH CFD RESULTS

CFD Modeling

A two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in a diaphragm pressure wave generator. Figure 6 shows the 2D axisymmetric model representing the validation experiment, which is connected to the buffer volume with a diameter of 40mm. The geometry used in the model is a 3^{o} portion of the cylinder, and it is meshed using 14520 elements. 2000 time-steps were used, and isothermal boundary conditions were applied in the simulations. Five cases were calculated with a range of frequencies from 5 Hz to 100 Hz. Both laminar and K-ω turbulent models were used for all the cases.

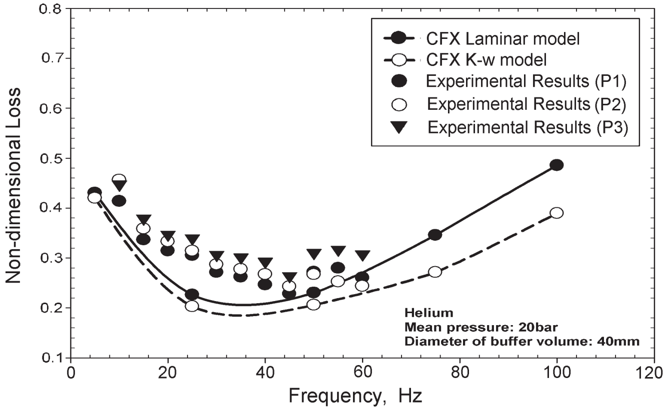

Figure 7 Comparison experimental data with CFX results

Figure 7 shows the non-dimensional loss plotted versus frequency for the CFX simulations together with the experimental data. The CFX predictions fit very well with the experimental data. Similar results were obtained at low frequencies for both laminar and K-ω turbulent models.

CONCLUSION

A two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in a diaphragm pressure wave generator. Good agreement was achieved between the CFD simulations and the validation experiments. Both the simulations and the experiments show that the hysteresis loss rises with increasing Peclet number in a piston-cylinder system with abrupt contraction in the cross section.

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