Recent Progress with an Adjustable Inertance Tube

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ABSTRACT

The cylindrical threaded adjustable inertance tube creates an acoustic element using the engagement of two threads. It is therefore possible to change the characteristics of the element easily and during operation by adjusting the rotational position of the outer screw thread. The threaded adjustable inertance tube has the capability to shift the phase angle between pressure and flow between 0 and -30 degrees, as demonstrated by previously reported experimental test results and supported by predictions made using the distributed component model. However, the performance of the current iteration of the device is limited by the leakage paths that are inherent between the engaged threads of the two screws. Since the working fluid flows through the leak to the average pressure in the channel formed by the root of the two screws, it is reasonable to connect these two flow channels in parallel to eliminate the leakage effect. Therefore, this paper reports the performance of the parallel threaded adjustable inertance tube using the appropriately modified distributed component model by eliminating the leaks terms and introducing another inertance tube in parallel with the original one. The preliminary modeling results suggest that the phase angle shift ability of the modified device will increase from -65 degrees to +40 degrees by using two inertance tubes in parallel.

INTRODUCTION

In previous reports [1-4], the development of an adjustable inertance tube for Stirling-type pulse tube refrigerators has been chronicled including analyses and measurements with linear, threaded conical, and threaded cylindrical adjustable inertance tubes. The present report continues the account with a update on the work-in-progress, and presents an encouraging calculation suggesting that an adjustable inertance tube can shift the phase angle between the pressure and flow oscillations in a pulse tube from -60 degrees to +40 degrees, altogether a shift of nearly 100 degrees.

Various models exist for designing inertance tubes that predict the resultant phase angle between the pressure and flow oscillations at the connection between the pulse tube and inertance tube as a function of the diameter and length of the inertance tube [5-7]. However, fabrication and assembly of all the components in a pulse tube refrigerator can result in a different phase angle during operation than desired. In most cases the phase angle during operation is unknown, but if the cooling performance is less than expected, it is reasonable to expect that the performance can be improved by adjusting the phase angle. Furthermore, an adjustable phase shifting mechanism can be useful for various operating modes, such as cooldown vs. steady state operation.

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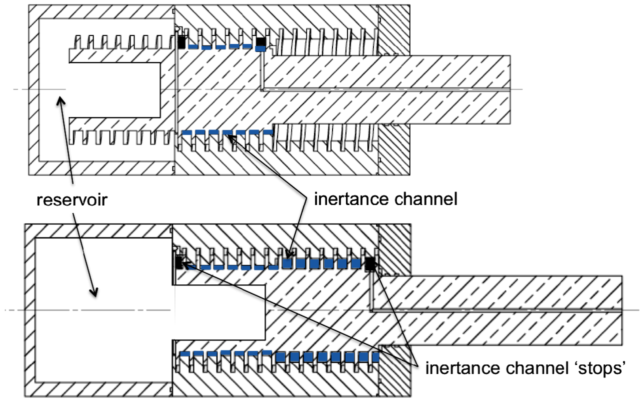

Figure 1. Threaded cylindrical adjustable inertance tube. The solid shaded regions highlight the helical channel between the root of the inner thread and tip of the outer thread that define the intertance tube or ‘channel’. The top figure displays the most compact setting where the length and hydraulic diameter of the inertance channel are 1.74 m and 7.4 mm respectively, while the bottom displays the most extended setting, adding 1.86 m of a channel with a hydraulic diameter of 14.5 mm to the overall length.

CYLINDRICAL ADJUSTABLE INERTANCE TUBE

Potential and Challenge

The adjustable inertance tube that presents the most promising ability to shift the phase over a large range with minimal impact on the associated acoustic power is the cylindrical threaded version. A recent report [4] demonstrated that the geometry shown in Figure 1 has the potential to shift the phase angle from +60 degrees to – 40 degrees. Here the helical channel that exists as the gap between the root of the inner screw and the thread-tip of the outer screw forms the inertance tube. The gas flow passage extends from the pulse tube through the centerline passage visible at the right side in Figure 1, behind the solid stop at the right end of the inner thread, along the helical inertance channel, and finally through a hole behind the stop at the left end of the outer thread, into the reservoir. The phase between the pressure and flow oscillation at the pulse-tube connection to the inertance tube shifts as a result of increasing the length of the inertance channel and at the same time increasing the contribution of the channel with a larger cross sectional area. However, a problematic feature of the geometry results from the gas leakage path between the threads; the leak significantly decreases the phase shifting potential of the inertance channel.

As reported [4], the modified version of the distributed component model for the cylindrical threaded inertance tube design that includes the effects of leaks between the threads also demonstrates an equivalent degradation in phase shifting potential. In the same report, an effort to eliminate the leakage path between the threads by applying vacuum grease to the threads of the inner screw provides significant, but incomplete, recovery of the phase shifting potential.

Using the thickness of the leakage path between the threads as an adjustable parameter, the modified distributed component model matches the measured length- and diameter-dependent phase shift at an operating frequency of 60 Hz with a gap size of 15.5 microns. Agreement between the model and measurements with the same thickness of the leak-gap degrades as the frequency is reduced. At the lowest measured frequency of 27 Hz, the deviation between the model and experiment ranges from -27 degrees to + 36 degrees dependent on the given length.

The model and measurement of the associated acoustic power, while in the same quantitative range, are also not in good agreement. In view of the significant degradation in the phase-shifting performance that is associated with the thread-to-thread leak, various options have been explored to mitigate the leak. The most promising option, depicted in Figure 2 uses the helical channel formed by

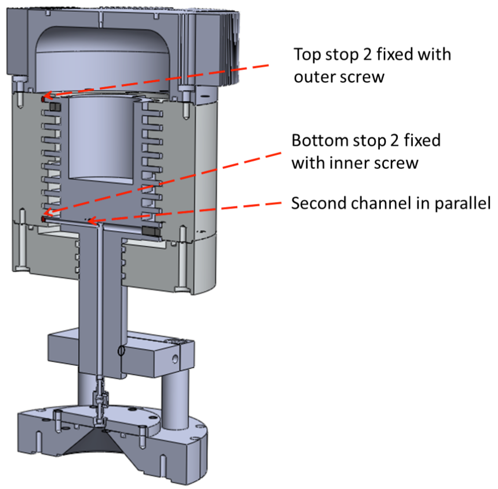

Figure 2. Cylindrical adjustable inertance tube. Two parallel helical channels are defined by 1) the gap between the root of the inner thread and tip of the outer thread, and 2) the gap between the root of the outer thread and tip of the inner thread.

the gap between the root of the outer screw and the thread-tip of the inner screw as an inertance tube operating in parallel with the original inertance channel. Spring-loaded stops, one fixed with the outer screw near the connection to the reservoir, and the other fixed with the inner screw near the connection to the pulse tube, define the ends for both of the parallel inertance channels. As the outer screw is turned from its most extended location, to its most compact location with respect to the inner screw, the effective diameter of the inner inertance channel changes from 11 mm to 7 mm while the diameter of the outer inertance channel remains constant at 2 mm. Over the same range, the length of both channels changes from 3.6 m to 1.74 m.

A passage connecting the inner and outer inertance channels at the pulse-tube end, and passages connecting both channels to the reservoir at the other end guarantee that the pressure is identical for both channels at those two locations. Since the geometry-defined inertance and compliance features of the two parallel channels are not the same, the pressures at any location along the helical length of the channels are not expected to be identical. However, as shown in Figure 3, the calculated pressure profiles for the two parallel channels are very similar.

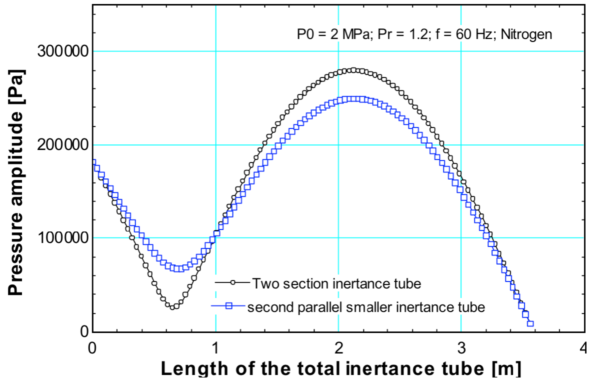

Figure 3. The Pressure profile along the length of the parallel helical channels. The 0 m location is the pulse tube end while the 3.6 m location is at the reservoir end.

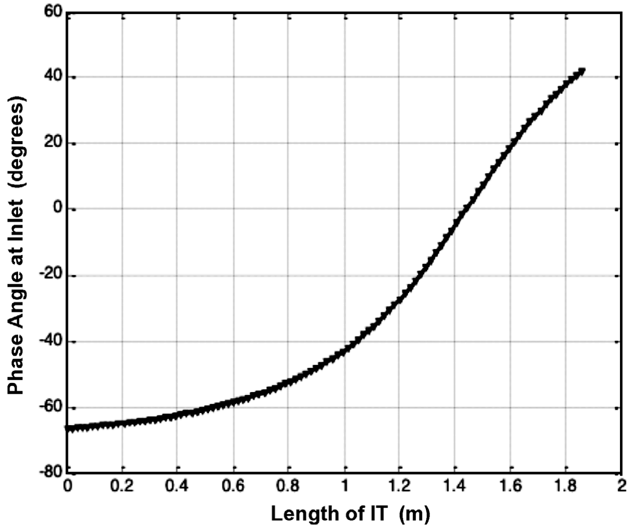

Figure 4. Anticipated phase shift produced by the parallel inertance channels as a function of the added length when the outer screw is turned from the compact location to the extended location.

In view of the small pressure difference between the two channels at any location, one may expect that the gas leak between the two channels is quite small. The resulting phase shift produced by the adjustable cylindrical inertance has been calculated using the modified distributed component model, including the leak between the threads, and is displayed in Figure 4. As shown there, the phase between the pressure and flow oscillations is expected to range from -65° to +40°, a change of more than 100° as the cylindrical threaded screw is turned from its most compact to its most extended configuration. During the fall and winter of 2016-2017 the required modifications will be made to the existing cylindrical screw so that it functions as two parallel inertance channels, and its operating characteristics will be measured.

SUMMARY

A progress update regarding the development of an adjustable inertance tube reveals that the cylindrical threaded design provides a large potential phase shifting ability. The leak between the channel formed by the gap between the root of the inner thread and tip of the outer thread and the channel formed by the gap between the root of the outer thread and tip of the inner thread can be mitigated by connecting the two helical inertance channels at both the pulse tube and reservoir ends, thereby creating a set of parallel interance tubes. The anticipated phase shift of the parallel inertance channel arrangement will be larger than 100 degrees.

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