An Experimental Study of the Influence of Cold Head Displacement on Single-Stage Gifford-McMahon Cryocooler System Performance [C1Po2B-01]

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Introduction

- A study was conducted to investigate the influence of cold head displacement speed on Gifford-McMahon (GM) cryocooler performance and seal life.
  - Cold head displacement speed is a function of cylinder diameter, displacer stroke, and operating frequency.
  - A larger cold head displacement speed results in larger system mass flow but smaller cycle pressure difference, while a smaller cold head displacement speed results in smaller system mass flow but larger cycle pressure difference. Cooling performance is proportional to pressure difference times displacement speed
  - Seal life—proportional to seal travel—is a function of cold head displacement speed and cylinder diameter.
- Testing investigated whether increased stroke or increased operating frequency had an advantage in achieving a desired cold head displacement speed.
  - With fixed cylinder diameter, regenerator, and timing, operating frequency and stroke length were varied
- A qualitative review of loss terms and a simple modelling of the system mass distribution was conducted to gain additional insight.

Test System Configuration

- Our F-70 compressor was used with a non-production single stage cold head with the following features:
  - Helium working fluid
  - The cylinder diameter was the same as our production CH-110 cold head.
  - The rotary valve timing was established to provide a desired cold end pressure-volume (PV) relationship
  - A control valve allowed adjustment of the drive stem mass flow so the desired PV relationship could be approximately maintained at different operating speeds while using a fixed valve geometry
  - A stepper motor was used to turn the valve at variable speeds
  - A “collar bumper” was used to minimize noise and vibration. This introduced void volume with an undefined small impact on performance. This feature was being investigated for potential production use.
  - Stroke length was varied using spacers or alternate geometry parts such that warm and cold end void volumes remained unchanged and there were only minimal changes to the regenerator geometry.
- Two different cold head configurations, A and B, were used in the testing reported here

Dependency of Losses on Stroke and Frequency

- Displacer regenerative cryocooler loss terms have been summarized by various people. Using discussions by Thirumaleshwar, et al,[1] White,[2] and Xu, et al,[3] as a basis:
  - Regenerator inefficiency
    - Thirumaleshwar et al show this loss as proportional to mass flow [1]
  - Cold end void volume
    - This loss is proportional to frequency [1,2]
    - Radial gap void volume (variably included here or as pumping loss) is proportional to frequency[1] or frequency^1.6.[2] Note: Xu, et al consider this loss noticeably less than predicted by White[3]
  - Pressure Drop
    - On a first order this loss is proportional to the square of the mass flow
  - Regenerator void volume
    - This loss is proportional to frequency only since regenerator void volume is fixed[1]
  - Shuttle loss
    - Proportional to the square of the stroke.[1,2] Note: the dwell fraction of cycle time is independent of frequency
  - Real gas, conduction, and radiation losses
    - Independent of stroke or frequency
  - Gas leakage past displacer seal – disregarded based on our test configuration
  - Cold end imperfect heat transfer losses—disregarded based on our test configuration
- In our consideration below, the losses dependent on mass flow (stroke x frequency) are lumped together and the losses dependent on frequency other than regenerator void volume are presumed relatively small and ignored

Mass Distribution Model

- A simple mass distribution model based on the compressor and cold head displacement speeds and the system volumes was used to characterize the relationship of changing cold head displacement speed.
  - Calculates cycle differential pressure using an experimentally derived mass flow equation for the F-70 compressor set equal to a cold head mass flow calculation similar to Thirumaleshwar, et al.
  - Calculates total cold end PV power
  - Initially fits the model to the data by adding a loss that is a fixed ratio to total PV power. As with PV power, this loss varies linearly with displacement speed

Results and Discussion

- Cold head configuration A
  - Figure 1 below shows 80K test results for a fixed 19 mm stroke and variable operating frequency. A grey curve is shown representing the mass model as initially fit to the data. Also shown is an orange curve representing the mass model with the regenerator void volume loss for 19 mm stroke added.

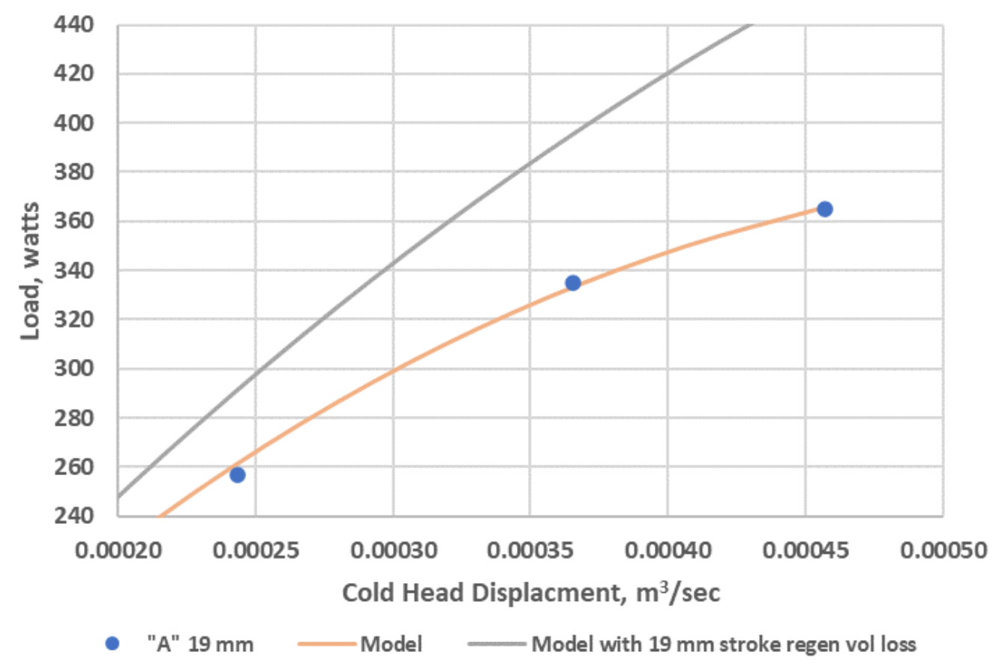

Figure 1. 19-mm stroke results with mass model curves

- Figure 2 below shows 80K test results for both the 19 mm stroke discussed above and a fixed 27 mm stroke. Also shown is a blue curve representing the mass model with the regenerator void volume loss for 27 mm stroke.

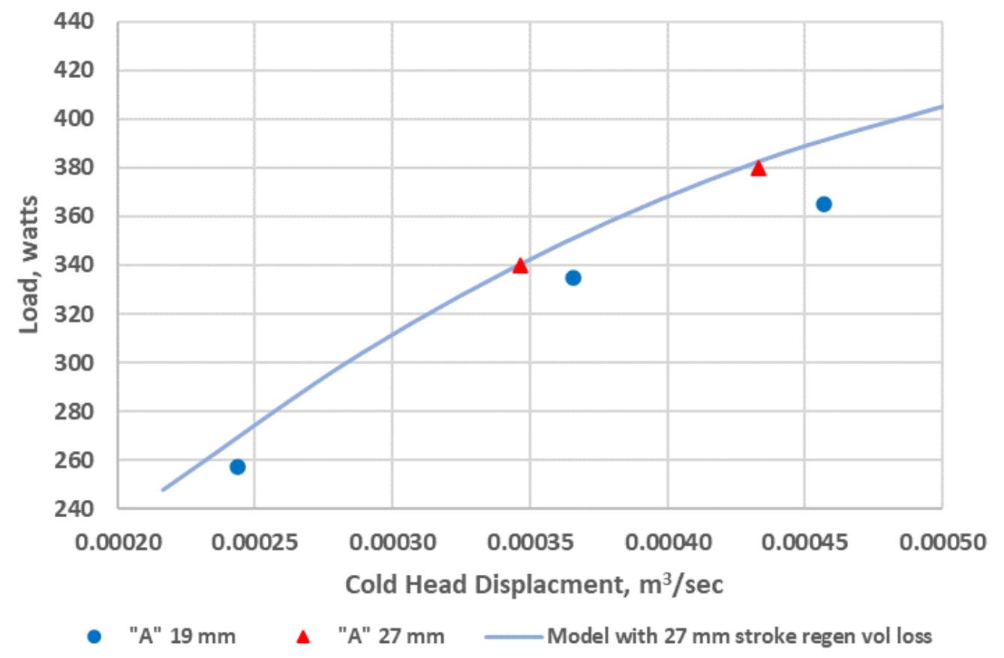

Figure 2. 19- and 27-mm stroke results with mass model

- From figures 1 and 2 we see that the model including the initial fit plus the regenerator void volume loss reasonably matches the results for varying both displacement speed and stroke length.
- Because of the successful fit of the orange and blue curves, the grey curve of figure 1 may represent a reasonable approximation of all losses other than regenerator void volume. When comparing the grey to the orange curve, one sees the strong frequency dependency of the regenerator void volume.
- A performance advantage is seen for achieving a given displacement speed with a longer stroke compared to a higher frequency

Results and Discussion

- Cold head configuration B:
  - Configuration B differs from A by having different internal flow passages, a different temperature sensor location, and a different charge pressure. Accordingly, a slightly different initial fit was used.
  - Figure 3 below shows 80K test results for a fixed 28 mm stroke and variable operating frequency. Also shown is a green curve representing the mass model. Again, a good match for the variation with displacement speed is evident.

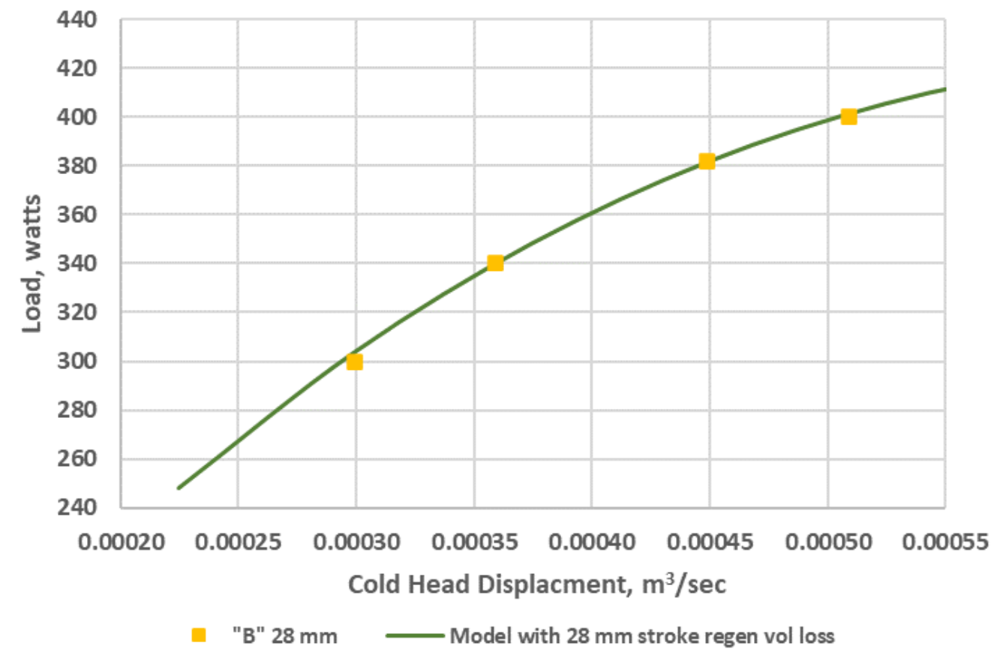

Figure 3. 28-mm stroke results with mass model curve

- Seal Life Considerations
  - Total distance traveled is used as an approximation of seal life and is calculated from 2 x frequency x stroke
  - Due to the loss terms, particularly those that are frequency dependent, trading higher cooling performance for shorter seal life has diminishing return.

Conclusions

- When achieving a desired cold head displacement with a fixed cold head diameter, a performance advantage is seen using a longer stroke compared to higher operating frequency
- A simple mass distribution model may be used as a design tool for optimizing cold head design.
- Seal life, dependent on displacement speed, is non-linearly traded against cooling performance

References

[1]M.Thirumaleshwar, S.V.Subramanyam, “Gifford-McMahon cyle — a theoretical analysis”, *Cryogenics*, Vol. 26, Issue 3 (March 1986), pp. 177-188.

[2]R.White, “Vuilleumier Cycle Cryogenic Refrigeration”, AFFDL TR-76-17, DTIC ADA027055, Apr. 1976.

[3]M.Y.Xu, T.Morie, “Numerical Simulation of 4K GM Cryocooler”, Cryocoolers 17, ICC Press, Boulder, CO (2012), pp.253-259.

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