Quantifying Thermal Expansion of Aluminum Components At Cryogenic Temperatures

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Introduction

This experiment is designed to identify a quantitative method to design cryogenic components for Portland State Aerospace Society's Electric Feed System (EFS). The EFS consists of two separate pumps used to feed isopropyl alcohol (IPA) and liquid oxygen (LOX). Liquid nitrogen (LN_2) will be used in this experiment due to safety requirements. The primary measurements demonstrate the effects that cryogenic temperatures have on the pump components.

Theory

Thermal expansion can be theoretically found as[1]:

$$\Delta L = L_m \alpha \Delta T \tag{1}$$

Here, ΔL is the dimensional change, L_m is the machined (initial) dimension, α is the coefficient of thermal expansion, and ΔT is the change in temperature. Note that $\Delta T = T_C - T_\infty$, where T_C is the cooled temperature and T_∞ is the ambient temperature of the room. Then the theoretical cooled length, L_C, can be calculated as:

$$L_C = L_m + \Delta L \tag{2}$$

Methods

Individual components were submerged in a container of LN_2 at $T_C \approx -196°C$ as shown in Figure 2. 12 distances were measured on the shaft, pump housing components, and bearing collar. The component measurement points are shown in Appendix A, Figure 4. Measurements were taken 3 to 5 times using micrometers or bore gauges, then averaged to increase accuracy. Each measurement was made initially at an ambient temperature of $T_m \approx 20°C$, then repeated after the component was submerged for two minutes in the cryogenic fluid. An example of a component before and after exposure to cryogenic temperatures can be seen in Figure 3.

Results & Conclusion

The experiment showed an average reduction in component size of 0.226%. The measured reductions in size did not match the theoretical values calculated. However, they displayed a direct linear correlation to the theoretical results, which can be seen in Figure 1. The relationship between room temperature, theoretical cooled, and measured cooled dimensions are shown in Table 1.

The trendline polynomial shown in Figure 1 can be substituted into Equation (2) and used to solve for the target machined dimension to achieve optimal cryogenic performance geometry. This formula is shown below, and its derivation can be found in Appendix B.

$$L_o = \frac{(L_c + 0.0014)}{(1 + [(1.0028)(\alpha(T_c - T_\infty))])} \tag{3}$$

This formula gives Portland State Aerospace Society a more reliable design criteria for any propulsion systems that are intended for use with cryogenic fluids, and will be utilized for the design and tolerancing of the cryogenic electric feed system.

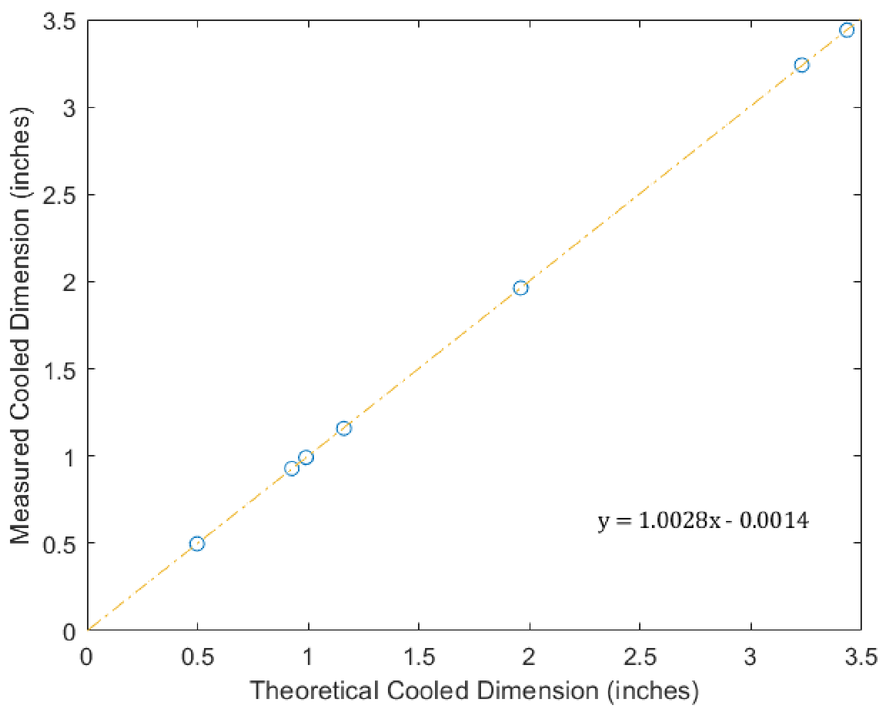


Figure 1: Measured Component Dimensions vs. Calculated Dimensions

Component		Measurement	Unit	Initial Length	Length @Cryogenic Temperatures		
					Theoretical	Measured	% Difference
SHAFT	Shaft Seal Diameter	B	[in]	0.5001	0.4976	0.4984	0.1617
SHAFT	Shaft Length	D	[in]	3.2470	3.2296	3.2400	0.3199
COLLAR	Bearing Diameter	A	[in]	0.9950	0.9900	0.9920	0.1969
CASE 1	Impeller Seat Diameter	A	[in]	3.4500	3.4328	3.4400	0.2081
CASE 1	Impeller Shaft Bore Diameter	B	[in]	0.9310	0.9261	0.9287	0.2761
CASE 2	Housing Internal Diameter	A	[in]	3.4500	3.4328	3.4408	0.2313
CASE 2	Housing Depth	B	[in]	1.1670	1.1612	1.1590	0.1898
S.R. Ring	Seal Seat Diameter	A	[in]	0.9940	0.9893	0.9919	0.2570
BRG. PLATE	Bearing Outer Diameter	A	[in]	1.9690	1.9594	1.9632	0.1920
						Average % Difference:	0.2259

Table 1: Theoretical & Measured Results of Component Geometries

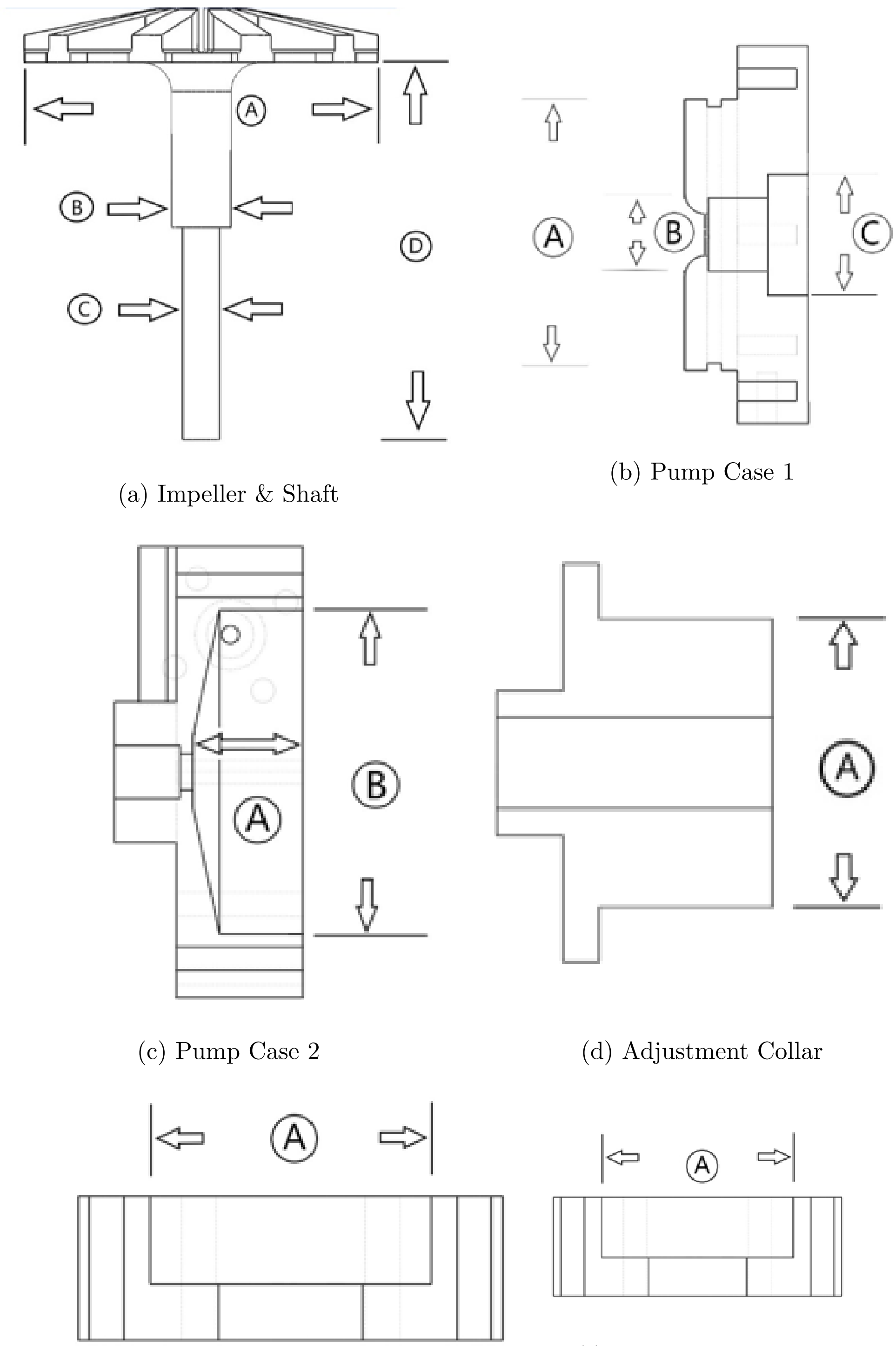
Appendix A: Additional Figures

Figure 2: Impeller Submerged in Liquid Nitrogen

(a) Impeller at Room Temperature Conditions

(b) Impeller After LN_2 submersion.

Figure 3: Effects of Cryogenic Temperatures on Impeller Component



(a) Impeller & Shaft

(b) Pump Case 1

(c) Pump Case 2

(d) Adjustment Collar

(e) Bearing Plate

(f) Seal Retaining Ring

Figure 4: Pump Component Measurement Locations

Appendix B: Sample Calculation

From Equations (1), (2), & Figure 1:

$$\begin{aligned}
L_c &= L_o + \Delta L \\
\Delta L_{actual} &= m \cdot \Delta L_{theoretical} + b \\
&= (1.0028)(L_o \alpha \Delta T) + (-0.0014) \\
\Rightarrow L_c + (0.0014) &= L_o(1 + [(1.0028)(\alpha(T_c - T_\infty))])
\end{aligned}$$

$$\boxed{L_o = \frac{(L_c + 0.0014)}{(1 + [(1.0028)(\alpha(T_c - T_\infty))])}}$$

Appendix C: References

[1] R. Budynas, K. Nisbett, “Shigley’s Mechanical Engineering Design” (2014, $10^{th} Ed.$)