IMPROVED THERMAL VACUUM CHAMBER TEMPERATURE PERFORMANCE VIA GASEOUS NITROGEN THERMAL CONDITIONING UNITS

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ABSTRACT

Many of today's thermal vacuum test programs require uniform and precise control over wide temperature ranges while minimizing operating budgets. These requirements have driven interest in energy-efficient gaseous nitrogen Thermal Conditioning Units (TCUs) for temperature management of shrouds and platens. Here we present recent innovations in TCU design for improved thermal performance. Compared to mechanical refrigeration systems, TCUs offer an increased temperature range (-180 °C to 150 °C) and negate the possibility of chamber contamination via shroud leaks. Gaseous nitrogen TCUs also provide better temperature stability, set point control, and significantly reduced steady state liquid nitrogen consumption compared to flooded liquid nitrogen shroud systems. Furthermore, because nitrogen closely adheres to the Ideal Gas Law, system modeling is relatively straightforward and system performance is highly predictable and stable. We will provide an overview of TCU characteristics, give examples of successful applications, and compare and contrast shroud performance. Methods for appropriately sizing Gaseous Nitrogen Thermal Conditioning Units will also be presented.

Key words: space simulation; thermal vacuum; TCU.

1. INTRODUCTION

The ability to satisfy thermal vacuum test parameters while remaining within budgetary constraints is an issue of intrinsic and practical importance. Solutions to this problem have traditionally fit into one of three categories. One is to utilize a recirculating heat transfer fluid to move waste heat to a refrigeration chiller for control of internal vacuum surfaces. However, these systems are limited by the usable temperature range of the heat transfer fluid, and a single fluid is often incapable of managing the temperature range required of many test protocols. Another solution is to vary thermal control surfaces using piped in liquid nitrogen (LN_2) trimmed by resistive heaters large enough to yield the desired test article temperatures. This is usually accomplished either using a flooded cold wall and large enough heaters to bring the test article to the desired temperatures, or by injected LN_2 via control valving and heat as needed into the system. While this former method can provide fast ramp rates with precision steady-state temperatures, the power and LN_2 consumption rates required can be staggering, possibly limiting the testing duration due to budget constraints and consumable availability. While the later method requires less consumables, stable control of cryosurface and test article temperatures is often difficult to achieve. Another option to manage thermal control surfaces is to use recirculating gaseous nitrogen (GN_2), recirculated by thermal conditioning unit (TCU). Here we will present an overview of TCUs characteristics compared to other methds, illustrate thermal shroud performance, and discuss appropriate TCU sizing for thermal systems.

Mechanical refrigeration systems offer easy-to-use closed-loop methods for controlling cryosurface temperatures. However, multiple challenges arise when specifying mechanical refrigeration systems. Refrigeration capacity, the ability to remove heat from the system, decreases with decreasing temperature. Additionally, recirculating heat transfer fluids exhibit a rapidly increasing viscosity with decreasing temperature. Consequently, a refrigeration system capable of removing 10 kW from the system at -50 °C may struggle to reach -70 °C. This often makes achieving desired system ramp rates below -90 °C a difficult and expensive proposition. Furthermore, many low temperature heat transfer fluids are hydrocarbon or silicone based, and any cryosystem leak may cause test article contamination. Concern over possible test article contamination may be a major deterrent for testing articles in a mechanical refrigeration based thermal vacuum system[1].

Rather than a mechanical refrigeration system circulating a liquid heat transfer media, gaseous nitrogen can be used. An appropriately sized gaseous nitrogen thermal conditioning unit (TCU) offers a simple solution for precisely and efficiently controlling cryosurface temperatures.

2. METHOD OF OPERATION

Thermal conditioning units are typically composed of a gaseous nitrogen circulator (or blower), a variable fre-

Figure 1. Typical gaseous nitrogen thermal conditioning unit (TCU). This 170 m^3/hour TCU can provide up to 10 kPa of head pressure over a temperature range of -180 °C to 150 °C.

quency drive (VFD) to control the blower speed, an inline heater, pressure measurement and control hardware, liquid and gaseous nitrogen supply valving, vent valving, mechanical or vacuum jacketed insulation, and a programmable logic controller (PLC) and Human-Machine Interface (HMI) for operating the system.

At a most basic level, system properties can be easily modeled via the Ideal Gas Law,

$$P = \rho R T, \tag{1}$$

where P is the gas pressure in Pascals, ρ the gas density, R the nitrogen gas constant, and T the gas temperature in Kelvin. By operating the TCU at a constant gas density (usually 4-6 kg/m^3), the system exhibits a direct relationship between pressure and gas temperature. By controlling the heater power and injecting or venting gaseous or liquid nitrogen into the recirculating circuit, the PLC is able to control the gas temperature and pressure in the system. This allows for easy control of the system over its entire temperature range, limited only by the liquefaction of the nitrogen heat transfer media and the upper temperature limit of seal materials and exterior paints[2].

At a given temperature, the heat transfer media must manage a heat load Q equal to the radiant heat transfer between the chamber and cryosurfaces, the active load of the test article, the work of the blower, mediated by the LN$_2$ injection and the inline gas heater. The temperature gradient between the TCU outlet and inlet is given by,

$$\Delta T = \frac{Q}{\dot{m} C_p}, \tag{2}$$

where $\dot{m}$ is the mass flow of the gaseous nitrogen and C_P is the specific heat of gaseous nitrogen, 1.04 J/g/K.

During temperature transitions, the additional work required to move the mass of the cryosurfaces must be considered.

$$Q' = M C_p' \delta T \tag{3}$$

where M is the mass of the cryosurfaces C_p' is the specific heat of the cryosurface material, and δT is the ramp rate of the cryosurface.

The cryosurface wall temperature, T_w can be determined by considering the convective heat transfer of the nitrogen gas into the cryosurface, Q'', either at steady state (when $Q'' = Q$) or during transition (when $Q'' = Q + Q'$).

$$Q'' = hA(T_w - T_{N_2}), \tag{4}$$

where A is the tube-wetted surface area, T_w is the temperature of the tube wall, T_{N_2} is the gaseous nitrogen temperature, and h is the convective heat transfer coefficient. The convective heat transfer coefficient is given by,

$$h = \frac{C_p \dot{m} J_m}{Pr^{2/3} A}, \tag{5}$$

where Pr is the Prandtl number and J_m is the Chilton and Colburn J-factor. This difference in bulk to wall temperature, $T_w - T_{N_2}$, sets a lower limit on achievable cryosurface temperature before N$_2$ liquefaction occurs, and can be an important consideration when choosing cryosurface materials and sizing TCUs.

3. THERMAL CONDITIONING UNIT SIZING

Appropriately sizing TCUs for a thermal vacuum system requires accounting for a variety of system variables. Fundamentally, the TCU must provide a great enough gaseous N$_2$ mass flow and pressure head to manage the thermal loads of the system. While a thorough discussion of the design and modeling of compressible fluid piping networks is beyond the scope of this work, we will compare the performance of four different sized TCUs connected to typical thermal vacuum test chamber. Here we present four different TCUs: a 170 m^3/hour TCU with 10 kPa of head pressure, a 170 m^3/hour TCU with a higher speed blower providing 42 kPa of head pressure, a 680 m^3/hour TCU with 10 kPa of head pressure, and a 2550 m^3/hour TCU with 20 kPa of head pressure.

We can use an example thermal vacuum test chamber to illustrate the performance of different sized TCUs. We can assume an 1100-series aluminum cylindrical D-tube-on-sheet shroud, 1.3 m diameter by 1 m long by 3 mm thick, inside a 1.5 m diameter 1.2 m long cylindrical vacuum chamber. The shroud has six parallel D-tube runs, each connected to an input and output header and spaced by 175 mm. A 0.8 m by 1 m by 25 mm d-tube on sheet platen provides fixturing for a 25 kg test article. We will assume the test article uniformly radiates 1 kW. The bottom of the platen features seven parallel D-tube runs spaced by 150 mm to input and output headers. Front and rear end cap shrouds provide an encompassing thermal environment. The end caps are 1.3 m in diameter and 3 mm in thickness, and feature eight parallel runs of D-tube spaced by 190 mm connected to input and output headers.

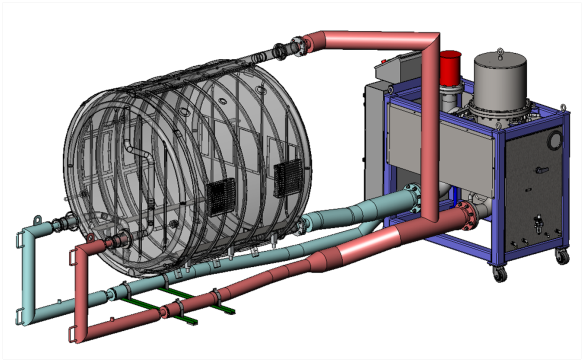

Figure 2. Illustration of a TCU connected to a cylindrical shroud. The vacuum chamber and other cryosurfaces are not shown for clarity. Pipes handling input gas are shown in blue, and pipes handling return gas are shown in red.

The system is plumbed such that the nitrogen flow passes through the platen and the door in parallel, with the outlet of the platen split to drive the cylindrical shroud and rear panel. An illustration of the connections are shown in Fig. 2.

Pipe and D-tube sizing needs to be adjusted to optimize the pressure drop for a given TCU blower. For a 170 m^3/hour TCU with 10 kPa of head pressure, 50 mm piping can be used to connect the TCU to the cryosurfaces, along with 50 mm headers. Nineteen millimeter diameter D-tube can be used for the cylindrical shroud and platen, with 12.5 mm D-tube for the end cap shrouds. For a 170 m^3/hour TCU with a higher speed blower providing 42 kPa of head pressure, line sizes can be decreased to 38 mm piping and headers, and 12.5 mm D-tube can be used for the system. For a 680 m^3/hour TCU with 10 kPa of head pressure, 200 mm connection piping and headers are used, with 31 mm D-tube for the platen, 25 mm D-tube for the cylindrical shroud, and 19 mm D-tube for the end caps. For a 2550 m^3/hour TCU with 20 kPa of head pressure, 250 mm connection piping and headers are used, with 41 mm D-tube for the cylindrical shroud and platen, and 31 mm D-tube for the end caps.

Using a TCU capable of a flow rate up to 170 m^3/hour and a head pressure of 10 kPa, the system can be moved at temperature ramp rates up to 2 K/min. However, due to the limited quantity of gas flow, significant temperature gradients will exist across the thermal surfaces, even at steady state temperatures. The cylindrical shroud exhibits a gradient of up to 10 K at a steady state temperature of -180 °C and a gradient of up to 15 K at a steady state temperature of 150 °C. End cap gradients are somewhat smaller, below 7 K at 150 °C, and the platen is uniform to within 1.5 K when at steady-state. Temperature gradients during transition can be as high as 60-65 K when ramping at 2 K/min.

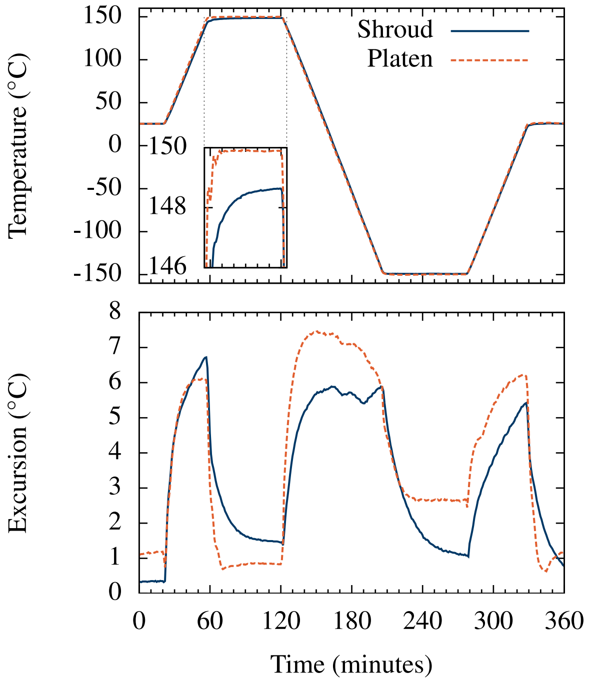

Figure 3. (Top) Average experimental shroud and platen temperatures, measured by four thermocouples across the shroud and three thermocouples across the platen, from ambient to 150 °C to -150 °C to ambient with test article under vacuum. Inset figure is the shroud and platen temperatures at steady-state 150 °C. The shroud is in series with the platen, causing the shroud temperature to slightly lag the platen temperature. (Bottom) The maximum temperature excursion measured across the respective cryosurfaces. Maximum nonuniformity observed is ±4 K during transitions and ±1.5 K at steady state.

The use of a higher speed blower allows for similar temperature performance in smaller D-tubes, pipes, and headers, which can offer a significant cost savings when cryo-control components must be located at a distance from the vacuum chamber or when retrofitting cryosurfaces with large pressure drops. The platen uniformity is again within 1.5 K at steady state temperatures, and the end caps are uniform to within 6 K at steady state. The cylindrical shroud uniformity is not quite as good, at 17 K at a steady state temperature of 150 °C. The increased power consumption of the higher speed blower has a secondary effect of shifting the ramping characteristics of the TCU. The additional energy from the higher speed blower reduces the ability of the TCU to ramp colder to -1.5 K/min, and increases the ability of the TCU to ramp hotter to 2.25 K/min. Ramping to 150 °C at this faster rate increases the cylindrical shroud transition gradient towards 85 K. These 170 m^3/hour TCUs are qualitatively better suited for driving individual platens or shrouds rather than whole systems. If the cylindrical shroud alone is driven by a high speed 170 m^3/hour TCU, the transition gradients are only 15-20 K while ramping at -1.5/+2.25 K/min.

A larger TCU, such as a 680 m^3/hour TCU, drives the system with significantly better results. The platen surface temperature is uniform to within 0.5 K at steady state, and the cylindrical shroud temperature has a steady state gradient of less than 5 K. The system can ramp at rates between -4 K/min and +3.5 K/min, and an experimental ramp data between -150 °C and 150 °C at ±3 K/min are shown in Fig. 3. At a ramp rate of 3 K/min, temperature gradients on the platen and shroud are generally below 6 K.

Utilizing an even larger TCU, such as a 2550 m^3/hour TCU with 20 kPa of head pressure, allows for greater thermal uniformity and higher ramp rates. At steady state the platen temperature is uniform to within 0.25 K across the platen surface, and the entire cryosurface has a gradient of less than 2.5 K. This size TCU can ramp the system at rates of up to ±18 K/min. The greatest tradeoff of such a powerful TCU is the significantly increased power and LN_2 consumption, with up to 30 kW of electricity and up to 7 L/min of LN_2 used at steady state, and 120 kW of electricity or 50 L/min of LN_2 being used during temperature transitions.

4. CONCLUSION

Gaseous nitrogen Thermal Conditioning Units (TCUs) have proven to be excellent tools for the control of thermal surfaces in vacuum test environments. TCUs provide a wide thermal control range with no possibility of test article contamination, excellent electricity and LN_2 consumption at steady state temperatures, and stable and uniform temperatures across cryosurfaces.

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