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BI-MATERIAL CONTROLLED DEMAND FLOW JOULE-THOMSON COOLERS

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INTRODUCTION

Joule-Thomson (JT) coolers have been designed to meet the needs of a wide variety of cryogenic refrigeration applications. They have been utilized mostly for their attributes as low cost, miniature, portable, reliable and fast cooldown open-cycle refrigerators.[1] They have been manufactured in a variety of forms with single or multiple stages of refrigeration and capable of operating with various refrigerants.[2] They are also made available with and without self-contained flow control mechanisms. Fixed orifice JT coolers that do not contain a mechanism to vary the refrigerant flow during operation produce refrigeration at a high rate when the supply pressure is high. They are good for fast cooldown applications but are inefficient for steady-state operation. Demand flow JT coolers that do contain a flow control mechanism adjust the refrigeration rate according to the heat load over a wide range of supply pressures and ambient temperatures in order to conserve refrigerant. Dual-orifice JT coolers are a combination of fixed orifice and demand flow types for use in special applications.[3]

Various refrigerant flow control mechanisms of the type adaptable for use with JT coolers include bi-metallic mechanisms,[4] gas-charged bellows mechanisms,[5,6,7] and bi-material mechanisms.[8] These flow control mechanisms are typically adjusted to respond in correlation with the temperature of the refrigerant at or near the cold end of the JT cooler or with the temperature gradient in the heat exchanger. These flow control mechanisms can usually be adjusted to provide a small excess of refrigeration, if desired, to assure a continual presence of liquid refrigerant at the cold end.

The heat that is transferred from the flow control mechanism to the colder refrigerant and heat exchanger during cooldown causes the flow control mechanism to either expand or contract. This temperature-induced movement is employed to operate a valve to reduce or throttle the flow of refrigerant as the temperature surrounding the flow control mechanism approaches a desired cold end operating temperature. After achieving the desired operating temperature, the same temperature sensitive movement is employed to regulate the flow of refrigerant in order to stabilize the cold end operating temperature under conditions of varying refrigerant supply pressure, ambient temperature, and heat load.

To date, demand flow JT coolers have predominantly used gas-charged metallic bellows mechanisms. In pursuit of a simpler, smaller, less expensive and more reliable device, the bi-material demand flow control mechanism has been developed.

MECHANICAL DESIGN COMPARISON

Gas-charged bellows demand flow control mechanisms are typically an assembly of a cylindrical bellows that is sealed at both ends and pressurized with a gas. One end of the assembly is fixed at some location relative to the JT cooler heat exchanger. The free end of the assembly is connected to a variable flow valve. The gas pressure in the bellows increases or decreases as the bellows is heated or cooled, which causes the bellows to expand or contract relative to the fixed end and to open or restrict the flow valve. The bellows temperature may be reduced to the point where the charge gas liquefies, depending on the refrigerant and operating conditions. The bellows is typically made of metal to contain the charge gas, and it is typically fabricated by an electroplated or electroformed method. The characteristics of the bellows are similar to a coil spring, such that its length, diameter, wall thickness, number of active convolutions and elastic modulus determine its spring rate. The charge gas and initial pressure are chosen for the desired operating temperature, and for the desired pressure and length bellows response (dP/dL and dL/dT). Typical response values for the miniature bellows used by APD Cryogenics are dP/dL = 5-20 GPa/m @ 300 K and dL/dT = 2-2.5 μm/K @ 100 K with a net available valve actuation force of 1-4 N. The flow valve is sized for the desired flow range and can be of various designs (e.g. a moveable needle point over a fixed circular orifice). The valve is typically adjustable for setting the initial flow rate. Typical miniature JT coolers have orifices or nozzles with diameters of 50-350 μm and flow rates of 1-10 std L/min (with N_2 @ 21 C and 6.9 MPa ΔP, referred to as Co as an APD Cryogenics standard). All these variables plus the assembly's coefficient of thermal expansion, its natural frequency as a spring-mass system, and its location relative to the heat exchanger's temperature gradient determine the response, sensitivity and hysteresis of this type of flow control mechanism. Gas-charged bellows are complex to design and manufacture, requiring lengthy empirical development, and therefor are a very long lead item when considering new product development or custom adaptations.

Bi-material demand flow control mechanisms are typically an assembly of a simply machined cylindrical rod.[8] Similar to the gas-charged bellows, one end of the rod is fixed at some location relative to the JT cooler's heat exchanger while the free end is connected to a variable flow valve. As the rod (i.e., the actuator) is heated or cooled, it either expands or contracts relative to the fixed end, and the flow valve is either opened or restricted. The material for the rod is chosen primarily for its thermal expansion characteristics relative to the thermal expansion characteristics between the intended anchor point with the heat exchanger and the variable flow valve. Any combination of materials can be used to provide the differential thermal expansion for a given temperature change. Since many plastics have higher coefficients of thermal expansion relative to metallics or ceramics, the best available combinations exist with them. Typical miniature bi-material mechanisms have a differential expansion of > 50 μm/(m · K) over the temperature range of 80-300 K. Choosing material combinations that provides the maximum relative dL/dT will then minimize the actuator's length. Presently, a typical high dL/dT value would be 1-1.5 μm/K @ 100 K. Although the low temperature sensitivity of the bi-material mechanism is less than that of the gas-charged bellows, the 300-80 K dL/dT response is similar. Additionally the bi-material actuator has an essentially infinite spring rate compared to the gas-charged bellows, and it can provide a valve actuation force several times greater than the gas-charged bellows. The adequate response and the lack of a gas charging fitting have allowed bi-material mechanisms to be made smaller than gas-charged bellows mechanisms. Because of the obvious simplicity of this design, having few variables, bi-material mechanisms are more quickly adapted to new products or custom applications.

Demand flow control mechanisms can be installed in JT coolers having various heat exchangers, such as the more prevalent finned tube heat exchanger[9] or a matrix tube heat exchanger.[10] APD Cryogenics has manufactured miniature demand flow JT coolers in sizes down to ∅ 5 mm x 23 mm long. Presently with bi-material control mechanisms, the lower limit on demand flow cooler size is estimated to be less than ∅ 3 mm x 15 mm long depending on the application. However, it must be remembered that shorter heat exchangers are also less efficient because of higher end-to-end heat conduction losses. Figure 1 displays the geometric comparison of gas-charged bellows and bi-material flow control mechanisms for a typical finned tube heat exchanger demand flow JT cooler. The photo inset displays the same with a ∅ 9.52 mm x 37.5 mm long JT cooler designed for a typical infra-red detector cooling application.

CRYOGENIC PERFORMANCE COMPARISON

The cooldown performance of a demand flow JT cooler is determined by the heat exchanger efficiency, pressure drop, supply pressure, ambient temperature, orifice size, by the thermal load of itself and the load to be cooled, and by the throttle response of the flow control mechanism. A JT cooler operating with nitrogen typically contributes ~ 50 % of the heat exchanger (i.e. the colder half) to the total thermal load. For the smallest demand flow coolers, the flow control mechanism typically doubles the contributed amount of thermal load. The throttle response of the flow control mechanism will effect the rate at which the flow is reduced in proportion to the load being cooled. The heat transfer from the flow control mechanism, both longitudinal and radial, and the thermal diffusivity are important factors in controlling the throttle response. For instance, a metallic bellows would respond faster than a plastic bi-material actuator. As the flow is throttled, the pressure drop across the exhaust side of the heat exchanger is reduced which reduces the saturation temperature of the liquid refrigerant at the cold end. The flow is continually throttled until the net refrigeration capacity is in some proportion with the steady-state heat load. The primary concern with any flow control mechanism is its balance between throttle sensitivity, or the ability to delay throttle, and stability after throttling. After throttling, the remaining transient cooldown of the load is governed by the rates of diffusion of heat flowing into the cold end from various parts of the load's assembly. Hence, a demand flow JT cooler can establish a stable liquid refrigerant temperature, but the load may not reach steady-state temperature until several seconds later.

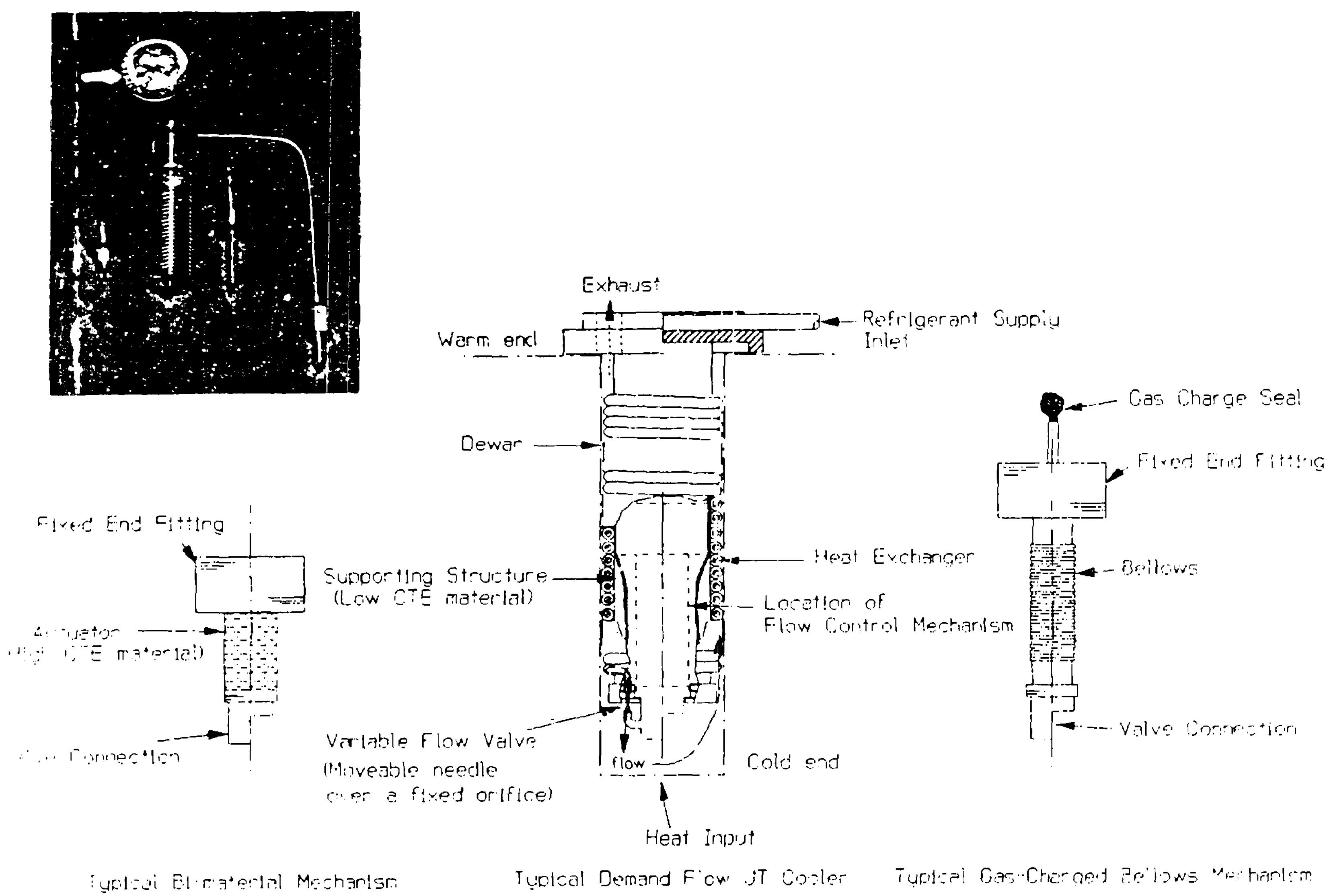

FIGURE 1: Geometric Comparison of Gas-Charged Bellows and Bi-Material Flow Control Mechanisms for a Typical Demand Flow JT Cooler (Photo Inset shows the same with a Javelin program JT cooler)

Bi-material controlled demand flow JT coolers have been made to provide identical cooldown performances compared to gas-charged metallic bellows controlled coolers at ambient temperatures from -40 C to 71 C. Performance with various refrigerants was also similar. If demand flow JT coolers are initially set to provide a minimum after-throttle flow rate with a given refrigerant, then they will usually provide a higher after-throttle flow rate when operated with a warmer boiling point refrigerant (and vice versa, a lower flow with a colder boiling point refrigerant). This effect can be worse with a gas-charged bellows mechanism, depending on the intended refrigerants and the chosen bellows charge gas.

After cooldown, the steady-state gas consumption and temperature stability of a demand flow JT cooler are determined by the heat exchanger efficiency, pressure drop, the internal heat loss due to conduction from the warm end, by the conduction, convection, and radiant heat losses entering the device being cooled, and by the response of the flow control mechanism to changes in refrigerant supply pressure and cold end temperature. The major performance differences between bi-material and gas-charged bellows flow control mechanisms have been observed during steady-state operation.

Gas-charged bellows controlled demand flow JT coolers have a flow control hysteresis that is inversely proportional with the refrigerant supply pressure. This is partly due to a non-linear dP/dT bellows response after the charge gas begins to liquify inside the bellows. It is partly due to the bellows spring rate that allows deflections and oscillations from refrigerant supply pressure and flow forces acting on the flow valve which is connected to the free end of the bellows assembly. It is also due to an imbalanced dP/dL response resulting from variations in the exhaust pressure via variations in the flow rate or local ambient pressure. As a result, these coolers typically exhibit some flow instability, increasing with decreasing supply pressure. The flow instability directly affects the cold end temperature stability and wastes refrigerant. These coolers can also exhibit a cyclic control behavior, basically on-off flow control. This is adjustable primarily by the initial flow setting of the variable flow valve. On-off flow control extends the steady-state operating time from a given quantity of refrigerant at the expense of temperature stability, and it increases the susceptibility of the flow valve to clogging from contaminants in the refrigerant during the "off" period. On-off flow control typically produces cold end temperature cycles of 1-10 K @ 0.05-0.5 Hz. To obtain a more proportional flow control, the many variables previously discussed must be balanced. Proportional flow control thus improves temperature stability and reduces the susceptibility to clogging by providing a higher average flow rate at the expense of more refrigerant consumption [11]

Bi-material controlled demand flow JT coolers typically exhibit better proportional flow control stability, and thus better cold end temperature stability, than gas-charged bellows controlled coolers. Temperature stability has been achieved within 0.5 K with < 0.1 K peak-to-peak variations @ 1 Hz - 1 kHz for extended periods. The more stable flow control also reduces refrigerant consumption, thus extending the steady-state operating time from a given quantity of refrigerant, without compromising temperature stability or increasing the susceptibility to clogging from contaminants in the refrigerant. The improved flow stability is attributed to the bi-material mechanism's dL/dT response, and its higher stiffness and net valve actuation force. This makes it less sensitive to temperature variations at the cold end, flow aberrations at the valve, or supply and exhaust pressure variations. The noticeably reduced susceptibility to clogging for bi-material controlled coolers is also attributed to the flow stability. However, when these coolers clog with excessive contamination they typically warm up to a higher temperature before recovering than do gas-charged bellows controlled coolers.

Figure 2 displays some of the best performance seen with both bi-material and gas-charged bellows controlled demand flow JT coolers. It plots the temperature stability of the center of a silicon disk epoxy bonded to an alumina substrate that is brazed to the cold end of a titanium alloy dewar bore. The coolers were both ∅ 9.52 mm x 37.5 mm long; PC3 is a bi-material controlled unit, and BFC6 is a gas-charged bellows controlled unit. The tests were conducted at 21 C with nitrogen in a blowdown mode from a fixed 0.1 L volume initially pressurized to 40 MPa. The total cooldown load, $Q_{(dewar + cooler)}$ was ≅ 300 J, and the total steady-state heat loss, $Q'_{(dewar + cooler)}$ was ≅ 0.29 W. The upper two traces compare the entire test run of each cooler. The lower two traces display the first 100-300 s of the same tests at a higher resolution. Data was collected at a higher sample rate for the first 300 s and at a reduced sample rate thereafter because of limited computer memory. The characteristics of the higher sample rate data should be envisioned as being superimposed over the lower sample rate data for the entire test. Note the differences in the throttle response during the cooldown phase, and the stability near the end of each test. Also, note the generally decreasing temperature as the test proceeds after cooldown. As the nitrogen supply pressure decreases from the fixed 0.1 L volume, the refrigeration capacity decreases, reducing the liquid fraction in the JT process. The flow control mechanism then senses a slight warming in the heat exhanger and responds by increasing the flow rate. Therefor, the decreasing temperature is not due to a decreasing flow and exhaust pressure; it is due to an increasing coefficient of heat transfer in the liquid nitrogen.[11]

RELIABILITY COMPARISON

Overall reliability with these types of mechanisms and JT coolers is typically related to maintaining manufacturing tolerances and assembly techniques at the highest possible quality level. The sensitivity of these devices to damage and contamination is naturally increased by their miniature size.

The obvious reliability concern with gas-charged metallic bellows demand flow control mechanisms is leakage of the charge gas. A total assembly leak rate of < 1 std pL/s of helium is necessary for a multi-year life. This problem can be well controlled by the use of porosity-free metallic bellows, proper sealing techniques, and appropriate solder and braze alloys. Long-term failures due to possible fatigue, creep, or micro-crack propagation have been studied during cyclic thermal fatigue tests. Several batches of different gas-charged bellows assemblies were cycled 10000 times per batch. Each cycle consisted of 20 s in liquid nitrogen, 40 s warm-up, 20 s in 90 C distilled water, and 40 s cooldown. A special machine was constructed for these tests, entitled the Bellows Aging Tester, which is now a standard manufacturing test at APD Cryogenics. The results showed the following failure rate for variously assembled gas-charged bellows: 0 failures

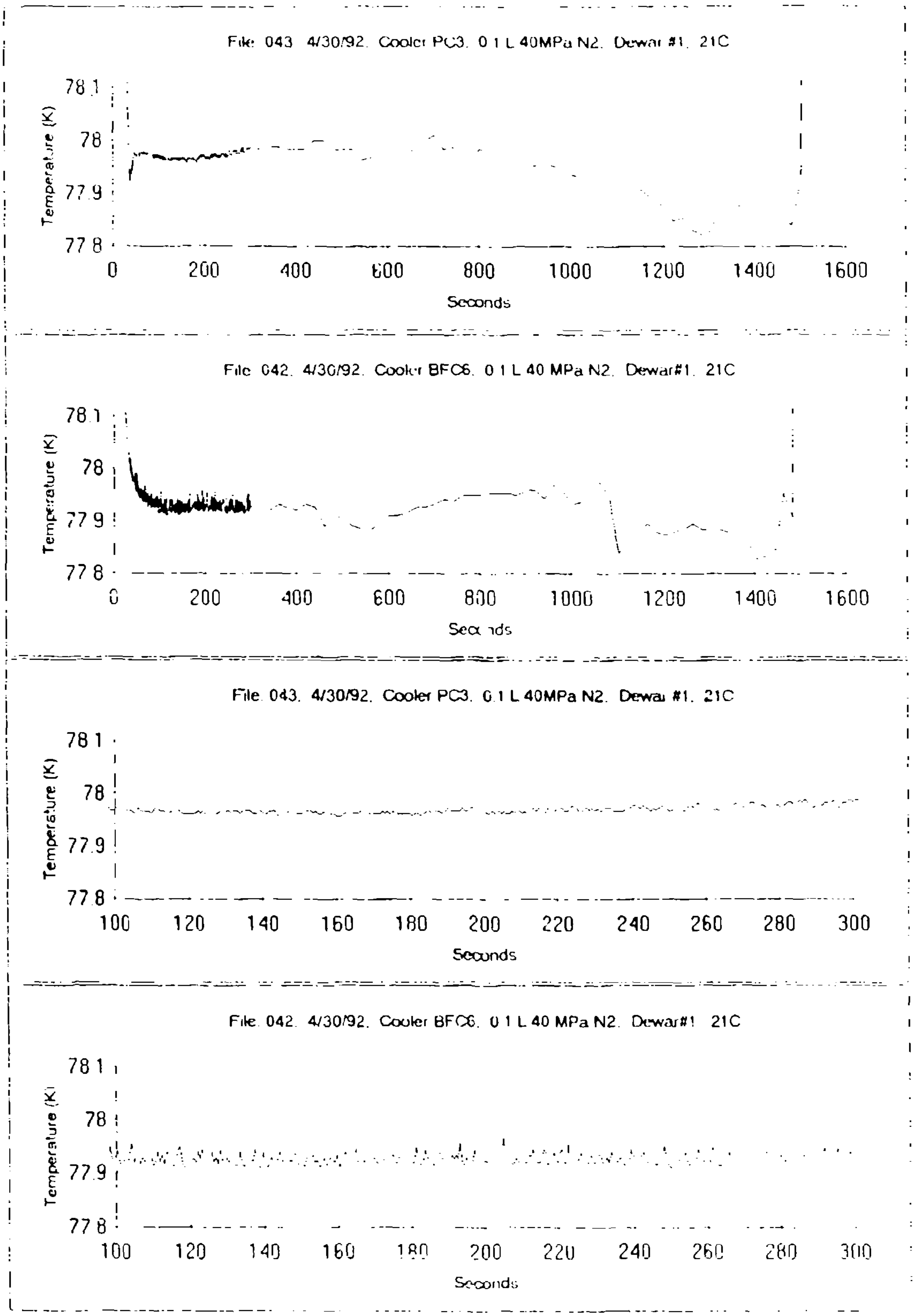

FIGURE 2 Performance Comparison of Bi-material (PC3) and Gas-Charged Bellows (BFC6) Controlled Demand Flow JT Coolers in Blowdown Mode

@ 0-600 cycles, < 5 % @ 0.6-1.7 k cycles, < 5 % additional @ 1.7-6.7 k cycles, and < 15 % additional @ 6.7-10 k cycles (i.e. < 25 % total failures over 10 k cycles). Failures due to gas loss were typically at joints and attributed to fatigue failure of the bond. The other major failure was the bellows itself becoming distorted (tilted, curved, or twisted). Distortion was attributed to fabrication stresses in the bellows being relieved.

Bi-material demand flow control mechanisms have essentially no mechanical failure modes, provided the assembly employs proper fastening techniques. No mechanical failures were revealed with a batch of assemblies during a 10 k cycle thermal fatigue test (4 min @ 77 K, 1 min warm-up, 4 min @ 70 C, 1 min cooldown). Other reliability concerns with bi-material mechanisms are primarily associated with the properties of the materials chosen. For instance, the use of certain plastics raises concern for possible failures due to exposure to excessively high temperature or humidity. Tests have been conducted on bi-material mechanisms that utilize thermoplastic polymers with low melting temperatures and low moisture absorption rates. Over the extreme temperature range of -51 C to 71 C per Mil-Std-810 there were no failures nor changes in operating performance after either short-term or long-term exposure. Exposure to higher temperatures of 80-110 C also did not cause mechanical failure, but did cause the operating performance to become inconsistent. In all cases the average flow rate after throttling increased. Therefor, the present temperature limit for these bi-material control mechanisms has been set @ 80 C. Exposure to humidity extremes of 0-100 % relative humidity did not cause any mechanical failures, but did cause inconsistent operation. Specifically, dry assemblies (vacuum baked for several weeks @ < 3 kPa and 70 C) were exposed to 100 % relative humidity for 5-19 days. This caused only a 2-4 % change in throttle response. Again, in all cases the average flow rate after throttling increased. To keep this issue in perspective, one must remember that > 2 ppm_v of water vapor is enough to cause a typical miniature demand flow JT cooler to malfunction.[11] Therefore, exposure to humidity is not desirable for any JT cooler.

SUMMARY

Bi-material flow control mechanisms have been developed to a level that offers an alternative to the more prevalent gas-charged bellows mechanisms for demand flow JT cooler applications. The bi-material mechanism reduces the complexities of product development and manufacturing for diverse customer applications. It allows for the design of smaller demand flow JT coolers. It has been shown to provide improved flow and temperature stability for better refrigerant utilization, and it improves the cooler's mechanical reliability.

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