A NOVEL CLOSED SYSTEM, PRESSURE CONTROLLED HEAT PIPE DESIGN FOR HIGH STABILITY ISOTHERMAL FURNACE LINER APPLICATIONS

Taylor Maxwell,[1] Jon Mott[2], Devin Pellicone[3], Darren Campo[4], and Richard Bonner[5]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

Helen McEvoy[6]
National Physical Laboratory, Teddington, Middlesex, TW11 0LW

Pressure Controlled Heat Pipes (PCHPs) are becoming more widely used in the temperature calibration industry due to their ability to provide highly uniform, stable, and repeatable temperature environments. These devices have been shown to achieve milliKelvin temperature stability by actively controlling the pressure within the heat pipe using a non-condensable buffer gas. This paper will discuss the operating principles of the PCHP and two alkali metal PCHP calibrator systems recently developed by Advanced Cooling Technologies, Inc. (ACT)

The first alkali metal PCHP calibrator system developed by ACT was delivered to Physikalisch-Technische Bundesanstalt (PTB) in 2014. This closed-system PCHP consisted of a vertically oriented Sodium/Inconel 600 PCHP with helium as the buffer gas. The results of a CFD analysis are discussed, which demonstrate the importance of proper placement of the radiation shield within the PCHP to minimize the dynamic pressure drop of the vapor. Preliminary experimental testing at 600°C and 800°C show temperature stability better than +/- 5mK for about 2 hours. The second PCHP system discussed in this work is currently under fabrication and will be delivered to National Physical Laboratory (NPL) in August 2016. The NPL PCHP system consists of two independently operated, closed-system alkali metal PCHPs (Potassium/Inconel 600 and Sodium/Haynes 230) which use helium as a buffer gas. Unlike the PTB PCHP, these units were designed to operate horizontally to allow for more flexibility during instrument calibration. Both PCHPs have 5x thermocouple wells on one end cap and a single blackbody cavity on the opposing end, which enable simultaneous thermocouple and IR camera calibration. Together, this dual-PCHP system is designed to operate over a temperature range of 400-1100°C, while maintaining better than 3mK stability. A complete discussion of the test results will be presented in a separate paper.

Key words: heat pipe, PCHP, temperature, calibration, isothermal, stability

---

[1] Project Engineer, Custom Products, 1046 New Holland Ave., taylor.maxwell@1-act.com, (717)-295-6823
[2] Engineering Technician, Custom Products, 1046 New Holland Ave.
[3] Lead Engineer, Special Products, 1046 New Holland Ave.
[4] Lead Engineer, Custom Products, 1046 New Holland Ave.
[5] Manager of Custom Products, 1046 New Holland Ave.
[6] Senior Research Scientist, Temperature and Humidity Standards, Hampton Rd. Teddington Middle

I. Introduction

Advanced Cooling Technologies has supplied heat pipes as isothermal furnace liners (IFLs) and heat pipe blackbody cavities (HPBC) to the temperature calibration industry since the company's inception in 2003. These devices provide suitable thermal performance for numerous applications with temperature stability on the order of 100 mK. However, for applications that require increased temperature stability and uniformity, more sophisticated technologies become necessary. Pressure controlled heat pipes (PCHPs) have been researched for several decades due to their superior performance in creating isothermal environments. However, the commercial availability of these devices is limited. ACT began internally developing PCHP technology several years ago on a NASA Goddard Phase II Small Business Innovation Research program and has since designed and fabricated two alkali metal PCHP calibrator systems with turn-key controls. The first PCHP system was delivered to Physikalisch-Technische Bundesanstalt (PTB) in 2014 and the second system is currently under fabrication and will be delivered to National Physical Laboratory (NPL) in August 2016. The design, fabrication, and testing of these systems will be discussed in more detail throughout the paper.

II. Background

Isothermal Furnace Liners and Blackbody Cavities

An Isothermal Furnace Liner (IFL) is a type of constant conductance heat pipe with an annular geometry. IFLs are used to achieve highly uniform temperature profiles within a furnace by redistributing heat to colder regions within a furnace. The temperature uniformity attainable in most applications is within 100mK over the entire axial length of the liner. This degree of uniformity allows the user to apply a precise set point with a single thermocouple and controller, which greatly simplifies thermal control and stability of the system. A heat pipe blackbody cavity (HPBC) is essentially an IFL with an internal cavity having either a hemispherical or conical shaped end cap. The cavity inner surface is typically oxidized or coated to achieve a high emissivity for calibrating infrared thermometry equipment.

Gas-Loaded Heat Pipes

In the heat pipe industry, a gas loaded heat pipe is typically categorized as either a Variable Conductance Heat Pipe (VCHP) or a Pressure Controlled Heat Pipe (PCHP). A VCHP is similar to a conventional heat pipe but usually has a reservoir at one end containing a specified amount of non-condensable gas (NCG), as seen in Figure 1. When heat is applied to the evaporator portion of the pipe, the NCG is swept toward the condenser end by the flow of the working fluid vapor. The NCG prevents the working fluid from reaching a portion of the condenser. As the evaporator temperature increases, the vapor temperature (and pressure) rises, which compresses the NCG (Figure 1 top) and thus more condenser is exposed to the working fluid. This increases the effective conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Figure 1 bottom). This reduces the amount of available condenser, decreases the effective heat pipe conductivity, and increases the evaporator temperature [1].

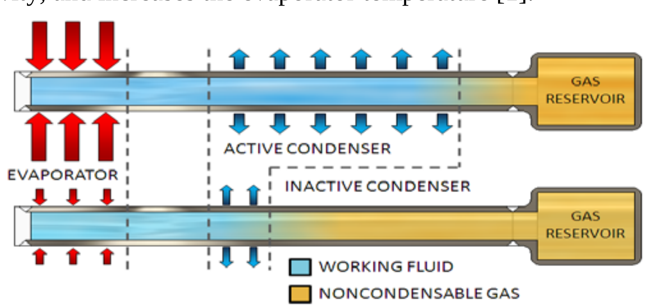

Figure 1. The working of a VCHP is illustrated. At high heat load, the temperature dependent saturation pressure of the working fluid is high and compresses the NCG into the reservoir. At lower heat input the working fluid temperature and pressure is lower, and the non-condensable gas expands into the condenser.

Pressure controlled heat pipes (PCHPs) are similar to VCHPs, in that, a vapor-buffer gas interface position in the pipe moves to vary the conductance of the heat pipe. The control mechanism in a PCHP, however, is active rather than passive. This provides a much tighter control of temperature and can allow changing of the set point after the heat pipe has been fabricated. There are two means by which the pressure (and temperature) can be controlled in a PCHP: 1) by varying the number of moles of gas in the system or 2) by varying the volume of the reservoir. In practice, these methods of control are realized by actively injecting or removing NCG from the system (open system), or by varying the volume of the reservoir by expanding or contracting a bellows (closed system).

Over the past several decades, the implementation of PCHPs in the field of thermometry has proved to be extremely useful. The applications extend from calibrating standard platinum resistance thermometers (SPRTs) and radiation thermometers to further improving the realization and dissemination of the International Temperature Scale of 1990 (ITS-90) and non-uniqueness [2-4]. Regarding the PCHP design, open system approaches which add or remove buffer gas to maintain a set point seem to be the most commonly studied throughout the thermometry community. Some researchers have shown that the use of a gas injection mode of control was capable of stabilizing the operating temperature against changes in input power or heat loss to within 0.001K for several hours [5]. The current paper discusses two open-system PCHPs which are capable of attaining comparable levels of temperature stability and are arguably less complicated than closed-system PCHPs.

III. PCHP Systems Developed for Metrology Labs

Design Overview of Physikalisch-Technische Bundesanstalt (PTB) System

The PCHP calibrator system for PTB was designed as an all-in-one, turn-key system with an operating temperature range from 600-1000°C and a temperature stability of +/- 5mK or better. In order to meet the operating temperature specifications, a combination of sodium working fluid and Inconel 600 envelope materials were used. The PCHP geometry included an outer diameter of 4.500 in. (114mm), and 6x thermowells with an internal diameter of 0.478 in. (12.1 mm) and length of 19.68 in. (499.7mm). The thermowells are accessible through the insulation panel on top of the furnace. The PCHP also features a chimney port which connects to the bellows and helium charging sub-assembly. This chimney extends out of the furnace through the insulation panel adjacent to the thermowell entry points. One thermowell is intended to serve as a primary feedback sensor for the control system, which is a Type R thermocouple. The additional thermowells are used for the sensors to be calibrated by the comparison method. A CAD model of PCHP can be seen Figure 2a. The PCHP is then installed into a commercial furnace that has been customized to accommodate the unique geometry of the PCHP (see Figure 2b).

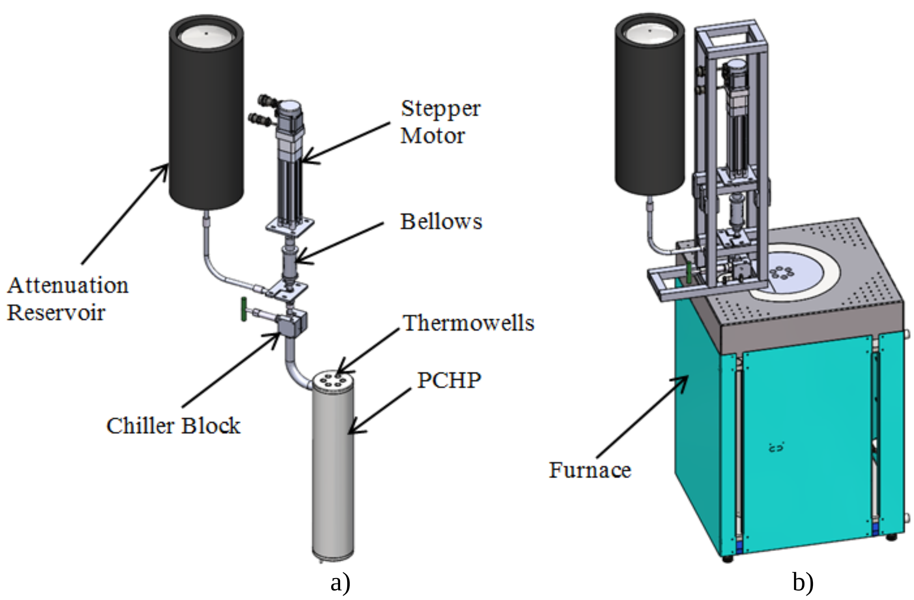

Figure 2. a) CAD representation of Sodium PCHP b) PCHP installed into furnace

The PTB PCHP is also equipped with a hydro-formed stainless steel bellows enclosed in a protective cylinder. The cylinder guides the bellows movement and prevents the bellows from squirming. Squirming is an undesirable sideways movement of the bellows, which is prevented by the use of a guide bore. The bellows movement is controlled by an electric servo motor and drive that is capable of +/-0.008 in. (0.02mm) positional accuracy.

Ultra-high purity Helium (+99.999%) is used as the buffer gas to control the operating pressure, and hence, temperature of the system. A helium charging sub-system (not shown in figure), allows the operator to pressurize the system to each corresponding set point temperature of interest. The system also includes an attenuation reservoir, which was intended to provide additional capacitance to the system for increased temperature stability. However, as will be shown in the sections below, the motor-controlled bellows system was capable of meeting the performance specifications without the use of the attenuation reservoir.

CFD Analysis of Radiations Shield

One factor that must be considered when designing a PCHP is the possible influence of the fluctuating furnace power on the temperature stability of the PCHP. As the furnace controller varies the power on and off to maintain a certain temperature set point, the radiative heat load on the PCHP varies and can result in unwanted temperature instabilities in the vapor space. For this reason, it is becoming common practice to incorporate a solid radiation shield that surrounds the thermowells within the heated zone of the furnace. However, for a PCHP with a fixed diameter, the addition of a radiation shield can also restrict vapor flow causing non-uniform temperatures along the pipe axis. In order to ensure a minimal dynamic pressure drop of the working fluid vapor, a computational fluid dynamic (CFD) analysis was conducted. A summary of this analysis is depicted in Figure 3.

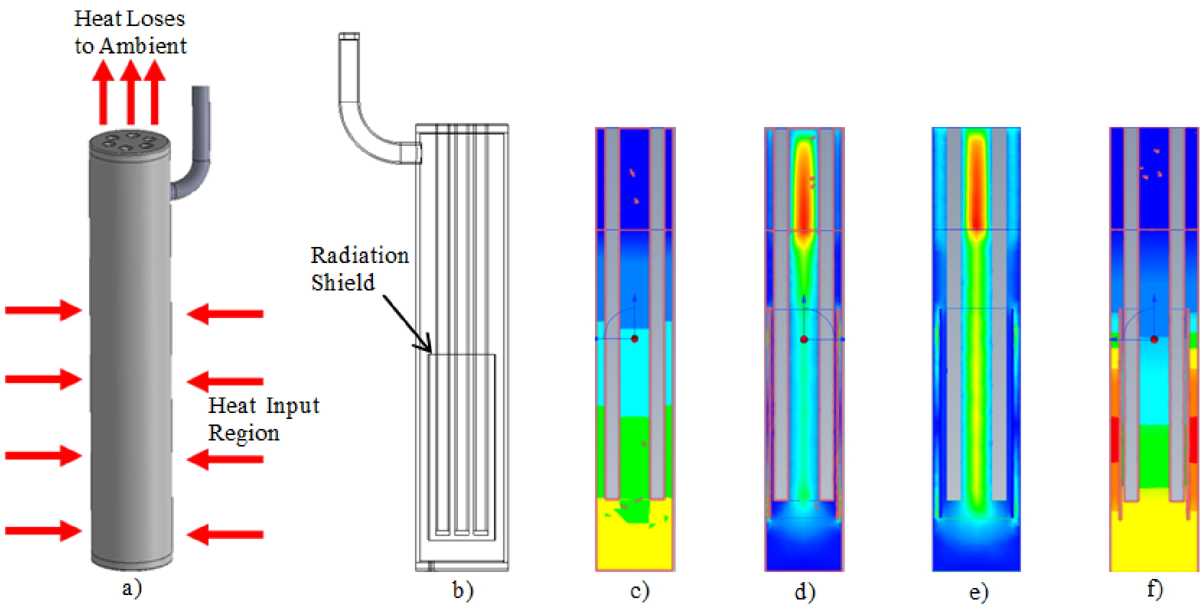

Figure 3. a) CAD model of PCHP showing heat input/output boundary conditions for CFD analysis, b) transparent view of PCHP showing position of radiation shield, c) Baseline case: 4.00in. OD, no radiation shield, ΔP = 22 Pa, d) Design 1: 4.00in. OD, radiation shield on center, ΔP = 283 Pa, e) Design 2: 4.50in. OD, radiation shield on center, ΔP = 46 Pa, and f) Design 3: 4.50in. OD, radiation shield offset, ΔP = 32 Pa.

The CFD analysis was conducted for sodium vapor properties at 600°C, where frictional effects were expected to be most prevalent due to the higher density. The vapor flow boundary conditions were determined by estimating the heat loss from the PCHP by radiation and natural convection. Figure 3c shows the CFD results for a baseline case where the PCHP outer diameter is 4 in. (101.6mm) and with no radiation shield present. For this case, the dynamic pressure drop was approximately 22 Pa. Figure 3d, e and f show the dynamic pressure results for 3 different PCHP OD/radiation shield configurations. Ultimately, it was found that the PCHP OD must increase from 4in. to 4.5in and the radiation shield be offset towards the thermowells to achieve a minimal pressure drop of 32 Pa.

Experimental Testing of PTB System

Figure 4 shows a picture of the fabricated turnkey PCHP system that was delivered to PTB. The stability of the PCHP Calibrator was measured at ACT's facility prior to commissioning at PTB to verify the system met specifications. The primary feedback sensor, the Fluke Type R thermocouple, was used for the temperature measurements. The PCHP Calibrator was located in a laboratory whose air temperature and air circulation rates were relatively constant, but it is postulated that under the proper environmentally controlled conditions, such as those in a high technology metrology laboratory, the stability can be further improved beyond the results represented herein. Prior to making any measurements, the furnace was run for several hours to allow it to reach full thermal equilibrium.

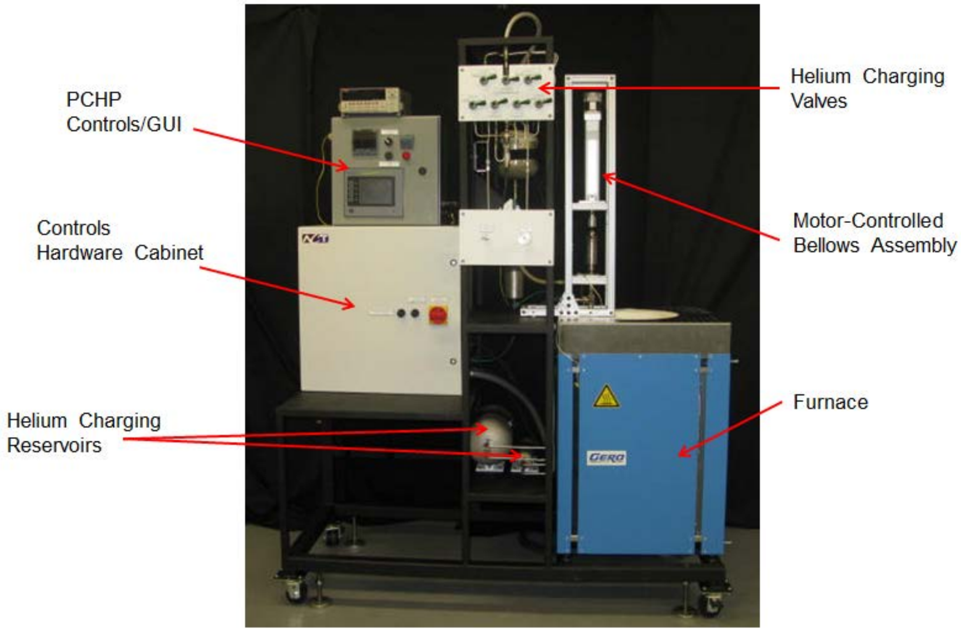

Figure 4. Fabricated Sodium/Inconel 600 PCHP turn-key system for PTB

For the stability measurements, the thermocouple was inserted to the bottom of a thermowell in the PCHP Calibrator. The thermocouple simply rested on the bottom of the Calibrator thermowell. It was not clamped or supported in any way. Readings were taken every second with the Keithley 2182A Nanovoltmeter that was calibrated traceable to NIST standards and recorded with a PC. The resulting data for measurements at 600°C and 800°C are shown in Figure 5 and Figure 6, respectively.

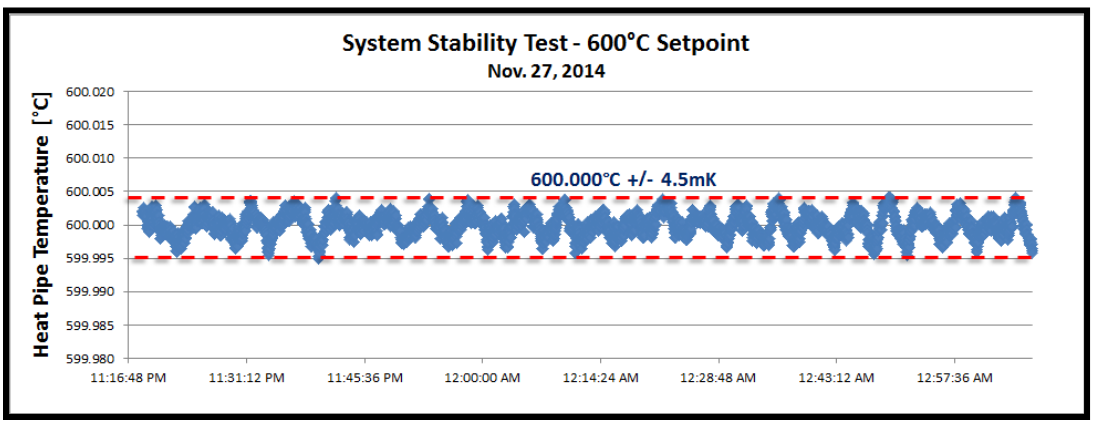

Figure 5. Temperature stability measurements of Sodium/Inconel 600 PCHP at 600°C

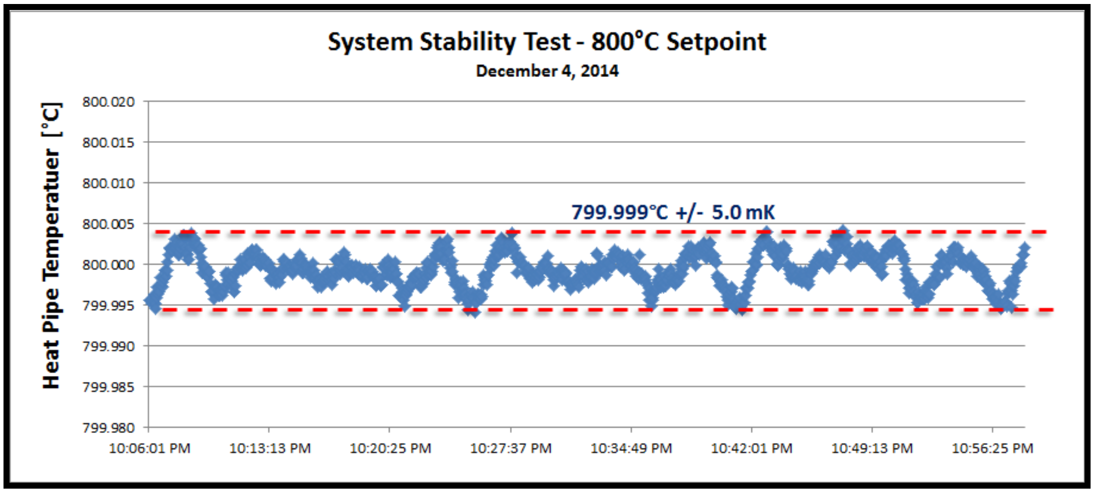

Figure 6. Temperature stability measurements of Sodium/Inconel 600 PCHP at 800°C

As can be seen in Figure 5 and Figure 6, the PCHP was capable of maintaining a temperature stability of slightly less than 5mK at 600°C for almost 2 hours, and a stability of 5mK at 800°C for 1 hour. However, since the delivery of the PCHP system to PTB, it has been reported that a stability of +/- 1mK has been achieved. Furthermore, both of the tests shown in the figures above were conducted with the helium attenuation reservoir disconnected from the system, as it was found to provide no improvement in the attainable stability. It is believed that the high precision and fast response time of motor-controlled bellows is sufficient to achieve the specified stability in this application. Use of the attenuation reservoir may be more beneficial during coarse temperature control, where pressure oscillations are relatively large; in order to minimize the time required to reach steady-state.

Dual-PCHP Calibrator System for National Physical Laboratory

The dual-PCHP calibrator system for NPL is also a turn-key system, but unlike the PTB system the NPL system contains two PCHPs that are independently controlled from a common controls system. While it would be possible to operate both PCHPs simultaneously, the controls algorithm was designed to limit the operation to one PCHP at a time to avoid any thermal interactions that might affect stability. Each PCHP is identical in design; however, they are comprised of different working fluids and envelope materials (Potassium/Inconel 600 and Sodium/Haynes 230). The two working fluids allow the system to operate over a wider range of temperature from 400-1100°C. The Potassium PCHP is designed to operate from 400-900°C and the Sodium PCHP from 700-1100°C. Both PCHPs must provide better than 5mK stability over a period of one hour and have a temperature uniformity of 100mK or better along the entire length of the thermowells.

Figure 7 shows a CAD model of the PCHP design for NPL. The PCHP main body has an outer diameter of 4 in. (102 mm), and features 5x thermowells and 1x blackbody cavity with a conical end cap. The thermowells have inner diameters of 0.512 in. (13 mm) and vary in length from 300, 400 and 500 mm. The blackbody cavity also has an inner diameter of 13 mm and a length of 400 mm. One of the 5 thermowells in the main body will be occupied by a Type R thermocouple to serve as the primary feedback sensor for the pressure control system. The additional thermowells will be used for sensors to be calibrated by the comparison method.

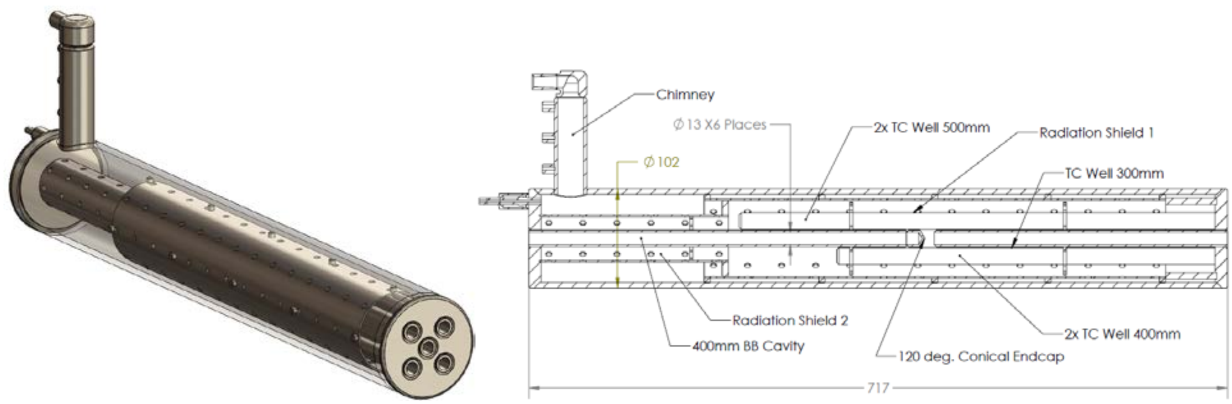

Figure 7. CAD model and drawing of the PCHP design for NPL system.

There are also two different size radiation shields incorporated into the PCHP design. The large radiation shield surrounds the thermowells within the heated section of the furnace and also partially covers the blackbody cavity. A smaller diameter radiation shield is used to cover the remaining section of the blackbody cavity to avoid restricting the vapor flow near the chimney port. In this region of the blackbody cavity, the influence of radiation from the furnace is expected to be minor, since it is not within the heated section of the furnace. However, the small diameter shield is also expected to prevent instabilities caused by any falling condensate generated in the chimney above.

The chimney port connects the bellows and helium charging sub-assembly. The chimney is perpendicular to the axis of the main PCHP body and contains 3 thermowells for monitoring the position of the buffer gas interface. Similar to the PTB system, a hydro-formed stainless steel bellows is enclosed in a protective cylinder, which guides the movement of the bellows and prevents squirm, as mentioned previously. Figure 8 shows the completed fabrication of the Potassium/Inconel PCHP along with a CAD rendering of the overall dual-PCHP system. As mentioned previously, the overall PCHP system is currently under fabrication and the performance results will therefore be published in a future paper.

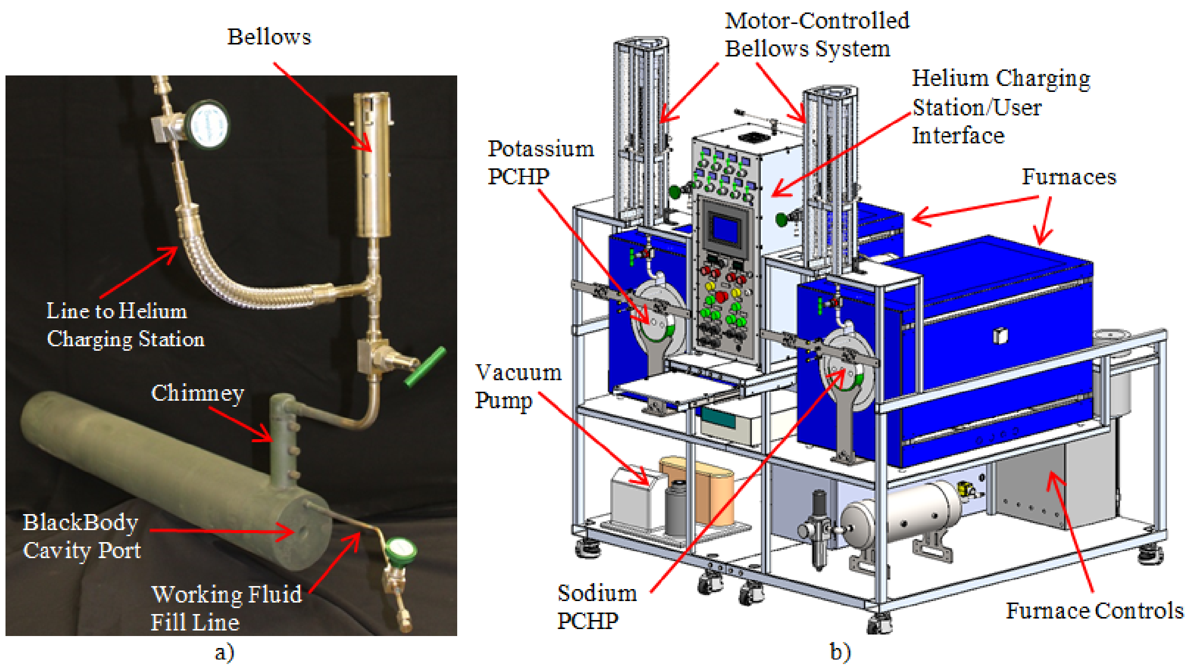

Figure 8. a) Fabricated Potassium/Inconel PCHP for NPL system, b) CAD model of turnkey dual PCHP system

IV. Summary

Throughout this paper the authors have described two alkali metal PCHP systems developed by Advanced Cooling Technologies, Inc. for delivery to two different temperature calibration laboratories. The first alkali metal PCHP calibrator system was delivered to Physikalisch-Technische Bundesanstalt (PTB) and consisted of a vertically oriented Sodium/Inconel 600 PCHP. A CFD analysis was conducted to determine the proper placement of a radiation shield within the PCHP to minimize the dynamic pressure drop of the vapor. Initial testing of the fabricated system at 600°C and 800°C showed temperature stability better than +/- 5mK for ~2 hours. The second PCHP system, which is to be delivered to National Physical Laboratory, was described as a dual-PCHP system. The PCHP system consists of two independently operated, closed-system alkali metal PCHPs (Potassium/Inconel 600 and Sodium/Haynes 230). Both NPL PCHPs were designed to operate horizontally to allow for simultaneous thermocouple and IR camera calibration, and expected to operate over a temperature range of 400-1100°C, while maintaining better than 3mK stability. Extensive testing of the system will be performed at NPL and results will be published in a separate paper.

Acronyms

CCHP	Constant Conductance Heat Pipe
VCHP	Variable Conductance Heat Pipe
PCHP	Pressure Controlled Heat Pipe
IFL	Isothermal Furnace Liner
HPBC	Heat Pipe Blackbody Cavity
PTB	Physikalisch-Technische Bundesanstalt
NPL	National Physical Laboratory
ACT	Advanced Cooling Technologies, Inc.

References

1. Sarraf, D., Tamanna, S., Dussinger, P., “Pressure Controlled Heat Pipe for Precise Temperature Control”, AIP Conf. Proc. 969, 3 (2008)

2. Yan, X., Zhang, J.T., Merlone, A., Wang, W., “NIM gas controlled sodium heat pipe”, AIP Conference Proc., Vol. 1552, Issue 1, pp.834 (2013)

3. Bonnier, G. and Renaot, A., *Metrologia* 39, pp. 363-367 (1996)

4. Marcarino, P., Dematteis, R., Li, X., Arai, M., De Groot, M., Nubbemeyer, H. G., “Preliminary Results on ITS-90 Non-uniqueness between Freezing Points of Al and Ag.”, In Proc. TEMPMEKO, pp.25-32 (1996)

5. W. B. Bienert, Heat Pipes for Temperature Control; AIChE 4th Intersociety Energy Conversion Conference, Washington, D.C. (1969)