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Gas-Controlled Heat Pipes for Accurate Liquid-Vapor Transition Measurements[1]

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At IMGC several gas-controlled heat pipes have been used to realize liquid-vapor transitions of pure fluids, such as water, potassium, mercury, and sodium. A very uniform and stable temperature zone has been realized in all cases, at the millikelvin level. Therefore, very accurate measurements of the phase-transition temperature are possible, using platinum resistance thermometers. Water and potassium heat pipes have been developed for the calibration of standard platinum resistance thermometers (SPRTs). Mercury and sodium heat pipes are used for vapor-pressure curve studies for primary thermometry. The temperature stability inside the heat pipes is maintained at the millikelvin level by means of a very accurate pressure control system specially developed at IMGC. The heat-pipe features and capabilities are summarized, together with a description of the pressure control systems. The most important results achieved using the gas-controlled heat pipes in primary thermometry and in liquid-vapor phase-transition curve measurements are reported here.

KEY WORDS: heat pipes; liquid metals; phase transitions; pressure measurements; temperature measurements; thermodynamic measurements; vapor pressure curves.

1. INTRODUCTION

In 1975, scientists of the CEC Joint Research Centre (JRC) of Ispra (Italy) suggested the possibility of using gas-controlled heat pipes for the realization of isothermal chambers with very high temperature uniformity and

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stability [1]. During the past fifteen years, there have been many efforts at IMGC to develop gas-controlled heat pipes for accurate temperature measurements. Some of those heat pipes have been used for the study of liquid-vapor transition curves, while others have been specially developed for comparison of thermometers in several temperature ranges and for the study of the International Temperature Scale ITS-90 non-uniqueness.

2. GAS-CONTROLLED HEAT PIPE

Usually cylindrical-shaped heat pipes are filled with small quantities of the so-called "working fluids," depending on the field of temperature and application needed [2]. Along the inside surface of the wall of the cylinder, a wick is placed; it is constructed, for example, from a few layers of fine gauze, by special machining, by applying a metal mesh, or combining these actions. One end of the tube is externally heated, causing the inside working fluid to vaporize and the vapor to move to the opposite end of the pipe. This part of the heat pipe is cooled, in order to condense the vapor back to liquid. The condensed liquid returns to the heated zone due to gravity and to the capillary structure on the inner wall of the heat pipe, thus closing a liquid-to-vapor and vapor-back-to-liquid cycle. A heat pipe realizes an isothermal measuring zone between the heated and cooled zones, since a stream of vapor flowing from the heated zone continuously rinses the liquid layer covering the capillary structure of the measuring zone.

The gas-controlled heat pipe is a special kind of heat pipe equipped with a gas-controlled line connected to the cooled zone that enables direct control of the inner pressure. In Fig. 1 a schematic view of the gas-controlled heat pipe is shown. An inert gas is used to control the vapor pressure of the working fluid. The controlling gas needs to have a lower density from that of the vapor of the working fluid, in order to form a stable interface between the two. Basically it is possible to recognize in a gas-controlled heat pipe two interfaces: one between the vapor and the liquid of the working fluid and another between the vapor and the gas. The vapor-liquid interface surrounds the measuring chamber. The vapor-gas interface is placed in the upper part of the heat pipe, closer to the cooled zone. Therefore, the controlling gas is almost at room temperature, thus obtaining a more stable interface and an easier gas control process. The temperature of the vapor-liquid interface is thermodynamically related to the pressure inside the heat pipe. This pressure can be controlled through the vapor-gas interface in the cooled zone. Therefore, the temperature inside the heat pipe can be controlled and maintained at any desired value, by controlling the pressure in the gas line, outside the heat pipe.

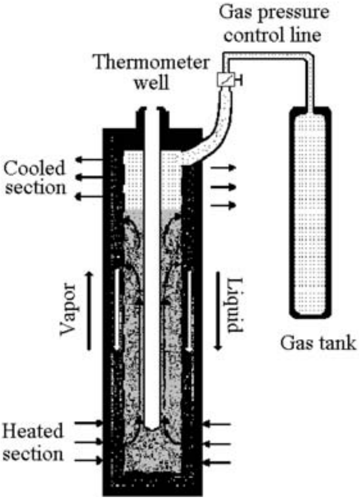

Fig. 1. Gas-controlled heat pipe.

Gas-controlled heat pipes used in thermometry are specially developed for this purpose. Recent ones are equipped with a lateral chimney used both as the cooling zone and to connect the gas control line. Inside the cylindrical chamber, one or more thermometer wells are placed. The liquid working fluid returns to the heated zone also along knurls machined around the external walls of the thermometer wells, in order to keep the measuring zone wet. This ensures a liquid-vapor interface all around the thermometer well. The measurement of the liquid-vapor phase-transition temperature is then obtained by means of standard platinum resistance thermometers (SPRTs) inserted in the wells. In some cases a mesh is also added to the knurls to increase the capillary structure and to improve the uniformity of the liquid layer, in order to obtain a complete phase-transition interface.

2. GAS-CONTROLLED HEAT PIPES FOR THERMOMETER CALIBRATIONS

2.1. Water Heat Pipe

Several Pyrex heat pipes have been manufactured at IMGC to study new working fluids and to test wire nets as capillary structures [3]. As a result of the transparency of the Pyrex, it is possible to obtain a better understanding of what happens inside the heat pipes. The upper cover is

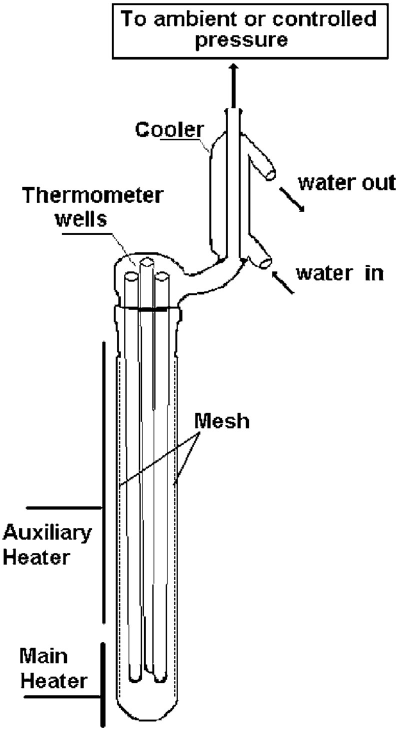

Fig. 2. Glass heat pipe.

easy removable, in order to allow changes inside the chamber. Figure 2 shows the design of one of these heat pipes.

The Pyrex heat pipes have been made with three thermometer wells, in order to compare different capillary structures obtained with cylindrical wire nets of different meshes placed around the thermometer wells. Another cylindrical wire net was placed in contact with the internal wall of the Pyrex tube.

Each heat pipe contains $\sim 80\,\text{cm}^3$ of bi-distilled and degassed water as a working fluid. The heat pipes were operating in air at ambient pressure. The heat pipe is accommodated for measurements in a small furnace. It has an automatic controlled heater at the bottom for the evaporation of the liquid and an auxiliary heater above it to extend the uniform temperature measuring zone to the chimney.

Figure 3 left shows an experiment carried out on the water heat pipe. The temperature in the water heat pipe slowly decreased by about 20 mK in two hours, following the ambient pressure. Nevertheless, during several

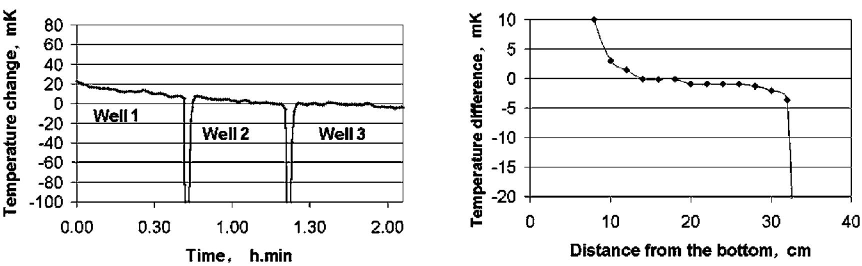

Fig. 3. Temperature uniformity among the wells (left) and along a well (right).

short periods of about 15 min each, the temperature stability was maintained well within 1 mK. This stability allows accurate measurements of the temperature distribution along each thermometer well and among the thermometer wells. After removal to room temperature and re-insertion, the thermometer reaches again equilibrium, in about 5 min. The temperature in each well is the same to within ±1 mK.

A very uniform temperature, within ±1 mK, was observed along the wells between 14 and 24 cm from the bottom of the heat pipe, as shown in Fig. 3 (right). The higher temperature at the bottom of the well was probably due to excessive heating. This heating is required to extend the liquid-vapor-liquid transformation up to the top of the heat pipe.

2.2. Potassium Heat Pipe

The potassium-filled heat pipe is made of an Inconel 600 cylindrical envelope of 3 mm thickness, 455 mm height, and 115 mm diameter, closed on both ends by disks of the same material. A lateral chimney, provided with a water cooler, is welded to the upper part of the cylindrical envelope and connects the inner volume of the heat pipe to the helium pressure line. Six thermometer wells, closed at the bottom, are welded to the top cover of the heat pipe to allow the thermometers to be inserted in the measuring chamber. The six wells are kept in the right position by an annular frame.

The capillary structure is a helical knurling covering the whole inner surface of the heat pipe, including the outer surface of the thermometer wells and the inner surface of the chimney. A cylindrical stainless-steel wire net of 90 meshes per square centimeter was positioned on the knurl of the inner surface of the external heat pipe wall. A heater wire of Ni–Cr 80 is wound on the outer wall of the cylindrical envelope, from the bottom up to 21 cm. Heating is provided by an ac power supply of 1.25 kW. The heat pipe has been filled at IMGC with 270 g of 99.95% pure potassium.

This heat pipe was developed to improve the calibration capability of the contact thermometry laboratory, between 450 and 960°C [4]. The pressure is controlled by means of a commercial pressure controller (Druck DPI 510), that is provided with two sensors: an absolute controller with a full scale of 35 kPa, and a relative controller referenced to atmospheric pressure with a full scale of 300 kPa. With these two sensors, the resolution of the instrument is better than 1 Pa up to 35 kPa and within 15 Pa above 35 kPa.

The temperature stability and uniformity in the measuring chamber have been measured at 100°C steps in the range between 440 and 940°C. At each temperature step, starting from 440°C, the heating power to the heat pipe was adjusted to ensure that the potassium fluid is rinsing all of the inner surface of the heat pipe without overheating the wall. Indeed, overheating would destroy the liquid-vapor interface in the overheated zone.

The temperature stability is more difficult to achieve at the minimum operating temperature, since $\mathrm{d}T/\mathrm{d}P$ has the highest value and the stability of the pressure controller is lower because it is related to the full scale of the sensor. Nevertheless, a temperature stability within ± 5 mK can be obtained for a period of over 8 h at about 440°C.

The temperature uniformity among the thermometer wells was measured by means of two thermometers inserted into separate wells. One thermometer was maintained in one well (No. 3) to measure the temperature stability. The other thermometer was moved to each well every 20 min. Figure 4 shows the results of the experiment carried out at 640°C.

All these measurements were repeated for every temperature step. As a result, the maximum temperature difference among wells is, on average, less than 10 mK. The temperature uniformity along the wells was found to be within 15 mK along the first 15 cm from the bottom of any of the thermometer wells, over the temperature range between 440 and 930°C.

3. GAS-CONTROLLED HEAT PIPES FOR PRIMARY THERMOMETRY

3.1. Pressure Control System

The pressure regulation is the key point in the gas-controlled heat pipes when a very stable pressure and temperature are required.

A dedicated pressure line has been made at IMGC to control the pressure inside the heat pipes [5]. The pressure control system drives the opening of servovalves and the movement of a bellows for coarse and fine pressure regulation. A pressure control sensitivity at the level of 10^{-6} is

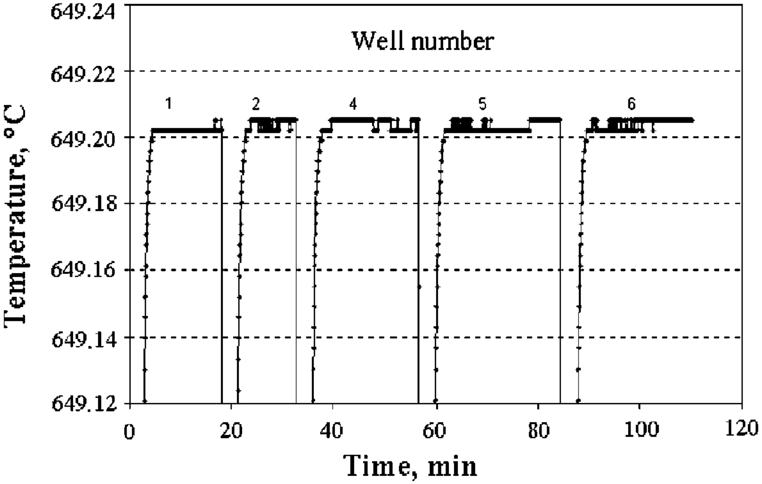

Fig. 4. Temperature uniformity among the wells at 640°C.

reached by using a dc motor to control movement of the bellows in a vessel of about 50 ℓ connected to a helium line of the heat pipes, for very short time intervals, within 6 ms. The developed software allows this time interval control.

The gas used to control the pressure inside the heat pipes is helium, in order to obtain a stable gas-vapor interface inside them. The gas used in the quartz pressure gauges and in the standard interferometric manobarometer (BIPM/Jaeger) for pressure reference is nitrogen. The separation between the two gases is obtained with a diaphragm transducer.

The temperature inside the heat pipes is measured by means of SPRTs. The resistance of the thermometers is detected by three automatic resistance bridges: an Automatic Systems Laboratories F18, through its scanner ASL 148/158, a Measurements International 6010B, and an NBS/CAPQ.

Two computers connected in a master/server configuration are used for the pressure control and temperature measurements. The server drives all temperature data acquisition instruments, such as the automatic resistance bridges and the multimeters. All temperature data are automatically recorded, and the information necessary for pressure control is sent to the master through a serial line. The master controls the helium pressure, and consequently the temperature inside the heat pipes. Figure 5 shows a schematic view of the system architecture.

Ad hoc software [6] has been developed to attain a high level of automation in the whole process of acquisition and control. Time action within a few milliseconds required by the fine control was obtained as

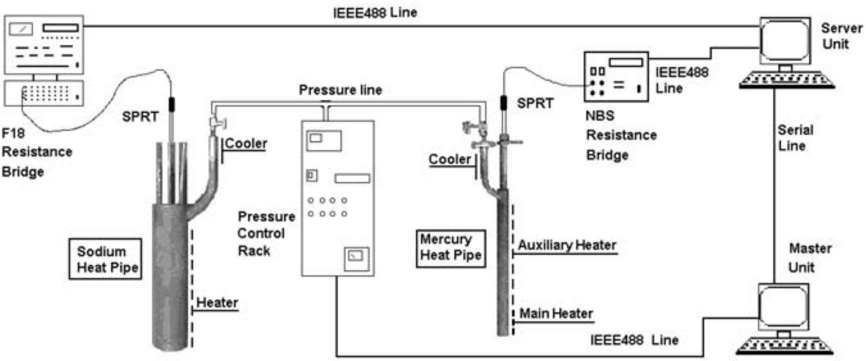

Fig. 5. Schematic view of the heat pipes and their pressure control system.

a result of specifically developed subroutines. Many modules and virtual consoles have been developed to let the whole system work without manual operation.

The described control system allows a new concept in pressure regulation: the use of the PRT as a pressure sensor. In this case the set point of the control is given as a resistance value. The resistance of a SPRT inserted inside the thermometer well of one heat pipe is read by an automatic resistance bridge driven by the server. The resistance value is then sent to the master that uses it as input of a PID algorithm to control the bellows action. As a result of the thermodynamic relation between the pressure and temperature of the boiling working fluid, the pressure change, due to the bellows action, results in a temperature change, which is read by the SPRT as a resistance change. This resistance change is then fed back into the control loop. The resolution of the resistance measurements and the sensitivity of the control of 10^{-6} provides a temperature stability of a few tenths of a millikelvin in each heat pipe. Figure 6 shows an example of the automatic pressure and temperature control.

The PRT regulation gives temperatures and pressures more stable than using a pressure gauge, even if the thermometer is installed in the sodium or mercury heat pipe. When the PRT is inserted into the mercury heat pipe, the long term stability of the SPRTs between 240 and 400°C allows a pressure stability of about 2.5×10^{-6} in the complete range from 8 to 200 kPa.

A chromel-alumel thermocouple has been mounted on the outer wall of the lateral chimneys of the heat pipes, some centimeters below the cooler for control of the position of the gas-vapor interface. A multimeter reads the voltages values from the thermocouple. The gas-vapor interface moves along the chimney of the heat pipe when the gas pressure is changed. When the pressure is increased, the vapor-gas interface goes down in the heat

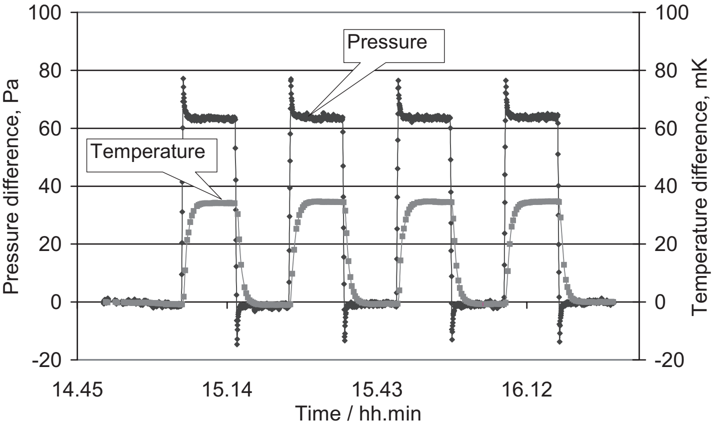

Fig. 6. Example of temperature and pressure automatic control at 103 kPa.

pipe, while a pressure decrease forces the vapor-gas interface to go up closer to the cooler, with the risk that sodium vapor solidifies closing the line between the heat pipe and the gas. Therefore, any pressure decrease has to be done very slowly, to avoid accidental overflows of sodium into the gas line, at ambient temperature.

3.2. Mercury Heat Pipe

One heat pipe, made by JRC of Ispra, has recently been filled with mercury. It is made of an Inconel 600 cylindrical envelope of 3 mm thickness, 465 mm height, and 30 mm diameter, closed on both ends by disks of the same material. A lateral chimney, provided with a water cooler, is welded to the upper part of the cylindrical envelope and connects the inner volume of the heat pipe to the helium line. A thermometer well allows the thermometers to be inserted into the measuring chamber. The heat pipe has been filled at IMGC with approximately 280 g of 99.999999% pure mercury.

The device is provided with a main heater at the bottom for the evaporation of the mercury and an auxiliary heater along the length of the heat pipe to extend the phase transition up to the chimney. Several experiments were carried out on the mercury heat pipe for the determination of the temperature distribution along its thermometer well, while varying the heating power supplied to the two heaters. The temperature distribution along the thermometer well was determined by measuring the resistance of a SPRT by stepwise removal and subsequent re-introduction, every 2 cm. Each measurement was performed 2 min after the SPRT setting in order to reach thermal equilibrium.

An initial finding was that a too high power supplied to the auxiliary heater can dry, at some points, the wall of the heat pipe, destroying the liquid-vapor interface; precaution is required.

A second finding was that the temperature values between 14 and 22 cm from the bottom depend slightly on the total power supplied to both heaters, but not on the power supplied to each one. This is due to the fact that the position of the interface between the mercury vapor and the helium gas is determined by the equilibrium between heating and cooling. The thermocouple on the chimney, about 5 cm below the water cooler, detects the interface position, set by manually adjusting the power supplied to the heaters. The position of the vapor-gas interface, so close to the cooler, does not appreciably change when the thermometer is slowly moved.

A third finding was that by removing or re-introducing the thermometer, a small pressure change is induced because of shifts in the vapor-to-liquid ratio. Indeed, a movement of the thermometer along the existing temperature gradient causes a small heat flux to or from the vapor that changes the amount of liquid and vapor. In order to compensate for the small pressure changes due to the movement of the thermometer, the pressure is accurately controlled by the previously described control system using a high temperature standard platinum resistance thermometer (HTSPRT) as a sensor, inserted in the sodium heat pipe connected in parallel. The control is able to compensate for these small pressure changes due to the movement of the thermometer. Figure 7 shows the curves obtained at 82 kPa with the above precautions being followed.

The curve shows a higher temperature in the bottom of the well, because the metal support of the well introduces a heat flux from the

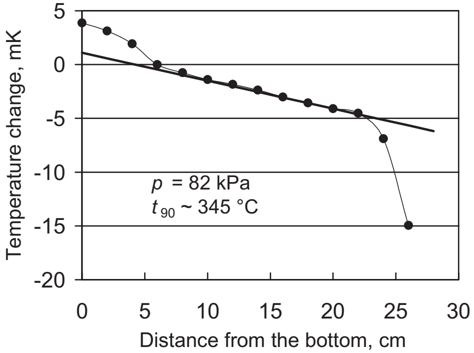

Fig. 7. Temperature profile along the thermometer well in the mercury heat pipe. The solid line indicates the calculated slope for hydrostatic effect.

external heater to the bottom of the well. The temperature profile is found to be linear from 14 cm up to 22 cm from the bottom. In this zone the curve follows very closely the Clausius–Clapeyron curve (solid line) for the hydrostatic pressure gradient given by the equation

$$\Delta p = \rho_{\mathrm{v}} g h \tag{1}$$

where ρ_{v} is the density of mercury vapor at 82 kPa, g is the acceleration of gravity, and h is the height of the vapor column above the measured point. The density of mercury vapor was derived from the literature [7]. For an evaluation of the hydrostatic pressure gradient, the density of mercury vapor may also be approximated, with sufficient accuracy, by use of the ideal gas law:

$$\rho_{\mathrm{v}} = p\,\frac{M}{R_0 T} \tag{2}$$

where p is the pressure (82 kPa), M is the molar mass ($200.61\ \mathrm{g \cdot mol^{-1}}$), R_0 is the universal gas constant ($8.314472\ \mathrm{J \cdot K^{-1} \cdot mol^{-1}}$), and T is the absolute temperature (~ 516 K).

The experiment was repeated at 8.36, 29.3, and 196.7 kPa, and in all cases, the temperature distribution along the thermometer well above ~ 12 cm followed the Clausius–Clapeyron relationship calculated from the above equation.

Using this mercury heat pipe, the relationship between vapor pressure and temperature of mercury was established between 10 and 101.33 kPa with an uncertainty within 0.10% at the 99% confidence level [8]. This relationship between vapor pressure p and temperature T is usually represented by the equation,

$$\ln \frac{p}{p_0} = \sum_{n=0}^{k-1} A_n T^{n-1} + B \ln \frac{T}{T_0} \tag{3}$$

where T_0 is the temperature at the standard pressure p_0, A_n and B are experimental coefficients, and k is a correlated empirical constant, depending on the substance and the range on the transition curve. Nesmeyanov [9] suggests that $\ln(p/p_0)$ requires at least 4 constants:

$$\ln\left(\frac{p}{p_0}\right) = a + \frac{b}{T/T_0} + c\,\frac{T}{T_0} + \ln\left(\frac{T}{T_0}\right) \tag{4}$$

where $p_0 = 101325$ Pa and $T_0 = 273.15$ K. This vapor-pressure equation has been fitted to the experimental pressure and temperature data acquired.

The fit has been evaluated by the least-squares method, and the calculated coefficients a, b, c, and d were found to be:

$$a = -17.5242$$

$$b = 14.8791$$

$$c = -9.69052$$

$$d = 40.$$

3.3. Sodium Heat Pipe

The sodium heat pipe operating at IMGC was constructed by the JRC of Ispra in 1995. This gas-controlled heat-pipe furnace has the same design, with six thermometer wells, as the potassium heat pipe previously described. A Kanthal heater wire is wound on the outer wall of the cylindrical envelope, all along the pipe.

This heat pipe was used in 1996 for the comparison of high temperature standard platinum resistance thermometers within ±0.5 mK over the whole range between 660 and 960°C, for the study of ITS-90 non-uniqueness [10].

Also, for this heat pipe, several experiments were carried out for the determination of the temperature distribution along each thermometer well and among the thermometer wells. Better reproducibility was found after the cooling of the thermometer wells with a stainless-steel rod at room temperature. The cool rod induces the sodium vapor to condense on the thermometer well in order to obtain the phase-transition layer completely surrounding it. This treatment is required each time the heat pipe is turned off at room temperature for a long time. The heat pipe can operate with the vapor-liquid interface completely surrounding the thermometer wells for months without any further treatments.

Figure 8 shows the obtained temperature profile in one thermometer well of the sodium heat pipe. The temperature distribution was uniform within a few tenths of a millikelvin up to 18 cm from the bottom. Indeed, for sodium, the hydrostatic effect of the vapor is about one order of magnitude smaller than for mercury.

The temperature measured in different thermometer wells is the same within ±0.3 mK, as soon as the transient induced by the transfer of the thermometer from one well to another is recovered by the pressure control. The temperature stability that can be achieved in the sodium heat pipe by controlling the pressure with a SPRT in the mercury heat pipe is, at about 1000 K, a few tenths of a millikelvin, as shown in Fig. 9.

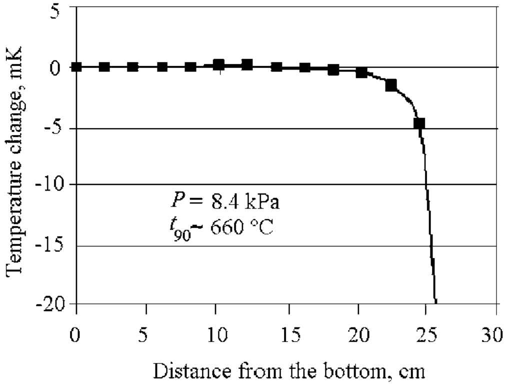

Fig. 8. Immersion temperature profile in the sodium heat pipe.

Using the sodium heat pipe, the relationship between vapor pressure and temperature of sodium was established between 10 and 200 kPa with an uncertainty of about 10 mK in temperature [11]. The relationship turned out to be the following:

$$\log P = -\frac{5427.094}{T} - 0.4011 \log T + 10.92888. \tag{5}$$

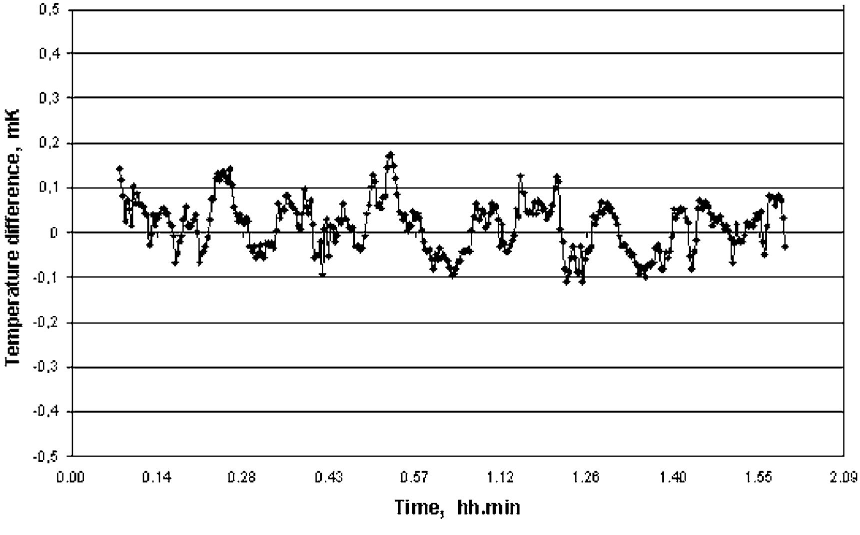

Fig. 9. Example of achievable temperature stability at 1000 K in the sodium heat pipe.

4. “TEMPERATURE AMPLIFIER”

The work carried out on the mercury and sodium heat pipes connected to the same pressure line provides a complete understanding on the new concept of a “temperature amplifier” [12]. Any temperature in the mercury heat pipe is thermodynamically related to a corresponding higher temperature in the sodium heat pipe.

The experiments for the evaluation of the temperature amplification curve have been carried out by determining the direct thermodynamic relationship $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ at 25°C steps in the sodium heat pipe from 660 to 962°C.

The pressure was measured by means of a MKS sensor and the temperature by means of a SPRT in the mercury heat pipe and two HTSPRTs in the sodium heat pipe, recorded by NBS and F18 resistance bridges. One more thermometer in a thermometer well of the sodium heat pipe has been used for temperature regulation.

Several experiments have been carried out for the determination of the derivative $\mathrm{d}T/\mathrm{d}P$ and $\mathrm{d}T_{\mathrm{Na}}/\mathrm{d}T_{\mathrm{Hg}}$ relations and the thermodynamic $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ curve.

4.1. Derivative Relations $\mathrm{d}T_{\mathrm{Na}}/\mathrm{d}T_{\mathrm{Hg}}$ and $\mathrm{d}T/\mathrm{d}P$

The first investigation has involved the evaluation of the $\mathrm{d}T_{\mathrm{Na}}/\mathrm{d}T_{\mathrm{Hg}}$ and $\mathrm{d}T/\mathrm{d}P$ relations. It was obtained by changing the pressure inside the two heat pipes in steps and measuring simultaneously both the sodium and mercury vapor-liquid temperatures and pressures. The pressure change was

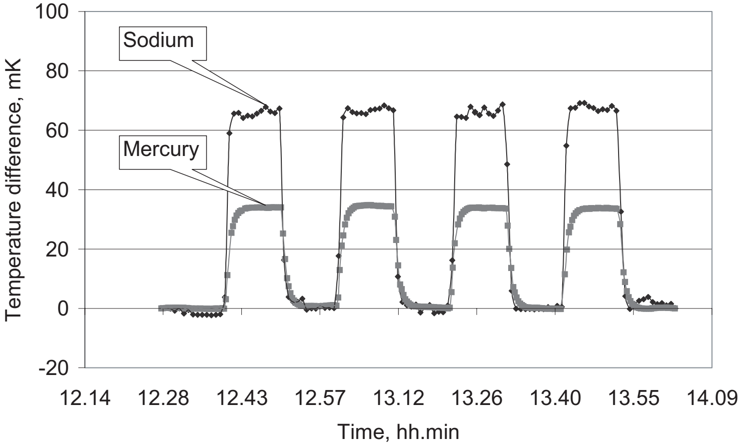

Fig. 10. Temperature changes in the mercury and sodium heat pipes at ~ 82 kPa.

Table I. $\mathrm{d}T/\mathrm{d}P$ Values and Their Relative Uncertainties

Pressure (Pa)	$\mathrm{d}T_{\mathrm{Hg}}/\mathrm{d}P$ ($\mathrm{mK \cdot Pa^{-1}}$)	Uncertainty ($\mathrm{mK \cdot Pa^{-1}}$)	$\mathrm{d}T_{\mathrm{Na}}/\mathrm{d}P$ ($\mathrm{mK \cdot Pa^{-1}}$)	Uncertainty ($\mathrm{mK \cdot Pa^{-1}}$)
8380	4.400	0.892	8.603	1.735
11721	3.356	0.482	6.586	0.937
16160	2.473	0.250	4.857	0.488
21924	1.990	0.156	3.926	0.302
29304	1.524	0.089	2.993	0.186
38636	1.262	0.056	2.487	0.116
50263	0.973	0.034	1.923	0.064
64610	0.807	0.022	1.602	0.043
82072	0.662	0.013	1.317	0.026
103260	0.530	0.009	1.049	0.018
128260	0.461	0.006	0.916	0.012
158580	0.395	0.005	0.786	0.011
196747	0.332	0.003	0.659	0.008

done by moving the bellows for a fixed time in one direction and, after ten minutes, in the other direction. Figure 10 shows a sample of both sodium and mercury temperature changes at about 82 kPa. The results of the experiments are reported in Table I. The $\mathrm{d}T_{\mathrm{Na}}/\mathrm{d}T_{\mathrm{Hg}}$ turns out to be linear at first approximation, causing the $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ relation to be, at least, quadratic.

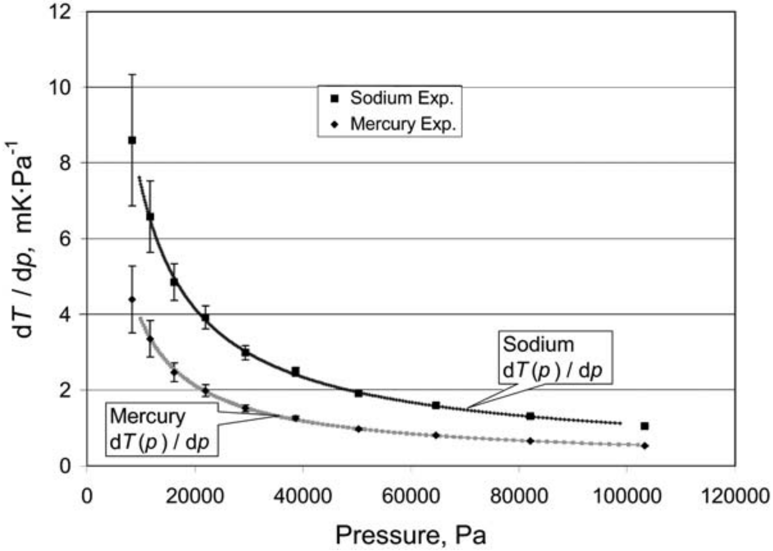

Fig. 11. $\mathrm{d}T/\mathrm{d}P$ experimental points with their uncertainties for the derivative relations from Eqs. (4) and (5).

The dT/dP experimental points for both sodium and mercury are reported in Fig. 11, together with their uncertainties and the curves obtained deriving the previously and independently evaluated $P(T)$ relationships.

4.2. $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ Relation

Measurements for the $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ relation determination have been carried out during the previous experiment at the same temperature steps. During this investigation the pressure has been maintained under PRT regulation.

The temperature measurements have been carried out, taking into account the self-heating effect for the measuring current in the resistance thermometers. The measurement sequence consisted of four steps: (1) SPRT in the mercury heat pipe, (2) HTSPRT No. 1 in the sodium heat pipe, (3) HTSPRT No. 2 in the sodium heat pipe, and (4) SPRT in the mercury heat pipe. The results are reported in Table II.

As seen from the evaluations of the $dT_{\mathrm{Na}}/dT_{\mathrm{Hg}}$ derivative relation in Section 4.2, $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ has to be, at least, quadratic. A quadratic fit has thus been evaluated, but with unsatisfactory results, as the residuals between the fitted relationship and the experimental values were found to be $\pm 0.02°\mathrm{C}$, which is larger than the uncertainties of the experimental values.

A cubic fit of the experimental data gives the following relation:

$$t_{\mathrm{Na}} = at_1^3 + bt_1^2 + ct_1 + d \tag{6}$$

Table II. Measured Temperatures for Mercury and Sodium

Pressure (Pa)	t_{Hg} (°C)	σt_{Hg} (°C)	t_{Na} (°C)	σt_{Na} (°C)
8.380	243.6795	0.0006	660.3632	0.0036
11.721	256.3956	0.0005	685.1024	0.0028
16.160	269.1787	0.0006	710.0556	0.0053
21.924	281.9277	0.0005	735.0117	0.0070
29.304	294.6513	0.0007	760.0027	0.0061
38.636	307.3345	0.0006	784.9919	0.0053
50.263	319.9679	0.0006	809.9654	0.0045
64.610	332.5730	0.0006	834.9680	0.0055
82.072	345.1012	0.0013	859.8996	0.0054
103.260	357.6389	0.0038	884.9310	0.0070
128.260	369.9755	0.0017	909.6510	0.0046
158.580	382.5275	0.0007	934.8807	0.0056
196.747	395.8102	0.0014	961.6863	0.0029

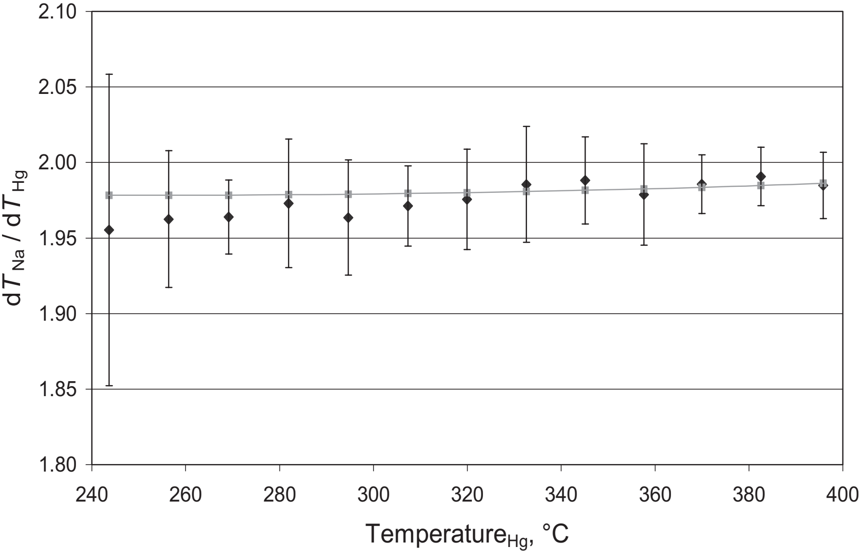

Fig. 12. Experimental dT_{Na}/dT_{Hg} points and the evaluated derivative relation.

where

$$a = (1.266 \pm 0.070) \times 10^{-7}$$

$$b = (2.591 \pm 0.003) \times 10^{-4}$$

$$c = 1.98008 \pm 0.00003$$

$$d = 810.0303 \pm 0.0008\,^{\circ}\mathrm{C}$$

$$t_1 = t_{Hg}/^{\circ}\mathrm{C} - 320.$$

Figure 12 shows experimental dT_{Na}/dT_{Hg} points, previously evaluated, their relative uncertainties at 1σ, and the derivative curve from Eq. (6). The results show good agreement between the experimental dT_{Na}/dT_{Hg} points and the derivative of Eq. (6).

5. CONCLUSIONS

The gas-controlled heat pipes used at IMGC for the realization of liquid-vapor transitions of pure fluids, such as water, potassium, mercury, and sodium allow temperature measurements at the millikelvin level.

The water and potassium heat pipes are used for accurate calibrations of contact thermometers by comparison. The mercury and sodium heat pipes have been used for the study of vapor-pressure curves for primary thermometry.

The connection of the mercury and sodium heat pipes to the same pressure line allows the use of a SPRT in a heat pipe for very accurate pressure control, beyond the normal resolution of pressure gauges. With this apparatus, the study of mercury and sodium phase transitions has been carried out at a level of a few tenths of a millikelvin in all the operating ranges of the heat pipes. The thermodynamic relation between the temperatures of vapor-liquid transitions of pure mercury and sodium has been determined. This relationship can be used to transfer the very high reproducibility of SPRTs below 400°C in the mercury heat pipe, within 2×10^{-7}, to high temperature in the sodium heat pipe, resulting in a reproducibility between 600 and 962°C better than that obtained with the HTSPRTs.

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