TEMPERATURE AMPLIFIER BY MEANS OF COUPLED GAS-CONTROLLED HEAT-PIPES

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ABSTRACT

BNM-INM and IMGC-CNR have been working during many years in the field of Gas-Controlled Heat-Pipes (GCHPs). These devices have been specifically developed for accurate temperature measurements, with ever improving thermal characteristics during the last 30 years.
A GCHP is based on the thermodynamic properties of the liquid-vapor transition of a given working fluid under a controlled pressure. The measuring zones of the more recent GCHPs, connected to an accurate pressure controlled line, present a temperature uniformity and stability at the millikelvin level in a very large range of temperature. The basic principles of GCHPs are reviewed and the most important results achieved by using this device in thermometry are presented.
By applying the same pressure to several GCHPs using different working fluids, the temperature in one GCHP is thermodynamically related to the temperature in another GCHP. It means that any temperature of a given working fluid, i.e. between 240 °C and 400 °C for a mercury GCHP, is able to be "amplified" in order to establish an unique and very reproducible higher temperature in another working fluid, i.e. between 660 °C and 962 °C for a sodium GCHP. This instrument, called "Temperature Amplifier" (TA), allows a considerable improvement in the calibration process of SPRTs at high temperature. Indeed, the operating temperature of the reference SPRT in the low temperature GCHP can be limited to 400 °C, and, consequently, the stability and reproducibility in the high temperature GCHP are largely improved. The experimental results lead to the possibility to use the TA above the Aluminum point as a possible alternative instrument in a future temperature scale.

1. INTRODUCTION

During the past twenty years, there have been many efforts at BNM-INM and IMGC-CNR to develop Gas-Controlled Heat-Pipes (GCHPs) for accurate temperature measurements. Most of the GCHPs used in the two laboratories have been manufactured by the Joint Research Center (JRC) of Ispra, that continuously improved these devices on the basis of the obtained results. Unfortunately, JRC of Ispra stopped construction of GCHPs in 1997, because of a change of activity. After that, BNM-INM acquired a GCHP in stainless-steel by the Institut für Kernenergetik und Energiesysteme (IKE) of Stuttgart, while IMGC-CNR started modifying some of the GCHPs made by Ispra, in order to test new working fluids and new capillary structures. Both BNM-INM and IMGC-CNR are now operating with several GCHPs connected to the same pressure line and using different working fluids. The resulting apparatus has led to the so-called "Temperature Amplifier" (TA), in which the temperature in one GCHP operating at low temperature is thermodynamically related to the temperature in another GCHP operating at higher temperature. This technique is very promising for improving the reproducibility at high temperature. The experience achieved by BNM-INM and IMGC-CNR in the field of the GCHPs and of the TA for temperature measurements are presented in this paper.

2. GAS-CONTROLLED HEAT-PIPE

2.1 The Heat–Pipe

The Heat-Pipe (HP) is a device that transfers heat with a very high thermal conductance, by evaporating fluid at one point and condensing it at another point. It is similar in some respect to a thermosyphon except for the fact that in the HP the liquid is transferred back to the evaporation area by capillary action through a wick structure, and not only thanks to gravity. Figure 1 shows the operating principle of a HP.

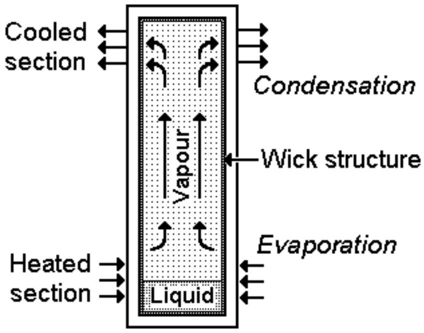

Figure 1: The Heat-Pipe.

Usually cylinder shaped, HPs are filled with small quantities of the so-called “working fluids”, depending on the field of temperature and application needed. Along the inside surface of the cylinder wall a wick structure is placed: it is constructed for example by specially machined knurls, by applying a metal mesh or a combination of these items. One end of the tube is externally heated, causing the inside liquid to vaporize and the vapor to move to the opposite end of the pipe. This part of the HP is cooled, in order to condense the vapor back to liquid. The condensed fluid returns back to the heated part of the HP due to capillary forces of the wick structure, thus closing a liquid-to-vapor and vapor-back-to-liquid cycle. Since the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from one end to the other end in the HP. The effective thermal conductivity of the device can be as much as 500 times that of a solid copper rod of similar dimensions.

Thanks to the capability of those devices in creating thermally uniform chambers, the use of HPs was extended to thermometry in the middle of the 70s. In thermometer comparison furnaces, HPs are used to maintain a better temperature uniformity in the measuring zone. HPs are also used inside fixed-point furnaces to keep the temperature uniform around the fixed-point cell. In this application the HP is placed between the heater and the cell. The working fluid inside the HP evaporates from its external wall, which is in contact with the heater, and condenses on its internal wall close to the cell. The temperature uniformity around the fixed-point cell is better than 0,01 °C, thus allowing an almost perfect control on the solid-liquid interface of the fixed-point. Several working fluids may be used, depending on the fixed-point temperature.

2.2 The Gas-Controlled Heat–Pipe

The GCHP is a special kind of HP equipped with a pressure line that enables a direct control of the inside pressure. An inert gas is used to control the vapor pressure of the working fluid. The gas needs to have a lower density than that of the vapor of the working fluid, in order to generate an interface between the two. This interface is established at a variable point along the vertical axis of the HP, depending on factors such as the heating power, the refrigerating capabilities, the pressure value, the kind of working fluid and controlling gas used. The inner chamber of the HP is in nearly isothermal condition, since it is continuously rinsed by a stream of vapor, flowing from the heated section to the cooled one. Basically it is possible to recognize in a GCHP two interfaces: one between the vapor and the liquid of the working fluid and another between the vapor and the gas. Figure 2 shows the operating principle of a GCHP.

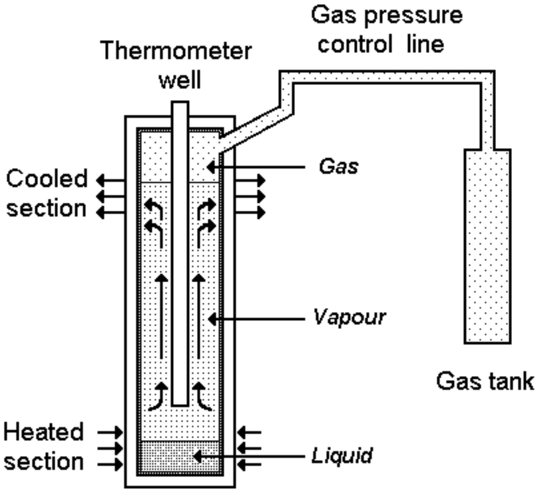

Figure 2: The Gas-Controlled Heat-Pipe.

For accurate temperature measurement, the vapor-liquid interface must surround completely the measuring chamber. The vapor-gas interface is situated in the upper part of the HP, close to the cooled zone. Therefore the controlling gas is almost at room temperature. This makes the gas control processes easier, and no peculiar attention on its temperature is required. The temperature of the vapor-liquid interface is thermodynamically related to the pressure inside the GCHP volume. This pressure can be controlled by the gas through a control line. Therefore, the temperature inside the GCHP can be controlled and maintained at any desired value, just by controlling the gas pressure.

2.3 The performance of a Gas-Controlled Heat–Pipe

The performance of a GCHP was first studied by Busse and Bassani [1]. A detailed theoretical analysis of the performance limits of an ideal and of a real HP thermostat was provided. It was demonstrated that in first approximation the temperature T in the measuring chamber is equal to the temperature T_i of the liquid-vapor interface around the measuring chamber, while the measured pressure P_m of the gas outside the GCHP is equal to the pressure P_v of the vapor inside the GCHP. Consequently, it follows that:

$$T = T_i(P_v) = T_i(P_m). \tag{1}$$

This means that the temperature in the measuring chamber and the pressure at the measuring instrument are related by the vapor pressure curve of the working fluid in the GCHP. From the Clausius-Clapeyron equation and the ideal gas law it follows that:

$$\frac{dT_i}{T_i} = \frac{RT_i}{ML}\frac{dP_v}{P_v}, \tag{2}$$

where R is the gas constant, M the molar mass of vapor and L the specific heat of vaporization. From equation (1), one obtains

$$\frac{\Delta T}{T} = \frac{RT}{ML}\frac{\Delta P_m}{P_m}. \tag{3}$$

According to the Pictet-Trouton rule, $ML \approx 10RT_b$, where T_b is the boiling point of the working fluid. Since the GCHPs are generally operated in the pressure region between about 8 kPa and 500 kPa, which corresponds in the first approximation to a temperature variation within ± 20% around the boiling point, the equation (3) may be written as:

$$\frac{\Delta T}{T} \cong 0.1\frac{\Delta P_m}{P_m}. \tag{4}$$

In practice, equation (1) has to be modified by a correction ΔT, and it becomes:

$$T = T_i\left(P_m\right) + \Delta T\,. \tag{5}$$

The correction is caused by the fact that equation (l) may be not strictly valid, because the measured pressure P_m of the gas may be not perfectly equal to the vapor pressure P_v inside the GCHP. This inequality depends on several factors listed in Table 1:

Table 1: Factors influencing the correction ΔT of equation (5)

	Effect	**Requirement**	**Correction**
1	Dynamic pressure drop in the flowing vapor.	Suitable dimensions of the GCHP and a lateral cooling chimney.	$< 10^{-7}$
2	Hydrostatic pressure variation in the vapor.	Suitable wick structure and power heating on the outside of the GCHP.	Clausius-Clapeyron immersion curve
3	Diffusion of the gas inside the vapor flow.	Adequate inert gas of lower density than that of the vapor, such as helium.	$< 10^{-7}$
4	Liquid-vapor interface distribution.	Suitable capillary structure around the entire surface of the measuring chamber.	$< 10^{-7}$
5	Impurity of the working fluid.	Continuous regeneration of the vapor-liquid interface with small concentration of non-volatile substances in the vapor and small solubility of inert gas and volatile impurities in the liquid.	$< 10^{-6}$
6	Rates of condensation and evaporation.	Adequate heating and cooling power to prevent the vapor from superheating and subcooling.	$< 10^{-6}$
7	Heat conduction through the measuring chamber.	Measuring chamber completely surrounded by the liquid-vapor interface to prevent heat fluxes.	$< 10^{-6}$
8	Heat radiation through the vapor.	Metal shield in the measuring chamber to prevent radiation through the vapor	$< 10^{-6}$

2.3 The Gas-Controlled Heat-Pipe for temperature measurements

During the last 30 years, the GCHPs design was largely modified. The initial version was simply a cylindrical tube with an internal thermometer well for the temperature measurements, as shown in Fig. 2 [2 - 6]. All the walls in contact with the working fluid were covered by machined knurls for the capillary structure. The heating zone was obtained by immersing the lower part of the cylindrical tube in a furnace, while the cooling zone was obtained by cooling the protruding part from the furnace by means of a water cooler. The pressure line was connected to the top of the cylindrical tube after the cooling zone. This type of GCHP, filled with sodium, showed a temperature uniformity within ±0.01 °C at about 883 °C along 15 cm of the thermometer well. Therefore, it is adequate for temperature measurements by means of High Temperature Standard Platinum Resistance Thermometers (HTSPRTs).

The most recent GCHPs are equipped with a lateral chimney used both as a cooling zone and to connect the gas control line, as shown in Fig. 3 [7 - 13]. The lateral chimney prevents the cooled liquid from dropping down in the measuring chamber and disturbing its temperature stability and uniformity. Inside the cylindrical chamber one or more thermometer wells are placed. The capillary structure of the GCHP provides to keep the measuring zone continuously wet. For several GCHPs, the capillary structure of the HP is improved by adding cylindrical stainless-steel wire nets on the machined knurls [11, 12]. This ensures a complete and uniform liquid layer all around the thermometer wells. In this way, the (HT)SPRTs inserted in the wells are completely surrounded by the liquid-vapor interface and correctly measure the liquid-vapor phase transition temperature. This type of GCHP is adequate for accurate comparison and calibration of (HT)SPRTs at the millikelvin level. Figure 3 shows this type of GCHP with its heater.

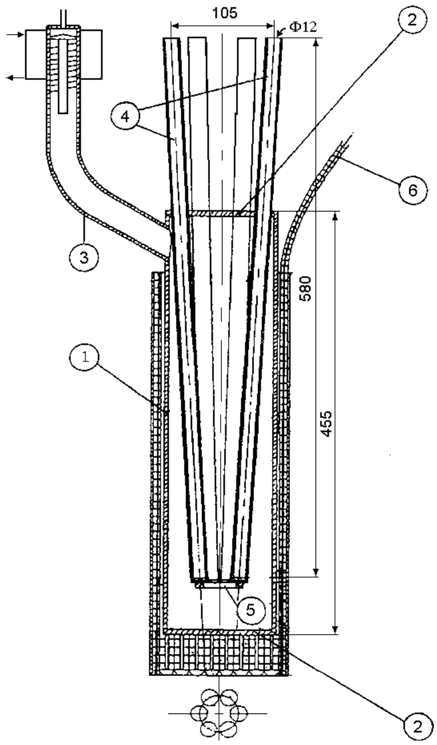

Figure 3: The BNM-INM and IMGC heat-pipes (1: cylindrical envelope; 2: end discs; 3: lateral chimney; 4: thermometer wells; 5: annular frame; 6: Kanthal heater).

The vapor of some working fluid operating at high temperature, such as sodium, is transparent to infrared radiation. In a last design of this type of GCHP, a metal shield was inserted in the vapor between the outer wall and the thermometer wells, in order to prevent the transmission of infrared radiation from the heater to the thermometer wells. A sodium GCHP of this type was used by IMGC-CNR to study the ITS-90 non-uniqueness between the Al and Ag fixed points [11]: a temperature uniformity within ±0.5 mK was achieved in each thermometer well and among them in the whole range from 660 °C to 962 °C. The effect of the infrared radiation in a BNM-INM sodium GCHP, without metal shield, was evaluated by connecting it to the same pressure line of the IMGC-CNR sodium GCHP with metal shield. The direct comparison showed the temperature in the BNM-INM GCHP to be 40-60 mK higher because of the radiation effect [14].

The GCHP of Fig. 3 is filled under an inert atmosphere of argon with about 250-300 cm^3 of working fluid [15]. The amount of the working fluid is calculated in order to have enough liquid to maintain all the surfaces of the measuring chamber wet. The liquid in the bottom of the GCHP must avoid contact with the thermometer wells. After filling, the GCHP is connected to the pressure line and the argon gas is substituted by the helium gas. Then, the GCHP is slowly heated to start evaporation of the working fluid. This operation is performed very slowly in order to prevent the surface of the measuring chamber from overheating when it is not covered by the liquid layer. When the HP starts to operate, a liquid layer covers all the surface of the measuring chamber. Precaution is required to avoid overheating and drying the surface of the measuring chamber, since the liquid-vapor interface may be easily destroyed in some point, giving an incorrect temperature measurement. When the liquid-vapor interface completely surrounds the measuring chamber, the measured temperature is thermodynamically related to the pressure in the GCHP volume. This pressure is controlled by the helium gas through the chimney.

Other GCHPs of different design have been specifically developed for special applications in thermometry. A GCHP for the realization of metal freezing points in adiabatic conditions was manufactured by the JRC of Ispra for BNM-INM [16, 17]. This GCHP was equipped with one single large measuring well for the introduction of a metal freezing point cell in place of the thermometer wells, but all the other parts were almost identical to those reported in Fig. 3. This GCHP was used by BNM-INM to realize the freezing point transition of silver with the calorimetric method and to evaluate the uncertainty in the fixed point realization due to the thermal conditions.

Other GCHPs were manufactured at IMGC-CNR in Pyrex, where the capillary structure of the measuring chamber have been obtained by means of cylindrical stainless-steel nets placed in contact with the inner wall of the glass body and around the glass thermometer wells [18]. This type of GCHP was specifically developed for the study of new working fluids, such as water and some of 3M^{TM} heat-transfer fluids, and for the test of wire nets of different mesh. The results of this test were essential for the improvement of the capillary structure of the IMGC-CNR mercury GCHP and to obtain, for the first time, a perfect agreement between the immersion characteristic measured in the thermometer well and the Clausius-Clapeyron profile [19].

2.4 The pressure control system

It was previously demonstrated that near 101 kPa a pressure variation is directly related to a temperature change by equation (1). Then, i.e. for a sodium GCHP, a pressure stability of ±1 Pa aver 101 kPa is required to achieve a temperature stability better than ±1.2 mK at the sodium boiling-point (~1156 K). At a pressure of 5 kPa, the millikelvin temperature stability can be obtained with a pressure stability of about ±0.1 Pa. The pressure control system should operate from 5 kPa to 500 kPa and be able to satisfy the above requirements, but no commercial pressure controller is available with such characteristics. On the other hand, a temperature stability at the 10 mK level can be obtained by means of a commercial controller able to work within ±10 Pa at 101 kPa and ±1 Pa at 5 kPa. Since any pressure gauge has an uncertainty related to its full scale, the range from 5 kPa to 500 kPa can be covered within the required uncertainty by means of two or more gauges. Therefore, each pressure controller needs to be equipped with two or more pressure gauges [4 - 13]. The general scheme of the pressure control system specially designed for GCHPs is presented in Fig. 4.

A control system for GCHPs is equipped with a pressure controller provided with a high pressure line for the pressure increases, and with a low pressure line for the pressure decreases. The high pressure line of the controller is connected through a reduction valve to a helium pressurized tank, while the low pressure line is connected to a vacuum roughing pump. The controlled pressure line of the controller is connected to the GCHP through a 30-50 L buffer volume, thermally insulated. This buffer attenuates any pressure fluctuation due to perturbations which may occur, for instance, when immersing a cold thermometer into the GCHP. A by-pass vacuum line connects the roughing pump directly to the GCHP and to the buffer for accurate cleaning of the pressure line, in order to guarantee always the maximum purity of the helium gas.

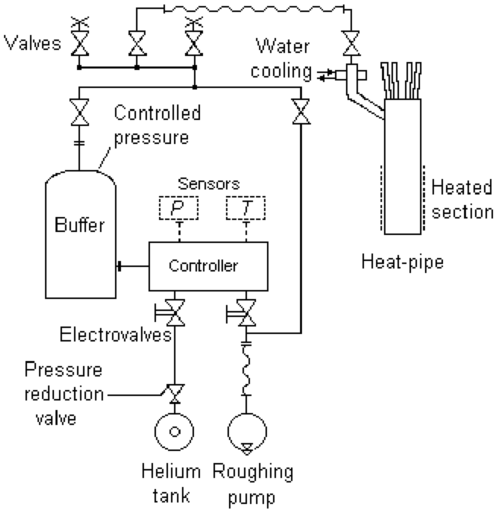

Figure 4: The pressure control system for GCHPs. Both a pressure gauge (P) and a PRT (T) can be used by the controller as sensor.

Both BNM-INM and IMGC-CNR have equipped their GCHPs for the calibration by comparison of platinum resistance thermometers and of thermocouples with a commercial pressure controller (the pressure calibrator Druck DPI 510 provided with two pressure sensors: one for lower pressure and the other for higher pressure) [12, 13, 20]. With this controller a temperature stability at the 10 mK level is obtained in either caesium, potassium or sodium GCHPs.

The control of the helium pressure in the GCHPs operating at the best level is obtained at IMGC-CNR by means of a computerized pressure control system [21, 22]. The pressure control is obtained by opening inlet and outlet electrovalves connected to high and low-pressure lines, for coarse regulation, and by moving a bellows inside the buffer volume, for fine control, thus achieving a resolution to within 1 ppm. A computer drives a multimeter for the reading of the pressure gauges and a data /acquisition control unit acting on the electrovalves and the bellows.

During experiments carried out at IMGC-CNR, the measured temperature in a GCHP immediately followed any pressure change, since the temperature depends on the pressure of the vapor in contact with the vapor-liquid interface [9]. When the vapor-liquid interface completely surrounds the thermometer, the delay induced by the metal well is negligible, because of the high thermal conductivity due to the liquid-vapor-liquid transitions. Therefore, the measured temperature can be used to control the pressure in a GCHP. The pressure control system realized at IMGC-CNR allows this possibility [10, 11]. The computer for the pressure control system also receives the temperature data from a single SPRT in one of the thermometer wells of the GCHP, and controls the helium pressure to a set-point value corresponding to the resistance of the SPRT. The use of a PRT as a sensor for pressure control in a GCHP allows very high pressure/temperature stability in the whole operating range, a performance not available with a pressure gauge [19, 23]. Indeed, the PRT sensitivity remains almost constant in a wide temperature range. Since pressure is thermodynamically related to temperature, this means that the PRT, used as pressure sensor, gives a better sensitivity than a pressure gauge having the sensitivity related to full scale. Figure 5 shows the temperature stability well within ±0.2 mK obtained in a mercury GCHP by using a SPRT for pressure control.

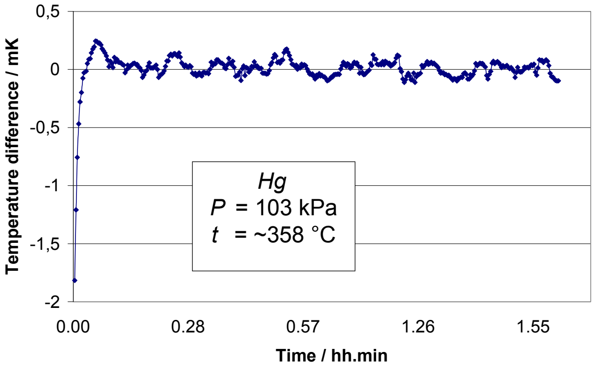

Figure 5: Temperature stability in a mercury GCHP with pressure control using a SPRT as sensor.

2.5 P-T relationship of some working fluids

Several working fluids have been used for the GCHPs of BNM-INM and of IMGC-CNR. The *P-T* relationship between vapor pressure *P*, in Pa, and thermodynamic temperature *T*, in K, is usually obtained by integration of Clausius-Clapeyron's equation. It may be expressed by the following logarithmic equation

$$\ln\frac{P}{p_0} = \sum_{n=0}^{k} A_n (T)^{n-1} + B\ln\frac{T}{T_0}. \tag{6}$$

where T_0 is the temperature at the standard pressure p_0, A_n and B are experimental coefficients, k is an empirical constant, depending on the substance and the range on the transition curve. In first approximation k may be set to 2, on the basis of a solution of equation (6) assuming a linear variation of the latent heat of vaporization with temperature. The coefficients A_1, A_2 and B of equation (6), approximated in this way, are available in literature for many working fluids.

The *P-T* relationship was directly determined independently by BNM-INM and IMGC-CNR for several working fluids used in their GCHPs, as sodium [7, 24], potassium [20, 24], caesium [24], mercury [25, 26] and dodecane [24, 27]. In some cases, three coefficients were sufficient. In other cases, more coefficients were needed in order to obtain a best fit of the experimental *P-T* data. The Fig. 6 shows the *P-T* curves, between the vapor pressure *P*, in Pa, and the ITS-90 temperature *T*, in K, of the working fluids commonly used in the GCHPs of BNM-INM and of IMGC-CNR.

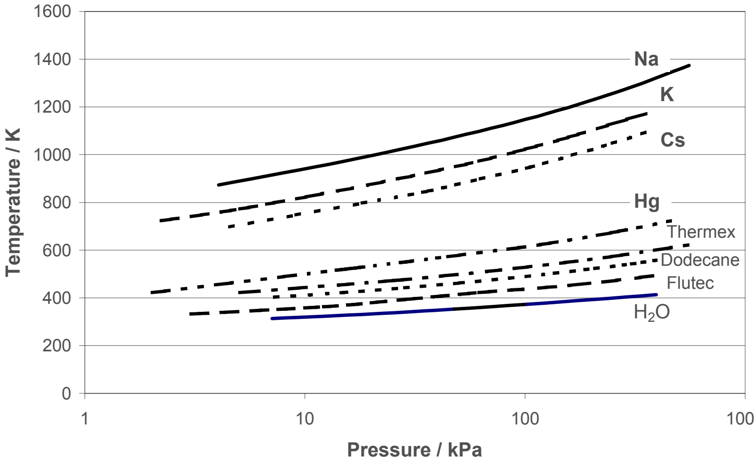

Figure 6: P-T curves of the working fluid commonly used in the BNM-INM and IMGC-CNR GCHPs.

Generally, the *P-T* relationships obtained by means of GCHPs, resulted at least one order of magnitude more accurate than those obtained with other methods. Indeed, with a GCHP the measured temperature corresponds to the equilibrium temperature of the vapor-liquid interface, while with other methods temperature is measured in the liquid or the vapor [28].

3. TEMPERATURE AMPLIFIER

By connecting several GCHPs to the same pressure line, the temperature in a GCHP using one working fluid is correlated to the temperature in another GCHP using a different working fluid. This is the direct consequence of equation (1): the temperature and the pressure in a GCHP are related by the vapor pressure curve of the working fluid in the GCHP. By means of two GCHPs, one using a working fluid with a boiling point at low temperature and the other using a working fluid with a boiling point at higher temperature, any temperature in the first GCHP is “amplified” to a corresponding temperature in the other GCHP. The apparatus resulting from connecting several GCHPs to a same pressure line is called TA. Both BNM-INM and IMGC-CNR have realized the TA, but following two different approaches.

3.1 The BNM-INM Temperature Amplifier

BNM-INM used GCHPs for the comparison-calibration of platinum resistance thermometers and of thermocouples. Its pressure control system is equipped with a commercial controller, that allows temperature stability at the 10 mK level, as described before. Three GCHPs, filled with sodium, potassium and dodecane, are connected to the same pressure line [13, 24]. Fig. 7 shows the TA apparatus used at BNM-INM.

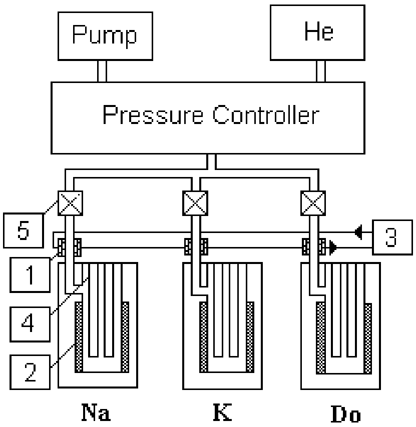

Figure 7: A schematic view of the BNM-INM “Temperature Amplifier” (1: cooled section, 4: thermometer wells, 2: heater, 5: valves, 3: cooling water).

The temperature t, expressed in °C, obtained in each GCHP is related to the same controlled pressure P by the vapor pressure relationship t=f(P) of the working fluid used in the GCHP. Therefore, the pressure value P in the line can be determined from the low temperature t_1 in the dodecane GCHP by means of the P=g$_1$(t_1) relationship of the dodecane, and then the high temperatures t_2 and t_3 in the sodium and potassium GCHPs can be determined from the t_2=f$_2$(P) and t_3=f$_3$(P) relationships of sodium and potassium. Therefore, the TA in Fig. 7 offers the possibility to calibrate a temperature sensor at 960 °C by using as reference a standard thermometer placed in a furnace at 250 °C. The temperature uncertainty in the high temperature GCHPs is evaluated from the uncertainty of the temperature measured in the low temperature GCHP and from the uncertainties of the inverse and direct vapor pressure relationships of the used working fluids, P=g$_1$(t_1) and t_2=f$_2$(P). The obtained accuracy is relatively poor, since the used relationships are logarithmic in both the t and P terms, as shown by equation (6). At 950 °C the TA apparatus allows an uncertainty of about 50 mK by using as reference a SPRT into the dodecane GCHP, at which temperatures (about 240 °C) the reference is not affected by instability.

3.2 The IMGC-CNR Temperature Amplifier

Since IMGC-CNR has developed a pressure control system using a PRT as sensor, as before described, the direct t_2=f(t_1) relationship between the temperatures in two GCHPs is used in the TA [10, 19, 23]. In a preliminary study, a diphenyl GCHP, operating between 165 °C and 290 °C, and a sodium GCHP, operating from 660 °C to 962 °C, have been connected to the same pressure line [10]. By controlling the helium pressure at about 30 kPa, a temperature of 206 °C in the diphenyl GCHP was "amplified" to about 762 °C in the sodium GCHP. The temperature stability was within ±0,15 mK in the diphenyl GCHP and within ±0,3 mK in the sodium GCHP. However, in spite of these encouraging results, good operating conditions could not be achieved: a temperature non-uniformity larger than 1 mK/cm was measured at all temperatures along the thermometer well of the diphenyl GCHP. This gradient was attributed to inadequate thermal properties of diphenyl.

To overcome those problems a new system was set up, where the sodium GCHP was used together with a new mercury-filled GCHP, both devices being connected to the same helium pressure line [19]. In the mercury GCHP, perfect agreement has been obtained between measurements on the immersion characteristics in its thermometer well and the Clausius-Clapeyron profile. This result opened the perspective of using the TA to thermodynamically relate two different temperature ranges, with the possibility of redefining one temperature range in terms of another. As a consequence, using sodium for the second GCHP, the very high reproducibility of SPRTs below 400 °C can be transferred to the temperature range above 660 °C, surpassing the characteristics of HTSPRTs. Fig. 8 shows the TA developed at IMGC-CNR. This apparatus consists in two GCHPs connected to a single pressure line and a pressure control system using a PRT in the mercury GCHP as sensor and driving valves and bellows for coarse and fine pressure regulation. A data acquisition system drives multimeters and resistance bridges for reading all temperature and pressure sensors.

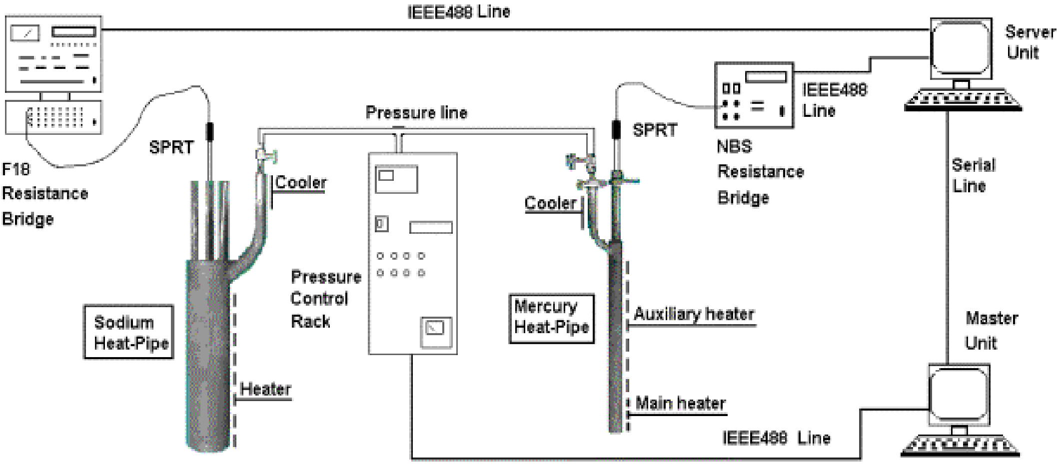

Figure 8: A schematic view of the “Temperature Amplifier” architecture.

In the study of the thermodynamic relationship between the liquid-vapor transitions of mercury and sodium, the position of the interface between the vapor and the helium gas in the chimney was detected in both GCHPs, as shown in Fig. 9, in order to correctly apply the hydrostatic head correction [23]. The position of the vapor-gas interface was detected by a thermocouple on the chimney of both GCHPs about 5 cm below their water cooler. The interface position was manually adjusted by increasing or decreasing the power supplied to the heaters.

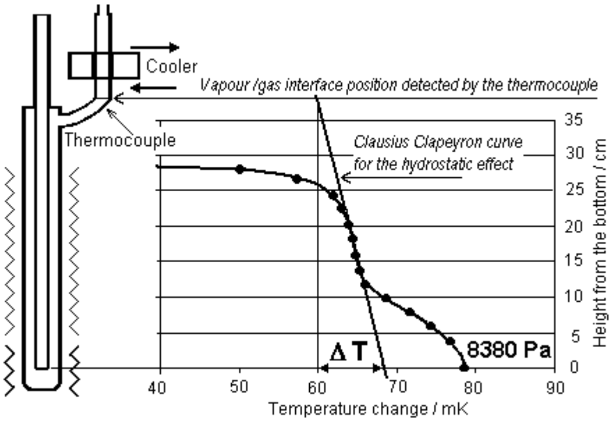

Figure 9: Detection of the vapor-gas interface position for the hydrostatic effect correction.

At pressure intervals equivalent to 25 °C in the sodium GCHP, four independent measurements have been carried out: the ratio between the t_{90} values for the mercury and sodium GCHPs has been determined and for small pressure steps the resulting temperature steps in mercury and in sodium have been recorded, as well as the pressure steps [23]. Pressure steps of about 0,06 % were obtained by moving the bellows for 20 s in one direction and, then, in the opposite direction. Fig. 10 and 11 show these pressure steps and the corresponding temperature steps in the mercury and in the sodium GCHPs at 8380 Pa and at 103260 Pa.

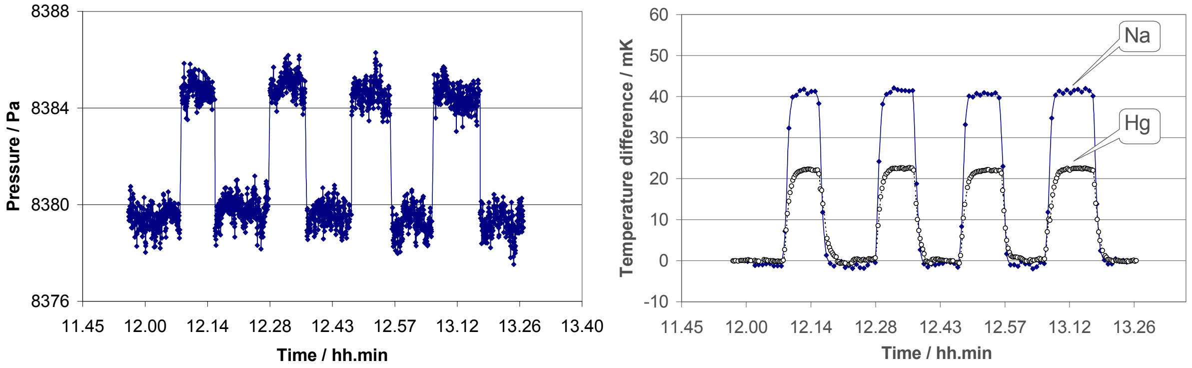

Figure 10: Pressure and temperature steps in the mercury and sodium GCHPs at 8380 Pa.

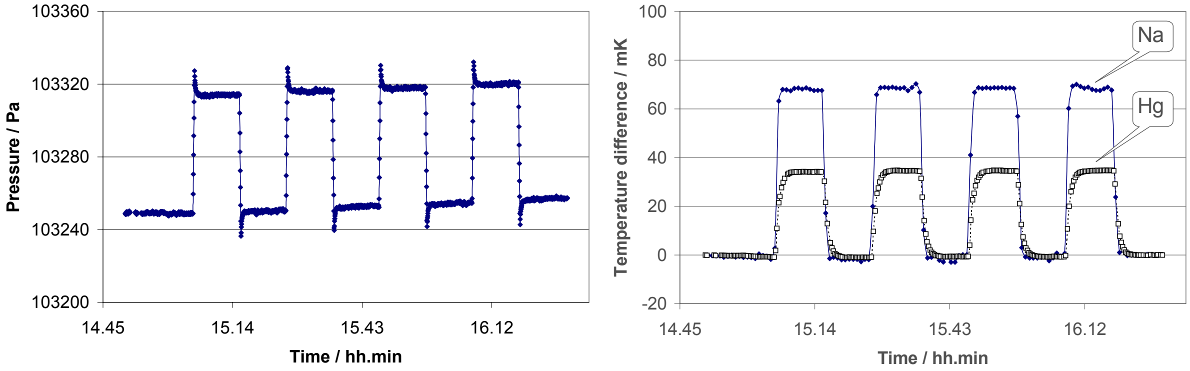

Figure 11: Pressure and temperature steps in the mercury and sodium GCHPs at 103260 Pa.

The two temperature graphs are very similar, since, within each of the Hg and Na temperature ranges, the sensitivity of the (HT)SPRTs remains almost constant. The two pressure graphs are quite different, since the stability and sensitivity of the pressure sensor is constant at ±1 Pa over the whole pressure range. Therefore, the advantage of using a PRT inserted in the thermometer well of the mercury GCHP to control the pressure is even more evident. With such a system, the pressure can be controlled in the whole range from 8 kPa to 200 kPa with a sensitivity beyond the resolution of any current pressure gauge. Indeed, a 25-Ω SPRT has, at 240 °C, a reproducibility within $4 \cdot 10^{-7}$, corresponding, at 8 kPa, to a pressure reproducibility of about 0,02 Pa, about 50 times better than that of the pressure gauge. Furthermore, the TA allows the above reproducibility, within $4 \cdot 10^{-7}$, of the temperature in the mercury GCHP to be extend also at high temperature, so obtaining in the sodium GCHP the same relative temperature reproducibility.

The $t_{\mathrm{Na}}(t_{\mathrm{Hg}})$ relation was determined by measuring the temperature in the mercury GCHP with a SPRT and the temperature in the sodium GCHP with two HTSPRTs, while the pressure was controlled using another SPRT as sensor [23]. A cubic polynomial fit provided a suitable interpolation of the experimental data, with residuals not exceeding ± 3 mK. The obtained cubic relation is:

$$t_{Na} = a\left(\frac{t_{Hg}}{t_0} - 1\right)^3 + b\left(\frac{t_{Hg}}{t_0} - 1\right)^2 + c\left(\frac{t_{Hg}}{t_0} - 1\right) + d \,, \qquad (7)$$

where:

a = 5,74 ± 0,32 °C
b = 34,73 ± 0,10 °C
c = 713,084 ± 0,009 °C
d = 882,893 ± 0,001 °C
t_0 = 356,619 °C

This relationship (re-calculated with t_0 equal to the mercury boiling point, instead of t_0=320 °C, as in [23]) is not logarithmic as the equation (6) of the vapor pressure relation, and the resulting accuracy can be greatly improved.

In summary, by controlling the helium pressure by means of a SPRT inserted in the thermometer well of the mercury GCHP, any temperature in the range between 240 °C and 400 °C can be "amplified" in the sodium GCHP connected to the same helium line, to one and unique temperature in the range between 660 °C and 962 °C, with a relatively constant reproducibility. This has been tested at 962 °C with 12 temperature determinations during 2 days, each lasting about 30 min, with the same measuring procedure used for the fixed point determination [23]. A standard deviation of 0,5 mK was found, comparable with the silver point reproducibility.

The described TA realizes the transfer of the very high reproducibility of the SPRTs below 400 °C, within $4 \cdot 10^{-7}$, to high temperature, obtaining between 660 °C and 961 °C a reproducibility surpassing that of the HTSPRTs. There are two main advantages: (1) any non-uniqueness due to the HTSPRTs can be overcome; (2) the calibration of the HTSPRTs can be carried out at any temperature of the range and can thus be limited to the maximum required operating-range.

4. CURRENT STATUS AND PROSPECTS FOR THE FUTURE

Both BNM-INM and IMGC-CNR have a TA apparatus operating in their laboratory. The TA at BNM-INM uses dodecane as working fluid in the low temperature GCHP. This organic fluid, as diphenyl previously used by IMGC-CNR in its first model of TA, shows a temperature gradient in the thermometer well of about 1 mK/cm in the whole operating range, possibly because of inadequate thermal properties of these organic fluids. Nevertheless, the obtained accuracy of about 50 mK at 950 °C is a very important result for the calibration of platinum resistance thermometers and of thermocouples. Moreover, the SPRT used as reference in such an apparatus can always be kept at low temperature and, therefore, the reproducibility at high temperature is not affected by instability or damage of the temperature reference.

The mercury GCHP used by IMGC-CNR in its TA apparatus exhibits a very high reproducibility, since the experiments showed a perfect agreement between the temperature gradient in the thermometer well and the Clausius-Clapeyron immersion temperature profile. Consequently, the very high reproducibility of a SPRTs between 225 °C and 400 °C in the mercury GCHP can be used to obtain a very high temperature reproducibility in the sodium GCHP of the TA, that surpasses the HTSPRTs reproducibility in the range between 660 °C and 962 °C.

Therefore, the TA, as realized at BNM-INM and at IMGC-CNR, is one of the most promising systems for very accurate high temperature measurements, and for improvement of the temperature scale between the Al and Ag fixed points. At this stage, the most important prospect for the scientific community is to diffuse the TA apparatus developed by BNM-INM and IMGC-CNR to all the other laboratories working in high temperature contact-thermometry.

Following this prospect and of the growing interest in the TA applications, IMGC-CNR has started to implement this plan:

1. Manufacture, by a firm in Turin, of new GCHPs for the TA [29]. Several types of GCHP are now available: equipped with three or six thermometer wells, either in stainless-steel or in Inconel 601, for the use at low or high temperature. The design of these new GCHPs is the result of a cooperation between JRC of Ispra and IMGC-CNR scientists.
2. Set-up at IMGC-CNR of a new laboratory for the cleaning, filling and characterization of the new GCHPs [30]. The new laboratory is expressly devoted to projects, studies, research, applications and maintenance of GCHPs and TA apparatus.
3. Manufacture, by a firm in Turin, of the automatically controlled furnaces for the new GCHPs.
4. Realization at IMGC-CNR of the prototype of a new pressure controller for the TA, provided with an I/O PC connection and acquisition/control software. The new controller uses a PRT as sensor for high sensitivity. After the final test of this prototype, the new pressure controller will be manufactured by a firm in Turin.
5. Assembly of the new TA apparatus. This consists in two new GCHPs, each with its furnace and water cooler, and in the pressure control system, with its controller, buffer, pressure line, helium tank and vacuum pump. The first assembly, with a mercury and a sodium GCHP, will be done in the new IMGC-CNR laboratory.
6. Circulation among the European laboratories of a complete TA apparatus made by IMGC-CNR, as agreed with the new Euromet project n. 772.

The first step of this plan is completed, while the second, third and fourth steps are in progress and they will be concluded by the end of this year. Successively, the assembly of the new TA apparatus with the new mercury and sodium GCHPs will start. After the characterization of the new TA, another will be manufactured for circulation among the European laboratories participating in the Euromet project. The results of this comparison will be very useful to assess the possible use of the TA for the realization of the future International Temperature Scale.

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