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A New Mercury Gas-Controlled Heat Pipe for Temperature Amplifier and as Calibration Facility

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Abstract At the Italian National Research Institute of Metrology, the activities and studies concerning gas-controlled heat pipes are constantly increasing in terms of involved personnel, instrumentation, and devices available. In the last two years, among the other activities, a totally new gas-controlled heat pipe operating with mercury as the working fluid has been designed, manufactured, and completely characterized. This heat pipe is made of stainless steel and provided with three thermometer wells. A dedicated furnace has been constructed and specific software algorithms have been implemented for the temperature and pressure control. This device will be used as a low-temperature reference for the new "Temperature Amplifier" and as a calibration facility for thermometers calibrated by comparison between 220°C and 450°C. All details regarding this heat pipe, including the assembly, filling, and testing procedures, and the complete characterization campaign are summarized here. Results in terms of temperature stability, uniformity, and time response are reported, and demonstrate the capabilities of this gas-controlled heat pipe to be a useful device for research and applications in contact thermometry. Another gas-controlled heat pipe operating with mercury and provided with six thermometer wells has been manufactured, and will be characterized for the contact thermometry calibration laboratory at INRiM and for other calibration companies in Italy; this device is also presented.

Keywords Gas-controlled heat pipes · Heat pipes · Mercury · SPRT calibration · Temperature amplifier · Temperature scale · Thermocouple calibration

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1 Introduction

During the past 15 years, there have been many efforts at the Italian National Research Institute of Metrology (INRiM) to develop gas-controlled heat pipes (GCHPs) for accurate temperature measurements [1,2]. The GCHPs are used in the field of temperature metrology, thanks to the highly uniform and stable temperature conditions achievable. The devices are operated both as thermometer calibration facilities [3,4] and in support of research on the International Temperature Scale ITS-90 [5–7]. They are filled with different working fluids, depending on the temperature range.

Two new models of GCHPs have been recently realized at INRiM [8] in stainless steel and in Inconel. Stainless steel GCHPs have been manufactured to be filled with low-temperature working fluids, such as mercury, and Inconel GCHPs have been filled with sodium for high-temperature use. A low-temperature GCHP with three thermometer wells and a high-temperature one, with six wells, have been connected to the same pressure line in the so-called "Temperature Amplifier" (TA) configuration. By applying the same pressure to the GCHPs, the temperature in one is thermodynamically related to the temperature in another. For this purpose, a new pressure control system, operating between 400 Pa and 400 kPa, has been developed in order to control the pressure inside the GCHPs. This means that any temperature between (240 and 400)°C for a mercury GCHP is able to be "amplified" in order to establish a unique and very reproducible higher temperature between (660 and 962)°C for a sodium GCHP.

The mercury GCHP has been recently characterized for temperature stability, uniformity along the wells, and response times over the whole operating range.

2 Mercury Gas-Controlled Heat Pipe

The heat pipe used in this project is made of stainless steel in the form of a cylindrical envelope closed on both ends by discs of the same material, and it has three thermowells. The dimensions are: 455 mm height, 64 mm diameter, and 3 mm thickness. From previous experience, the heat pipe is charged with 1.7 kg of mercury to ensure correct operation. Another gas-controlled heat pipe operating with mercury and provided with six thermometer wells has been manufactured, and will be characterized for the contact thermometry calibration laboratory at INRiM and for other calibration groups.

The power required to maintain the mercury liquid/vapor phase transition inside the GCHP is provided by a specifically designed furnace equipped with two separate heaters (Fig. 1). The main heater (base) is used to keep the fluid boiling, while a second auxiliary one (lateral) maintains the temperature of the heat-pipe wall close to the boiling temperature, in order to help the fluid evaporate from all vertical surfaces, thereby increasing the temperature uniformity. The wires are wound on the outer wall of the cylindrical envelopes at different heights. The energy is provided by a single ac power supply, since the resistances of the two wires were designed to provide the correct power ratio between the base and lateral heaters when operating from the same voltage.

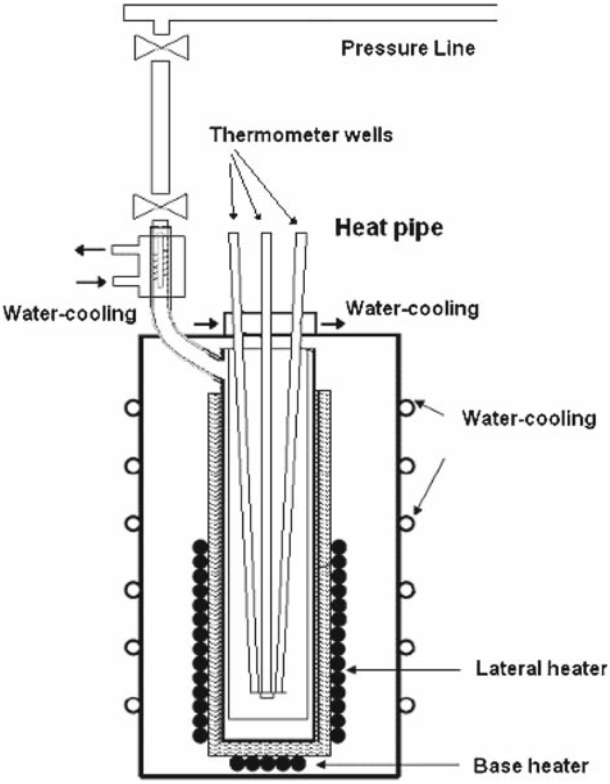

Fig. 1 Schematic of the GCHP and its furnace

Three separate cooling lines have been designed and mounted. The first line provides the necessary cooling to the chimney of the GCHP, in order to keep it working properly; it represents the fundamental cooling that causes the vapor to condense back to the liquid state and return to the bottom of the GCHP. The second cooling line keeps water flowing on the top of the thermometer wells to increase the amount of fluid condensation around the measuring zone. The third water-cooling line is used to cool the furnace. The amount of water flowing in each of the three cooling lines is separately controlled to guarantee the best heating/cooling ratios and thus achieve the best operating capabilities of the heat pipe.

3 Control System

This GCHP realizes the mercury liquid–vapor phase transition over all the measurement volume. Since equilibrium is constantly maintained by means of appropriate heating and cooling, a temperature change immediately occurs with any pressure change. Therefore, as is well known, the temperature inside the GCHP can be controlled by controlling the pressure of the phase transition. A vapor/gas interface is realized with helium as the control, or buffer, gas.

A new pressure control system has been designed and manufactured at INRiM [9]. It is based on the use of a standard platinum resistance thermometer (SPRT) to sense the temperature inside the heat pipe. The controller actuates electromechanical valves connected to a series of volumes of various sizes to control the pressure, and therefore the temperature, inside the GCHPs.

The pressure control system for the GCHPs is equipped with a pressure controller provided with a high-pressure line to increase the pressure, and with a low-pressure line to decrease the pressure. The high-pressure line of the controller is connected through a pressure regulator to a pressurized helium cylinder, while the low-pressure line is connected to a vacuum pump. The controlled-pressure line is connected to the GCHP through a 50 l buffer volume that is thermally insulated. This buffer attenuates any pressure fluctuations that may be due to perturbations.

A resistance bridge interfaced to a computer running task-specific software receives the pressure/temperature value and determines the pressure variation. The pressure controller, specifically designed, regulates the pressure within a relative variation of 1 ppm between 400 Pa and 400 kPa. This degree of pressure control guarantees a corresponding temperature control well within a millikelvin at any temperature within the operating range of the GCHP. Temperature stability within fractions of millikelvin is achieved at intermediate temperatures, where the system exhibits the best performance.

A pressure line is required to connect one or more GCHPs to the same controller, thus ensuring that they are operating at the same pressure. A thermally insulated buffer volume has to be connected to the helium line to the heat pipes.

4 Performance

Maintaining the mercury heat pipe under pressure control, some tests and evaluations were carried out to evaluate and improve its temperature uniformity and stability.

The power supplied to the heaters was changed in steps until the best ratio between the base heater and the lateral one was found. The optimum cooling-water flow value was also investigated. Those trials were performed by measuring the temperature uniformity and stability at each power level.

Table 1 shows the optimal power of the base heater (P_b) and lateral heater (P_l) for several working temperatures corresponding to the liquid–vapor phase transition of the mercury at the respective pressure p. Excessive increases of heater power lead to

Table 1 Optimal heating power at different temperatures

T	p (kPa)	T_c (°C)	P_b (W)	P_l (W)
235	5	100	75	30
310	40	110	90	35
365	120	170	150	55
385	160	190	160	60
445	390	280	190	70

excessive drying inside the heat pipe, thereby increasing the temperature above the boiling point of the working fluid.

4.1 Stability

Using the SPRT as a sensor for direct temperature control, it is possible to obtain very good stability at any pressure value in the range studied. The temperature stability was found to be well within 1 mK over the whole temperature range, and the temperature could be maintained for any required time, even for days, under pressure control. This result is obtained by means of specific PID algorithms implemented in the software that take into account the parameters of the whole system, such as its thermal drift and inertia, and the consequent response time. The control parameters were chosen by investigating the system behavior and its physical characteristics.

The stability of the temperature achievable with this mercury GCHP has been tested since excellent thermal conditions have been achieved. As shown in Fig. 2, the

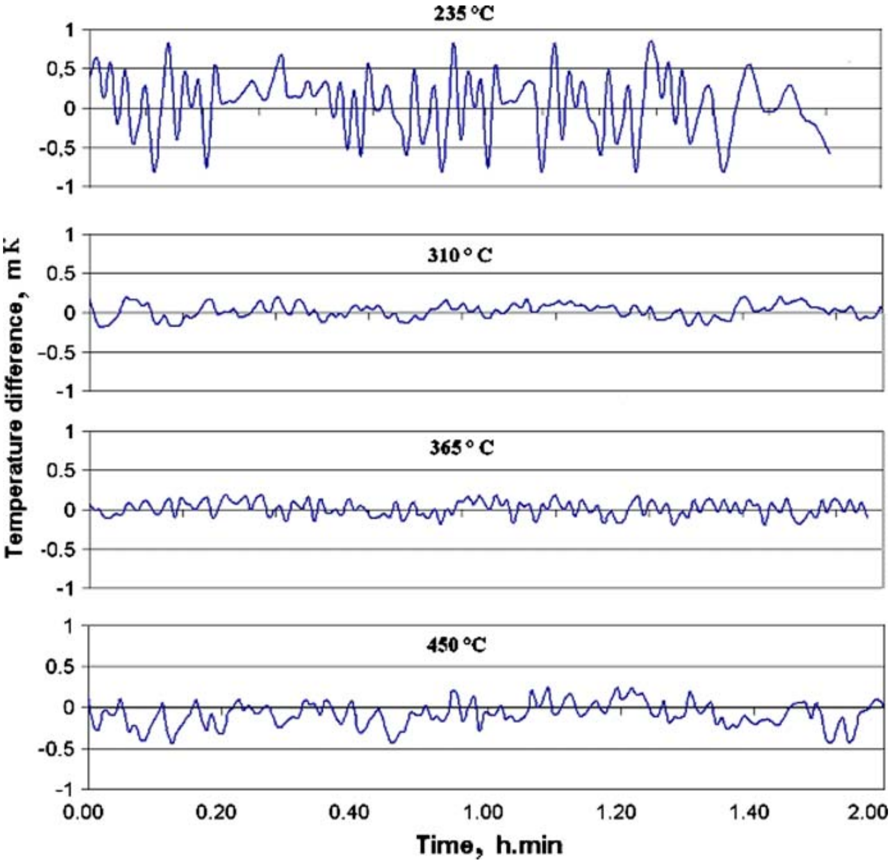

Fig. 2 Temperature stability in the GCHP at different temperatures

temperature is indefinitely stable within a few tenths of millikelvin over a wide range of working temperatures thanks to the performance of the pressure controller and the construction characteristics of the GCHP. Stability at the millikelvin level was obtained for lower and higher operating temperatures, due to non-symmetric conditions at the pressure controller inputs. At low pressure values (below 5 kPa) or at high pressures (above 400 kPa), the system suffers from the very high-pressure difference between the pressure setpoint and the helium cylinder or the vacuum pump, respectively.

4.2 Uniformity

The temperature gradient along the vertical axis (uniformity) of the GCHPs is a parameter that requires careful and thorough investigation. In such devices, the uniformity is mainly (but not only) due to the relative position of the temperature sensor with respect to the height of the vapor column [10], and depends on the vapor–gas interface temperature (T_c) measured with a thermocouple placed on the chimney of the GCHP, since this measured temperature is proportional to the distance between the helium/vapor interface and the position of the cooling coil in the chimney. From previous investigations, the uniformity improves when T_c increases until an optimal value is reached. It is necessary to find the optimal T_c for every working temperature, and to keep it stable around this value by maintaining the equilibrium between the heater power and the amount of water flowing in the cooling coils.

The power control is obtained using a programmable device (M3-ASCON®) that accepts the input of a temperature sensor, compares the actual temperature to the desired control temperature, and provides an output to a power supply element. The input sensor is an S-type thermocouple whose junction is placed on the chimney of the GCHP and the control element is an electromechanical relay. The temperature of the chimney is correlated with the position of the gas–vapor interface and its control is therefore fundamental for optimum temperature stability inside the heat pipe [11].

By programming the proper PID constants to account for the thermal inertia and the response time, T_c is kept stable at the set-point value. The PID algorithm consequently controls the power supplied to the GCHPs. Figure 3 shows the trend of T_c under "on-off" control, and the change in behavior when the PID control is switched on. By maintaining T_c within one kelvin over the whole temperature range, the best temperature uniformity is achieved.

When the best conditions in terms of pressure control are achieved, the temperature uniformity inside the thermometer wells of the GCHP reproduces the Clausius–Clapeyron profile. When the proper power distribution conditions are also achieved, the uniform zone is increased, as shown in Fig. 4.

4.3 Response Time

The capabilities of the GCHPs and the PID algorithms that were implemented allow changes in pressure and, consequently, changes in the temperature set point to be reached relatively quickly. The PID algorithms are designed for different requirements: wide temperature changes, small temperature changes, and accidental pressure changes.

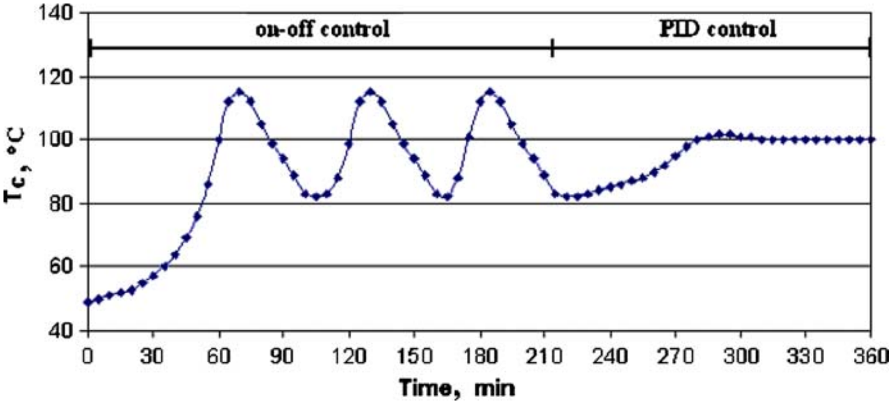

Fig. 3 Control of the vapor/gas interface temperature in a mercury heat pipe at a set point of 100°C

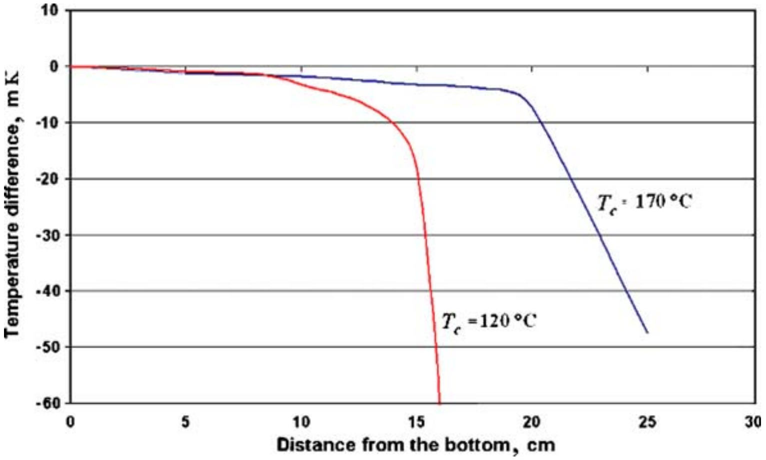

Fig. 4 Uniformity in the thermometer wells for two different values of the vapor/gas interface position

4.3.1 Wide Temperature Changes

After a temperature set point value has been selected, the program automatically evaluates the pressure difference that the pressure controller must supply. The routines evaluate the desired temperature difference and automatically reach the new set point. Changes of 30 K are achieved within a few minutes within the whole working range, allowing the temperature to be maintained at the best stability achievable under PID control, as shown in Fig. 5.

4.3.2 Small Temperature Changes

For thermometer calibration, as well as for research purposes, the evaluation of the sensitivity of the sensors may be required. The system is able to generate small, precise temperature changes at the millikelvin level. When the system is forced to execute steps

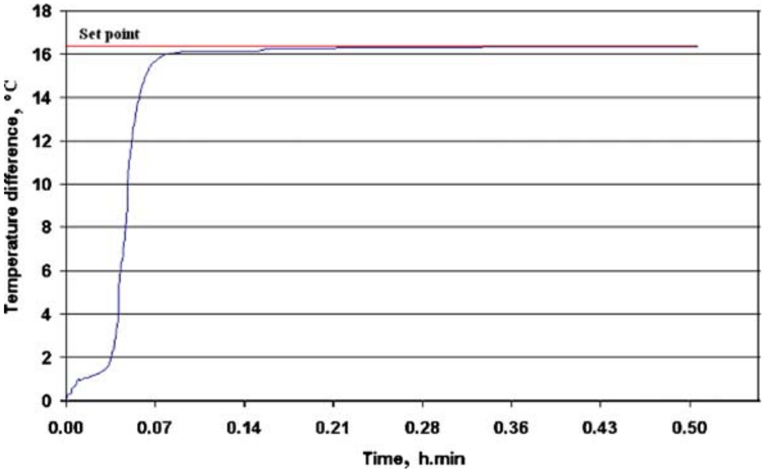

Fig. 5 Temperature change

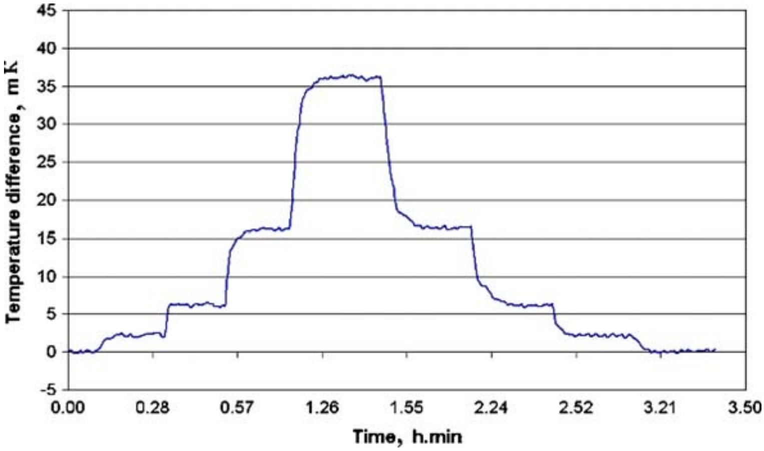

Fig. 6 Response time

of a few millikelvin, control stability is reached within minutes (Fig. 6). This operation is often used to evaluate the corresponding temperature difference in another GCHP in the temperature amplifier configuration, to evaluate the dT_A/dT_B relations for the liquid–vapor phase-transition temperatures of two different working fluids, A and B.

4.3.3 Accidental Pressure Variation

Sometimes an accidental pressure variation may occur, due, for example, to extra vapor cooling, and consequent pressure reduction, when a cold thermometer is inserted in a well of the GCHP. In this case, specific PID routines are implemented to quickly return the system to the most stable condition. Figure 7 shows the difference of the

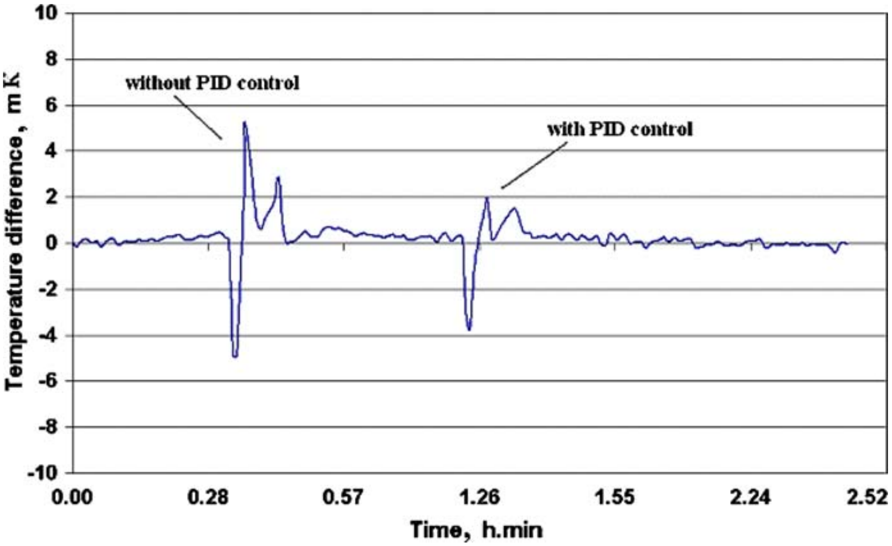

Fig. 7 Effects due to the insertion of a cool thermometer in a well, with and without PID control

effect due to the insertion of the thermometer in a well with the PID control switched on or off.

5 Applications

The performance obtained with the device presented here are the result of the new GCHP design and of improvements to the power system, the water-cooling, the software, and the control algorithms. These improvements come from the experience acquired in this field of thermal metrology at INRiM and from the research activities on new standards for contact thermometry. The capabilities of this device are satisfactory for the calibration by comparison of SPRTs, industrial PRTs, or thermocouples.

Other similar stainless steel heat pipes provided with six thermometer wells have been manufactured and will be filled with mercury and devoted to providing calibration services. Two new stainless steel GCHPs, operating with mercury and provided with six thermometer wells, have already been manufactured and will be characterized. The first will be delivered to the Quality Centre of the "Politecnico di Torino" and the second one to the contact thermometry calibration laboratory at INRiM. Figure 8 shows the six-well GCHP and its furnace. The devices will be used for calibration by comparison between (240 and 450)°C.

In support of metrology research and applications, a complete "Temperature Amplifier" apparatus was developed at INRiM by connecting this three-well mercury-filled GCHP to the same pressure-controlled line of a six-well sodium-filled GCHP. In this application, the mercury GCHP presented here is used as a low-temperature reference for the TA and the performance achieved is also satisfactory in this case. Research devoted to new temperature standards between the Al and Ag fixed

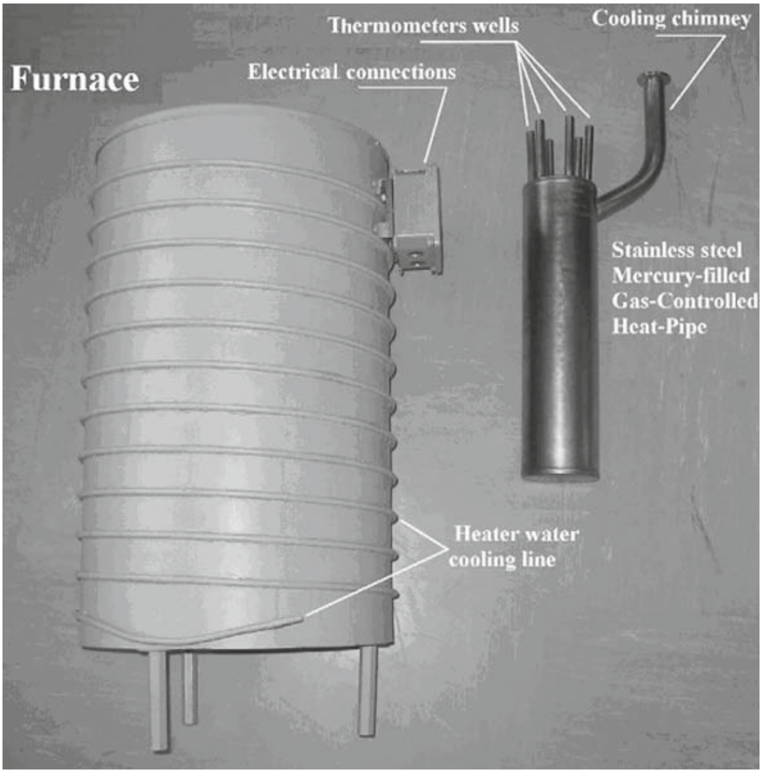

Fig. 8 New stainless steel mercury-filled GCHP and the dedicated furnace

points [12] has been proposed under the iMERA project [13]. Another TA, and consequently another mercury GCHP, will be assembled for the Chinese National Institute of Metrology (NIM) [14] where similar studies will be carried out.

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