Int J Thermophys (2017) 38:185
DOI 10.1007/s10765-017-2322-7

TEMPMEKO 2016

Implementation of a Water Heat Pipe at CETIAT

J. O. Favreau[1] · E. Georgin[1] · B. Savanier[1] · A. Merlone[2]

Received: 1 September 2016 / Accepted: 23 October 2017 / Published online: 2 November 2017

Abstract CETIAT's calibration laboratory, accredited by COFRAC, is a secondary thermometry laboratory. It uses overflow and stirred calibration baths (from − 80 °C up to + 215 °C), dry blocks and furnaces (from + 100 °C up to + 1050 °C) and thermostatic chambers (from − 30 °C up to + 160 °C). Typical calibration uncertainties that can be reached for platinum resistance thermometers in a thermostatic bath are between 0.03 °C and 0.06 °C. In order to improve its calibration capabilities, CETIAT is working on the implementation of a gas-controlled heat pipe (GCHP) temperature generator, used for industrial sensor calibrations. This article presents the results obtained during the characterization of water GCHP for industrial applications. This is a new approach to the use of a heat pipe as a temperature generator for industrial sensor calibrations. The objective of this work is to improve measurement uncertainties and daily productivity. Indeed, as has been shown in many studies (Dunn and Reay in Heat Pipes, Pergamon Press, Oxford, 1976; Merlone et al. 2012), the temperature of the system is pressure dependent and the response time, in temperature, follows the pressure accordingly. Thanks to this generator, it is possible to perform faster calibrations with smaller uncertainties. In collaboration with INRiM, the GCHP developed at CETIAT works with water and covers a temperature range from + 30 °C up to + 150 °C. This device includes some improvements such as a removable cover, which allows us to have different sets of thermometric wells adjustable according to the probe to be calibrated, and a pressure controller based on a temperature sensor.

Selected Papers of the 13th International Symposium on Temperature, Humidity, Moisture and Thermal Measurements in Industry and Science.

✉ J. O. Favreau
Jacques-olivier.favreau@cetiat.fr

1 CETIAT, Villeurbanne, France

2 INRiM, Turin, Italy

This article presents the metrological characterization in terms of homogeneity and stability in temperature. A rough investigation of the response time of the system is also presented in order to evaluate the time for reaching thermal equilibrium. The results obtained in this study concern stability and thermal homogeneity. The homogeneity on 200 mm is better than 5 mK and with a calibration uncertainty reduced by a factor of three.

Keywords Calibration · Heat pipe · Temperature generator · Thermometry

1 Introduction

Heat pipes have been studied, manufactured and used for several decades in thermodynamic applications, heat transfer purposes or industrial needs [3]. Moreover, gas-controlled heat pipes (GCHPs) have been studied within the last twenty years, namely for metrological applications [4–6]. Among National Metrology Institutes (NMI) using GCHP, INRiM (Italy) has the most significant experience with them and could be considered as a reference institute for GCHP technology. GCHPs have been mainly developed for primary thermometry purposes [7,8].

Heat pipes use the thermodynamic relationship between temperature and pressure in a fluid during liquid–vapor phase transition. GCHP also uses this principle with a gas line which enables direct control of the inner pressure. Thus, by controlling the pressure of the system it is possible to cover a wide range in temperature. From the Clausius–Clapeyron equation and from the ideal gas law comes:

$$\frac{dT}{T} = \frac{RT}{ML}\frac{dP_s}{P_s} \tag{1}$$

where R is the universal gas constant, T the liquid–vapor interface temperature, M the molar mass of the vapor, L the latent heat of vaporization of the fluid that is used, and P_s the saturation vapor pressure.

From Eq. 1, it appears that any variation in pressure leads to a direct temperature change in the system. Thus, the internal temperature of the heat pipe can be regulated by a pressure variation. Furthermore, the main interest in a heat pipe is to have a quasi-adiabatic zone at its center. This is the thermally useful area for calibrations in terms of homogeneity and thermal stability. The object of this study is to check the thermal performance of this type of heat pipe.

In practice, to initiate the heat effect, we bring a fluid to the boil. The steam is propagated into the condenser and the condensed fluid returns to the heating zone for a new cycle. The internal walls of the heat pipe are covered in mesh so that the fluid can circulate by capillary action. On the walls, the fluid is present in both forms: liquid and gaseous. In the lower part, heating elements are placed to vaporize the fluid. In the central part of the heat pipe, the subsonic velocity of the fluid vapor and the two phases makes it possible to obtain a quasi-adiabatic zone. This is the area which is useful for calibrations in terms of homogeneity and thermal stability. The pressure and condensation settings make it possible to obtain the widest possible adiabatic zone.

The object of this study is to check the thermal performance of this type of heat pipe using water.

2 Design of the GCHP at CETIAT

The general design of the GCHP has been jointly carried out by INRiM and CETIAT, while the realization and machining have been provided by Criotec Impianti, a major gas and cryogenic systems manufacturer. It is an open heat pipe. This original heat pipe is equipped with a thermal equalization block and a removable cover. A further feature is the length of the glove finger corresponding to the depth of immersion in a calibration bath. These elements are visible in Fig. 1. The dimensions and the assembly of the elements are provided in the diagram on the left. The metal mesh and the thermal block are visible in the picture.

These elements are retained by a cover. It is removable and allows the sealing of the heat pipe. Figure 2 shows the schematic diagram of lids. It is composed of two removable covers where thermowells are set.

The advantage of this type of heat pipe with a removable top is that it facilitates the configuration for the installation of thermometers. Moreover, there is a better fit with the diameters of the thermometers to be calibrated. A heat pipe system with a removable top allows for making different types of wells adapted to the thermometers to be calibrated—see Fig. 2.

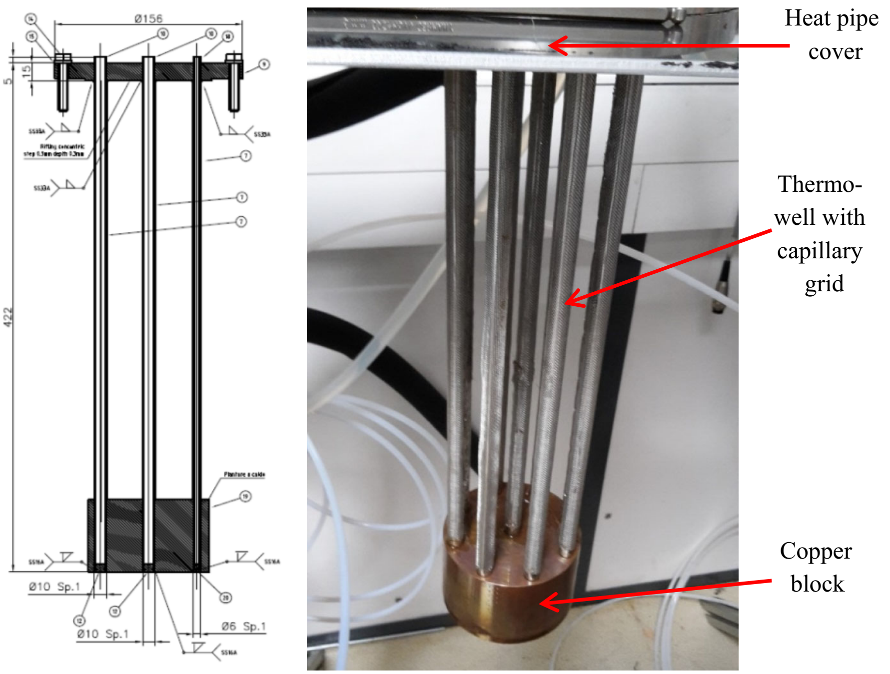

Fig. 1 Thermowells equipped by equalization copper block and capillary grid

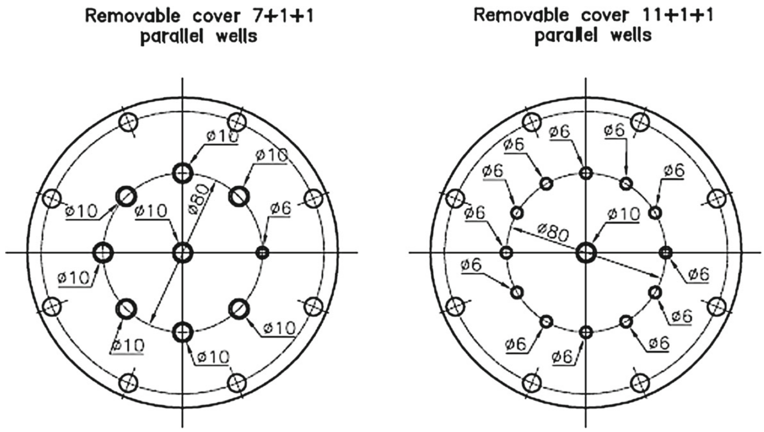

Fig. 2 Cover configurations: 8 + 1 thermowells and 12 + 1 thermowells

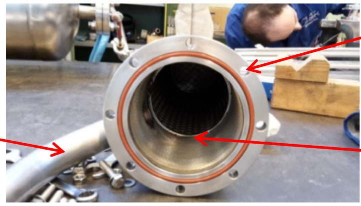

Fig. 3 Inner view of the heat pipe

This cover and the thermowells are fixed into the protective envelope. It consists of a stainless steel cavity. The internal volume is of eight liters; 250 ml of demineralized water is introduced into the heat pipe for this study. A connecting chimney is attached to the top of the heat pipe. A metallic mesh covers the internal walls. This mesh system allows the circulation of the fluid by capillarity. An O-ring and nuts seal the heat pipe. These elements are shown in Fig. 3.

The assembled heat pipe is shown in Fig. 4. On the outer wall are fixed heating bands. There is one on the bottom and then every 3 cm along the heat pipe. In order to check the sheath temperature of GCHP, six thermocouples have been set along the heat pipe axis. Type K thermocouples are used to monitor the temperature of the wall. The quality of regulation of the wall will make it possible to optimize the heat pipe effect. The chimney makes it possible to connect the heat pipe to the pressure circuit, while also making it possible to condense the steam. The heating elements vaporize the fluid inside the heat pipe. The steam rises to the condenser and then returns to the heating zone by gravity. The lateral heating resistances make it possible to improve the heat pipe effect. If the wall is cold, the fluid will condense. For heating the system, there are up to five heated zones which can be controlled independently. For this study, only the two lower heating zones are used. In order to check the sheath temperature of GCHP, six thermocouples have been set along the heat pipe axis.

The operation of the heat pipe is associated with regulating elements. The most important element of this GCHP system is the heat pipe, the pressure control circuit and the condenser circuit. These elements are shown in Fig. 5. The pressure regulating

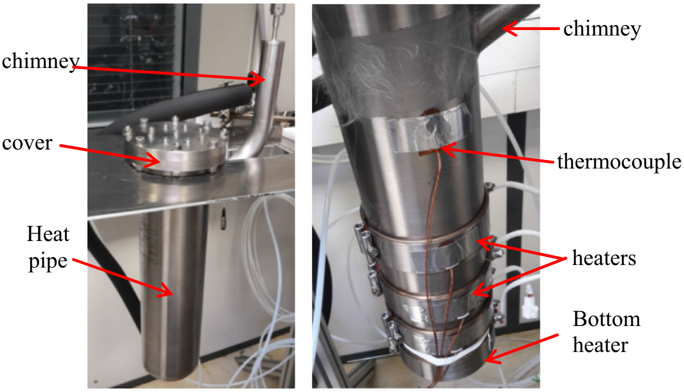

Fig. 4 Picture of general assembly, heaters and thermocouple implantation

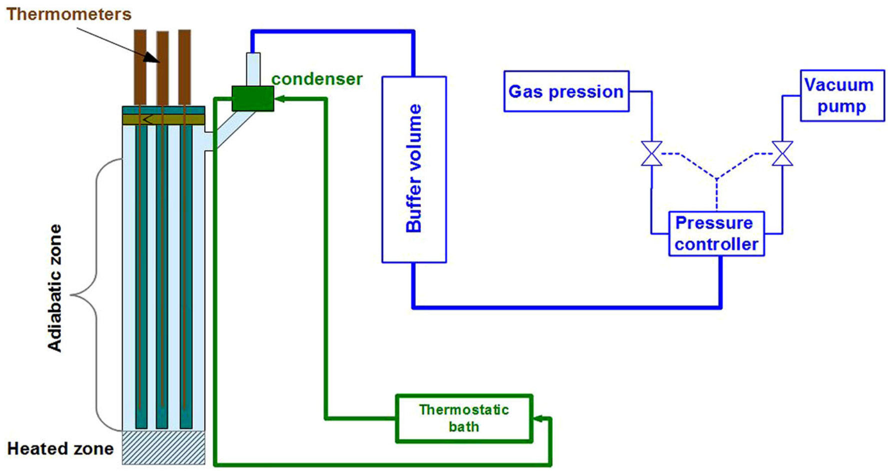

Fig. 5 Schematic diagram of GCHP

circuit is connected to the heat pipe by the connecting chimney. A condenser is also attached to the chimney. The condenser prevents also the fluid from entering into the control gas circuit.

In Fig. 5, we can see the different elements of this GCHP system. On the left, in light blue, is the useful part of the heat pipe, where the probes to be calibrated (shown in brown) are introduced into this central zone. The right part, in bright blue, represents the pressure control circuit. The most important element is the control system (GE Druck PACE 6000) which regulates the internal pressure of the heat pipe. On one of the Pace 6000's inlets, a nitrogen bottle is connected with pure gas (nitrogen 99.99 %) which allows the pressurization and on the other a turbo-molecular vacuum pumping station (Adixen Drytel 1025) which provides a vacuum. This assembly makes it possible to generate a pressure variation from 4 kPa to 200 kPa. At the exit of the Pace 6000 and before the entry of the heat pipe, there is a buffer volume which acts like a capacitor

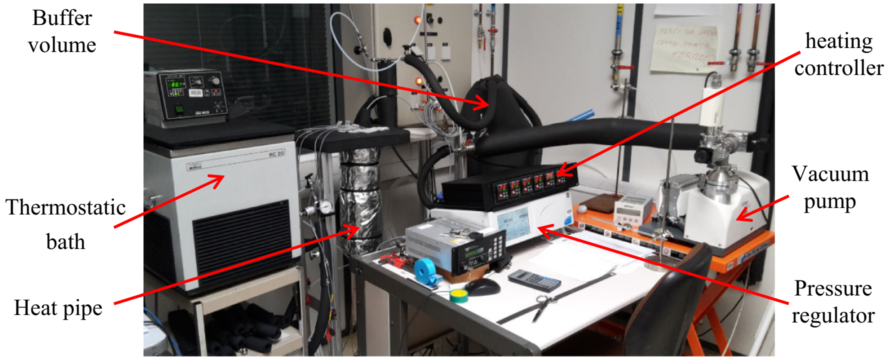

Fig. 6 Photograph of the experimental system, left: thermostatic bath, center: heat pipe, right: regulation system and vacuum pump

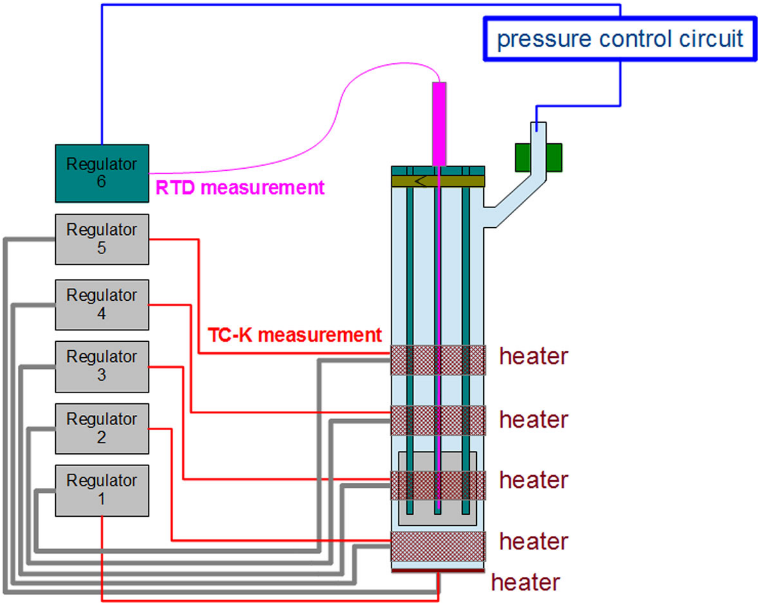

Fig. 7 Schematic diagram of GCHP controllers

in absorbing the variations in pressure, improving the stability of the pressure. The buffer volume is 50 liters. In green, the condensation circuit is indicated. It consists of a condenser and a thermostatic bath. The condenser is made of copper pipe and fixed around the chimney of the heat pipe. A Lauda RC20-type thermostatic bath generates the low temperature, using alcohol as the fluid. This condensation circuit is insulated to avoid ambient condensation.

The picture (Fig. 6) shows the thermostatic bath, the heat pipe with its insulation, the buffer volume, the heating regulator, the pressure regulator and the vacuum pump. The heat pipe insulation is made with three layers of multilayer fiberglass insulation.

The heating controller (in black) makes it possible to regulate five zones of the heat pipe independently. In the diagram at Fig. 7, the operation of the heating regulator is detailed. The heating circuits are indicated in gray. The red lines correspond to the thermocouple measurements of the wall temperature.

For this preliminary study, the fluid used is pure water. GCHPs are intended to be used from + 30 °C up to + 150 °C, which corresponds to an internal pressure of 4 kPa to 200 kPa. Dry nitrogen gas is currently used for pressurizing the system, and a vacuum pump used to obtain a low pressure in the heat pipe.

3 Characterization

3.1 Principle and Instrumentation

Because of the heat pipe effect, it is important to control the condensation of steam at the chimney level. This control makes it possible to obtain a GCHP with a very long (> 200 mm) and homogeneous internal adiabatic area (< 5 mK). However, to guarantee this, it is necessary to condense very effectively at the level of the condenser in order to avoid the escape of steam into the control circuit. This is important, so all the steam must be condensed in a short space. To guarantee this, we used a stirred bath using alcohol.

The first stage of the characterization work consists of finding the relationship between the desired temperature in the inner part and the heating power in order to ensure the widest possible adiabatic zone. To set up the heat pipe, the saturation vapor curve of the water is used, as this saves time on settings. The installation of the heat pipe effect is verified by a thermal profile along the vertical axis. To do this, a standard platinum resistance thermometer (SPRT) is used. The pressure and the temperature of the condensation are optimized to obtain the best thermal profile. It is accepted that the adjustments are correct if the axial homogeneity is less than 5 mK over a length of 200 mm. These settings allow us to obtain the pressure/temperature curve for the heat pipe studied.

The GCHP characterization starts under the same conditions as for calibrating industrial probes. For these measurements, thermal coupling, such as thermal grease or paste, has not been used. For this study, six calibrated PRTs are used. At each temperature level, lateral and axial uniformity, stability and the response time of the system measurements are carried out. With regard to lateral uniformity, the double weighing method, also known as Gauss' method, is used. This method is described in [9]. It involves reversing two thermometers to deduce the temperature difference between two wells. This makes it possible to compensate the intrinsic errors of the thermometers. If T_{A1} is the measurements of the temperature in the well "A" with thermometer "1" and T_{B2} is the measurements of the temperature in the well "B" with thermometer "2," the homogeneity between the two wells A and B is

$$\frac{(T_{A1} - T_{B2}) + (T_{A2} - T_{B1})}{2}. \quad (2)$$

These results are presented in the next section, for four temperature levels: + 30 °C, + 45 °C, + 90 °C and + 110 °C.

Temperature measurements are performed with PRT sensors (Pt-100 type) with a metallic sheath 200 mm long and a standard platinum resistance thermometer (SPRT) with a quartz sheath 400 mm long. A thermometer fixing system has been specially developed. It guarantees both the positioning and moving of the thermometers. The recording system consists of a computer and data acquisition system. We use an Keysight 34972A data acquisition unit to connect the thermometers. This data logger switch unit consists of a 3-slot mainframe with a built-in 6.5 digit DMM (digital multimeter). The acquisitions are made every ten seconds. Measuring chains consist of temperature sensors and multiplexer which are calibrated in CETIAT's thermometry laboratory. The uncertainty of the characterization sensors is 0.03 °C. The reference temperature probe is calibrated at LNE, and the uncertainty is 0.01 °C. It set in the central thermowell, while characterization devices under calibration (DUC) are set into the others. The immersion depth available for the study is 400 mm.

Pressure control is ensured by GE Druck PACE 6000 high-precision pressure controllers and indicators with a vacuum module. The standard pressure range is 4 kPa to 470 kPa, and the performance precision is 0.005 % of measured value. The pressure controllers were calibrated in CETIAT's pressure laboratory. The uncertainty of calibration is better than 100 Pa. Therefore, the measurements are traceable to the International System of Units and all calibrations are performed under COFRAC accreditation (French ISO 17025 accreditation body).

3.2 Temperature Profiles Results (Axial Homogeneity)

The axial homogeneity (thermal profile) of each well is measured. To do this, the probes are lifted simultaneously by 20 mm in the axis as far as the exit of the heat pipe. Only the reference probe remains at the bottom of the well in order to check for good thermal stability. The temperature of the latter must not vary by more than 2 mK. Prior to each measurement, a stabilization time of at least 20 min is used for thermal stabilization. This time is necessary especially for measurements in front of the exit of the heat pipe. Thermal leakage through the sensor sheaths largely explains this result.

The points visible on the graphs (Fig. 8) correspond to the maximum temperature difference observed over 20 min between the bottom temperature and the corresponding temperature at the position of the sensor materialized on the "distance from bottom" axis.

The axial homogeneity obtained is in accordance with the objective. It is about 5 mK per well over a height of 200 mm with respect to the bottom of the well. Beyond this, the thermal profile degrades with the heat pipe output. The temperature gradient is about 10 mK. Nevertheless, it is partially due to heat losses through the sheaths of the PRT probes. The stainless steel sheaths lead to thermal losses by conduction.

Axial homogeneity at the well outlet can be improved by improving thermal coupling and using specific probes (without stainless steel sheaths).

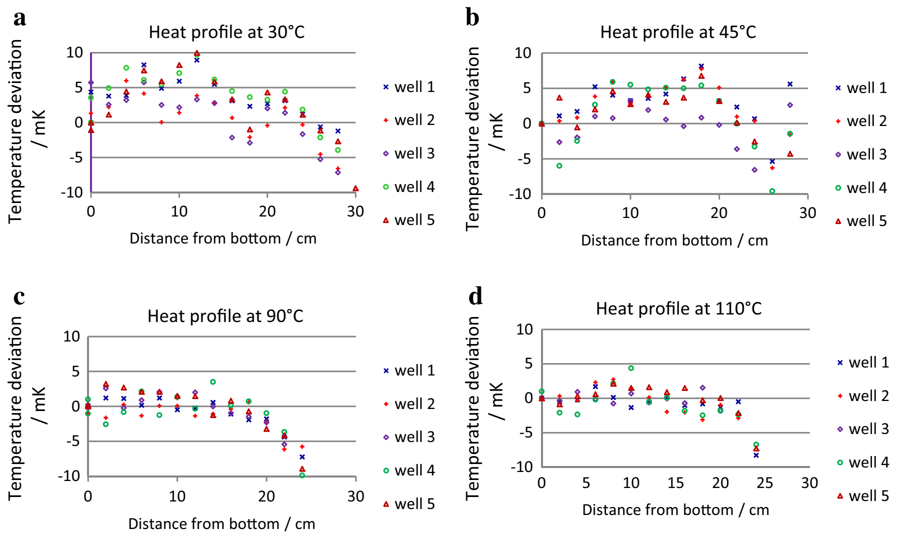

Fig. 8 Temperature profiles for four temperatures. (a) Temperature profile at 30 °C. (b) Temperature profile at 45 °C. (c) Temperature profile at 90 °C. (d) Temperature profile at 110 °C

Table 1 Summary table of lateral homogeneity

	Well 1/2	Well 3/4	Well 5/6
30 °C	3 mK	3 mK	4 mK
65 °C	2 mK	3 mK	2 mK
90 °C	4 mK	2 mK	2 mK
110 °C	1 mK	1 mK	1 mK

3.3 Lateral Homogeneity Results

The lateral homogeneity has been measured, at the moment, only for the maximum immersion depth, that is to say at the bottom of the thermowells. Three pairs of thermowells have been measured according to the Gauss' method [9]. The results, for each temperature level, are presented in Table 1. The observed lateral homogeneity is better or equal to 4 mK. The results are very similar for different temperature levels, and they also show a good reproducibility. The results correspond to the maximum temperature difference observed over 20 min between two wells.

These results are satisfactory since they are obtained without optimization of the measurement conditions. The characterizations are carried out under the same conditions as those used for industrial calibrations.

The characterization thermometers are deployed without thermal coupling fluid. Therefore, there was air present between the wall of the heat pipe wells and the sheaths of the probes. This is excellent for the future functionality of the heat pipe in calibration situations.

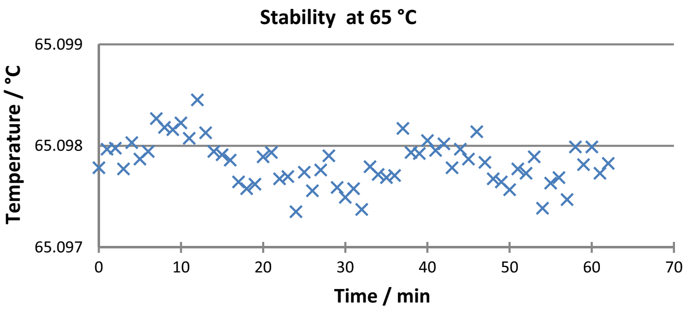

Fig. 9 Graphic representation of the thermal stability results obtained at 65 °C

Table 2 Summary table of thermal stability

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6
30 °C	3 mK	2 mK	5 mK	2 mK	2 mK	5 mK
65 °C	2 mK	3 mK	4 mK	4 mK	3 mK	2 mK
90 °C	3 mK	5 mK	6 mK	5 mK	4 mK	4 mK
110 °C	2 mK	3 mK	5 mK	4 mK	2 mK	3 mK

On an interesting note, we found a very good homogeneity of the surface temperature of the heat pipe in the characterization tests. This opens up new possibilities for calibrating surface sensors, particularly at high temperatures: For example, heat pipes could be good generators for calibrating clamp-on temperature sensors.

3.4 Thermal Stability in Time

Once the heat pipe effect is achieved, the thermal stability in time may be tested. On the following graph (Fig. 9), we can visualize an example of the thermal stability obtained at a specified temperature level.

The thermal stability obtained is 2 mK for about one hour which is better than required for our application. This is caused by the quality of the nitrogen pressure regulation in the heat pipe. For this measurement, we used calibrated SPRT.

Table 2 shows the results obtained for four temperature levels and for all the thermowells tested. For these measurements, the acquisition time is 20 min.

The overall resulting stability is better or equal to 6 mK at the different temperatures tested. The results obtained for thermal stability are consistent with our objective.

4 Conclusion

Despite a characterization which is still in progress, a temperature range from + 30 °C to + 110 °C has been investigated. It is found that, from the bottom to 200 mm of the heat pipe, the homogeneity and stability are in accordance with the objective, where the temperature must be lower than 5 mK. Thus, the first results are very promising and give confidence for further developments up to 150 °C. The homogeneity must be also improved for low immersion sensors. Other types of sensors without metal sheaths will certainly be required to characterize the low immersion of the heat pipe wells.

These results have been obtained by directly controlling the pressure of the heat pipe. The next step will be to implement a controller system for the pressure based on the measured temperature in the inner part of the heat pipe. This work will be also be carried out by an uncertainty evaluation and by an inter-laboratory comparison. The final level of uncertainty should be around 10 mK, which is three times better than the current uncertainty. This type of GCHP generator will improve the accreditation scope of CETIAT.

References

1. P.D. Dunn, D.A. Reay, *Heat Pipes* (Pergamon Press, Oxford, 1976)
2. A. Merlone et al., 20 Years of progress in the use of gas-controlled heat pipes for thermodynamic measurements, in *16th International Heat Pipe Conference (16th IHPC), Lyon (France)* (May, 2012)
3. P. Marcarino, G. Bonnier, *Temperature amplifier by means of coupled gas-controlled heat-pipes* (IMEKO Proceedings, 2010), p. 5–11
4. K.D. Hill, M. Gotoh, The vapour pressure of sodium between 660 °C and 962 °C. Metrologia **33**, 49 (1996)
5. K.D. Hill, M. Gotoh, The vapour pressure of caesium between 370 °C and 660 °C. Metrologia **33**, 307 (1996)
6. E. Renaot, J.O. Favreau, M. Elgourdou, G. Bonnier, Thermal Characteristics of a Dodecane Heat pipe over the Range from 190 to 260 °C and Related Impurity Effects, in *AIP Conference Proceedings*, vol. 684 (2003), p. 945
7. P. Marcarino, A. Merlone, Towards new temperature standards for contact thermometry above 660 °C. Metrologia **39**, 395–398 (2002)
8. A. Merlone, R. Dematteis, P. Marcarino, Gas-controlled heat pipes for accurate liquid–vapor transition measurements. Int. J. Thermophys. **24**, 695–712 (2003)
9. FD X 07-028, Procédure d'étalonnage et de vérification des thermomètres - Estimation des incertitudes sur les mesures de température oct (2002)