Int J Thermophys (2009) 30:257–264
DOI 10.1007/s10765-008-0495-9

# Development of a Heat-Pipe-Based Hot Plate for Surface-Temperature Measurements

**L. Rosso · N. Koneva · V. Fernicola**

Published online: 12 August 2008


**Abstract** The development of a flat heat-pipe-based hot plate operating in the temperature range from ambient to 200 °C is presented here. The aim of the design was to improve the heat-transfer performance in order to provide almost ideal thermal uniformity of surface and volume temperature profiles, thereby ensuring a minimal temperature gradient and a small effective thermal resistance. The device was investigated to evaluate its performance in view of its potential use as a calibration apparatus for surface-temperature sensors. An accurate characterization was carried out to estimate the surface-temperature stability and uniformity under different thermal conditions. Measurement results showed temperature stability within 0.03 °C and uniformity of the heat-pipe (HP) hot-plate surface better than 0.08 °C. As a result of its high thermal conductivity, a small perturbation (<0.2 °C) of the temperature field both on the surface and inside the device chamber, when a contact probe is applied on its surface, was obtained. The study of the HP hot plate and the performed tests suggest that such a device has potential as a calibration apparatus for surface-temperature sensors.

**Keywords** Contact probe · Heat pipe · Hot plate · Surface-temperature sensor

## 1 Introduction

Several industrial and scientific applications call for practical and emissivity-independent measurements of the surface temperature of solid bodies. As contact-type thermometers are often used in these applications, a traceable calibration of such

L. Rosso (✉) · V. Fernicola
Thermodynamics Division, Istituto Nazionale di Ricerca Metrologica (INRIM),
Strada delle Cacce 91, 10135 Torino, Italy
e-mail: l.rosso@inrim.it

N. Koneva
Heat and Mass Transfer Insitute, Minsk, Belarus

probes is required. Different calibration methods and facilities have been developed by the national metrology institutes (NMIs) over the last few years [1–4]. Calibration systems are generally based on a temperature-controlled hot plate that provides a stable and reproducible surface temperature. The temperature of the reference surface is obtained through extrapolation of the temperature values measured by two or more calibrated thermometers embedded into the plate at different depths. Other calibration setups ensure a uniform temperature field across the reference plate by partially immersing it in a thermostatic bath and maintaining its upper surface above the level of the liquid. In this case, a calibrated thermometer, embedded into the plate just under the calibration surface, enables the measurement of the surface temperature [5]. Where the above-mentioned calibration facilities are not available, temperature probes are calibrated by total immersion in a thermostatic bath.

When a calibration by immersion is performed, the probe is brought into thermal equilibrium with the surrounding environment, i.e., the liquid bath. However, this condition is far from the actual operating conditions of the sensor, in which a sensor-to-surface thermal interaction occurs. In this case, because of the presence of contact resistances at the interface between the sensor and the surface, thermal equilibrium is not established. As a consequence, the resulting temperature difference between the surface and the center of the sensor leads to a biased estimate of the temperature of the surface. On the other hand, the calibration of contact probes by means of hot plates takes place under conditions closer to those found in real applications, thus yielding a more realistic calibration correction for practical use. Of course, a contact thermometer cannot make surface-temperature measurements with the same accuracy as temperature measurements made in thermal equilibrium. In fact, the best measurement capabilities for surface-temperature measurements available at the European NMI facilities range approximately from 0.2 °C to 2 °C from ambient temperature to about 300 °C. In order to establish the degree of equivalence of such national standards for surface temperature, a EUROMET intercomparison was recently carried out [6].

In order to improve the performance of the hot-plate systems, a flat heat spreader, based on heat-pipe (HP) technology [7], was designed and constructed at the HTMI and its potential application to surface thermometry for contact probe calibration was investigated. The operating principle of the device affords a very high thermal conductivity—more than one order of magnitude greater than the thermal conductivity of metal blocks—and potentially makes it a "quasi-ideal" heat source, thus resulting in a smaller thermal perturbation when the sensor to be calibrated contacts the reference surface. The high thermal conductivity enables estimation of the surface temperature through the measurement of a single thermometer embedded in the HP, thus avoiding the temperature extrapolation and the consequent errors. These features should improve the calibration uncertainty of surface-temperature sensors.

The HP was integrated into a dedicated temperature control system, and the performance of the whole system was investigated at INRIM. An accurate characterization was carried out to evaluate the surface-temperature uniformity and stability over the operating range from ambient to about 200 °C under different thermal conditions. A study of the perturbation effects introduced by the contact probe on the surface was also performed using an independent, remote measurement method based on phosphor thermography [8].

## 2 Description of the Device

### 2.1 Principle of the HP Hot Plate

The HP hot plate is a high heat transfer device that enables quick changes and stabilization of the surface temperature. Consequently, it is not influenced by the application point of a heat loss element on the surface itself. The fast thermal response is due to the evaporation–condensation process, because the heat transfer depends on the velocity of the vapor flow and not on the heat transfer rate through the spreading surface [7,9].

The HP can transfer heat with a small temperature gradient between the condenser and the evaporator surface, resulting in a small temperature difference between the condenser and the temperature probe in the vapor channel. The working fluid vaporizes in the evaporation section and flows toward the cold regions. The latent heat of vaporization is transferred to the condenser surface where the vapor is cooled by natural convection and by the temperature probe applied to its external surface.

The heat transfer medium (water with a total mass of 7 mg) constantly circulates inside the device. At equilibrium, the liquid phase of the heat transfer fluid is assumed to follow the predictions of fluid mechanics. The liquid returns in the form of a thin liquid film to the evaporator along the vertical adiabatic section (by gravity and by the capillary force) under the action of the capillary pressure gradient. The vapor forms directly above the vapor–liquid interface in the evaporator. The mass flow rate is a maximum at the opening of the liquid transport channel of the adiabatic section, decreasing to zero at the central point of the condenser and evaporator where the liquid film also becomes thinner.

### 2.2 Design of the HP Hot Plate

The construction of the HP hot plate followed the principles of a gravitational heat pipe, where the condenser is placed above the evaporator as shown in Fig. 1. In such a case, the thermal performance of the device depends on the effective thermal conductivity of the wick, since its variable thermal resistance largely contributes to the overall thermal resistance. Modeling of the steady-state operation was carried out in the temperature range from ambient to about 200 °C by approximating the temperature distribution through a network of thermal elements, with defined thermophysical properties, connected by constant thermal resistances [10]. The dimensions and geometry of the device were chosen to match the size of the hot plates used in the INRIM surface thermometry calibration system [11]. The HP is a vacuum-sealed cylinder, 100 mm outer diameter and 86 mm inner diameter, made of OFHC copper. Each inner wall (wall thickness 7 mm) is coated with a high thermal conductivity sintered copper powder medium. A porous medium was used for better temperature uniformity and to improve the heat transfer, even with a small temperature difference. The porous structure (metal particles with a dendritic shape and a porosity value of 0.55) has a uniform thickness of 2 mm and promotes capillary surface wetting in the condenser, the evaporator, and the adiabatic zones. At the same time, it avoids any increase in the thermal resistance at the inner walls due to film boiling. Such a porous structure

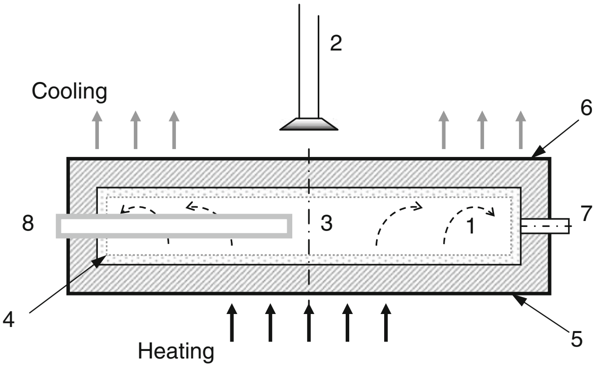


**Fig. 1** HP structure and principle: 1—evaporation–condensation cycle; 2—surface temperature probe; 3—vapor channel; 4—porous sintered wick; 5—evaporator surface; 6—condenser surface; 7—filling line; 8—PRT probe well

also allows uniform spreading of the liquid film in the condenser. Heat is supplied to the device by thermal conductance from a heat source at the bottom to the evaporation section. Inside the HP, a single axial vapor-flow channel is formed in which the water vapor pressure sets the internal pressure. A temperature well (55 mm in length and 6.5 mm in outer diameter) runs through the adiabatic zone in the middle of the vapor channel; it houses a short-stem PRT used for measurement of the equilibrium temperature.

## 3 Experiments

### 3.1 Temperature Control System

The setup used to test the device is shown in Fig. 2. The reference surface temperature is generated on the condenser surface of the HP. The device was mounted on a flat, round heater and was surrounded by a micro-porous thermal insulator. The system was equipped with a guard-ring heater to reduce the radial heat loss, thereby achieving better temperature uniformity. A PID controller drove a voltage-controlled power supply to adjust the block temperature. A Pt-100 sensor was used as the control sensor. The equilibrium temperature was measured by a short-stem PRT embedded in the HP itself and connected to a 8 1/2-digit multimeter.

### 3.2 Characterization of the HP Hot Plate

The tests on the HP hot plate were aimed at evaluating the performance of the device in view of its use as a calibration apparatus for surface temperature. To this end, its metrological characterization was addressed to estimate the temperature stability and surface-temperature uniformity for different thermal equilibrium conditions, i.e., with and without the contact probe to be calibrated. The temperature stability, obtained through measurements of the embedded PRT, resulted in a peak-to-peak value of less than 0.03 °C over the whole operating range. A remote measurement method, based

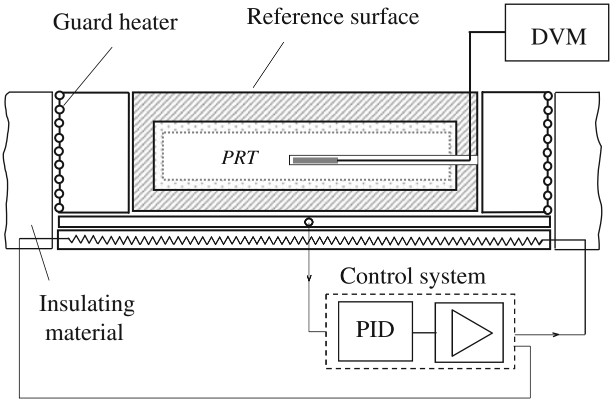


**Fig. 2** Block diagram of the experimental system used to test the HP hot-plate device

on fluorescent decay-time temperature sensors, was exploited to evaluate the surface-temperature uniformity [8]. A two-dimensional array of fluorescence sensing dots was applied to the HP hot plate by means of a thick-film coating technique. An optical fiber, close to the surface, conveyed the excitation light from a laser diode to the various point sensors and transmitted the fluorescent response to the detection stage. In such a way, a thermal map of the HP hot-plate surface was obtained. Figure 3 shows the surface temperature as a function of radial position as measured by the fluorescence sensors at various temperatures (50 °C, 100 °C, 150 °C, and 185 °C) along two orthogonal radial directions depicted by filled and open symbols, respectively. For each temperature, the broken line represents the best fit to the resulting profile. A temperature uniformity of better than 0.08 °C was obtained over the whole temperature range.

Further investigations were carried out to evaluate the perturbation of the surface-temperature profile, and the ability of the device to recover its equilibrium temperature, when a probe is put in contact with its surface. The temperature along a radial direction was measured by means of the fluorescent point sensors when the probe was applied and then removed from the center of the HP hot-plate surface. Figure 4 shows the resulting surface-temperature change detected at 100 °C, 150 °C, and 180 °C as a function of the radial position. As expected, the effect due to the contact probe is a maximum near the probe (at $x = 0$) and decreases with distance.

The thermal perturbation introduced by the contact probe was also investigated by simultaneously comparing the surface temperature and the inner equilibrium temperature before and after applying a probe to its surface. Figure 5a represents the surface-temperature change at 150 °C as obtained from fluorescence decay-time measurements of the sensors placed near the application point of the contact probe, while Fig. 5b shows the inner temperature as measured by the embedded PRT. A comparison of Fig. 5a and b highlights that the temperature change is slightly higher on the surface than inside the device (0.2 °C vs. 0.14 °C). This is consistent with the fact that the disturbing effect of the probe is higher on the surface near the contact point. However, it should be noted that the disturbance is comparatively small in magnitude, both on the surface and inside the HP chamber, thanks to the high thermal conductivity of the device.

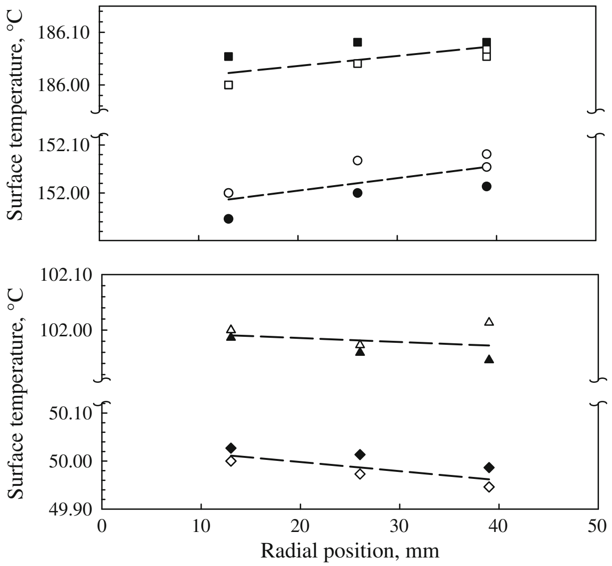


**Fig. 3** HP hot-plate surface temperature along two radial directions (filled and open symbols) at various temperatures. Broken lines are best fit lines to show the temperature profile

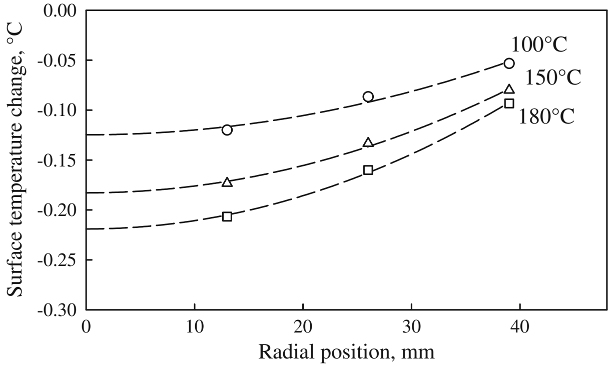


**Fig. 4** Surface-temperature variation of the HP hot plate due to the contact probe applied to the center of its surface at various temperatures

## 4 Discussion

The investigations of the developed HP hot plate were useful in evaluating its characteristics under different thermal conditions. The actual operating range of the device, due to the use of water as the working fluid, is limited to 200 °C because of the internal pressure limits; however, such a range can be easily extended by using other working fluids.

The measurement results, obtained by fluorescence decay-time thermometry, showed the temperature uniformity of the HP hot plate surface to be better than 0.08 °C.

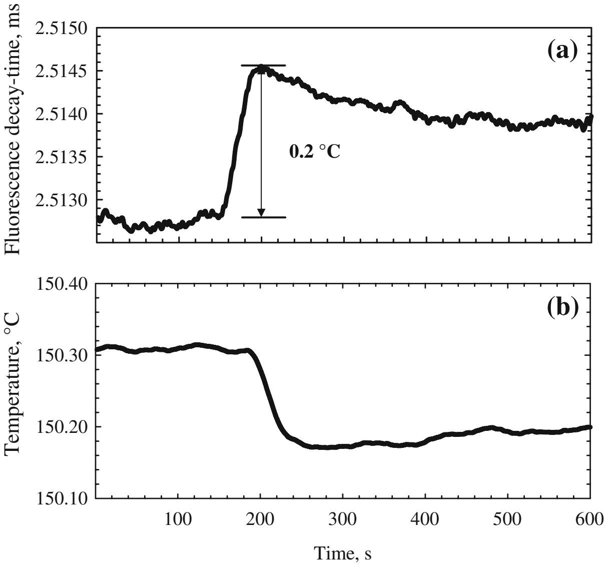


**Fig. 5** (**a**) Change of the surface temperature and (**b**) the inner equilibrium temperature of the HP hot plate before and after applying a probe to its surface

It is interesting to note that a continuous change in the slope of the surface-temperature profile occurs as the temperature increases from ambient to 200 °C (see Fig. 3). The surface temperature and its stability are perturbed when a probe is put in contact with the surface, although the measurements showed a comparatively small change in the surface temperature (about 0.2 °C) and an even smaller change inside the device (about 0.14 °C). The measurements also pointed out that the disturbance introduced by a probe on the temperature field inside the device is much lower than that obtained under the same conditions with a hot-plate system [11]. Thanks to its high thermal conductivity, this device is less sensitive to thermal perturbation when calibrating a probe. As a result, the equilibrium temperature of the chamber, as measured by the embedded PRT, is a good estimate of the actual reference surface temperature, even when the latter is perturbed by the presence of the probe to be calibrated. This feature suggests a different approach to the calibration procedure compared to that generally followed for hot-plate-based calibrations. When a probe to be calibrated is applied to its surface, the reference temperature can be determined through the measurement of a single temperature using the embedded PRT.

The above results show that such a device has the potential to be used as a calibration apparatus for contact surface-temperature sensors. In principle, it could also be used for the calibration of radiation thermometers, although an accurate determination of the surface emissivity would also be required.

**Acknowledgments** The authors would like to acknowledge that parts of the work were supported by the INTAS program of European Commission within the project INTAS Ref. No. 3-55-1757. Thanks also go to the reviewer for the useful suggestions and comments given to the authors.

## References

1. IMEKO TC12, in *Proceedings of the Workshop on Surface Thermal Measurements*, Budapest, Hungary, (1995)
2. F. Edler, M. Gorgieva, J. Hartmann, M. Wagner, in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by B. Fellmuth, J. Seidel, G. Scholz (VDE Verlag, Berlin, 2002), pp. 1105–1110
3. R. Morice, E. Andras, E. Devin, T. Kovacs, in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by B. Fellmuth, J. Seidel, G. Scholz (VDE Verlag, Berlin, 2002), pp. 1111–1116
4. EA Temperature and Humidity Expert Group, *Questionnaire Results on Surface Contact Thermometer*, European Cooperation for Accreditation (1999)
5. M.J. De Groot, High Temp.-High Press. **29**, 591 (1997)
6. E. Andras, Comparison of the reference surface temperature apparatus at NMIs by comparison of transfer surface temperature standards, EUROMET Project P635—Final Report (Budapest, Hungary, 2003)
7. P.D. Dunn, D.A. Reay, *Heat Pipes* (Pergamon Press, Oxford, 1994)
8. L. Rosso, V.C. Fernicola, A. Tiziani, in *Temperature: its Measurement and Control in Science and Industry*, vol. 7, part 2, ed. by D.C. Ripple (AIP, Melville, New York, 2003), pp. 1045–1050
9. S.W. Chi, *Heat Pipe Theory and Practice* (McGraw-Hill, New York, 1976)
10. N.S. Koneva, L.S. Domorod, in *Proceedings of the 6th International Seminar on Heat Pipes, Heat Pumps, Refrigerators*, Minsk, Belarus, (2005)
11. F. Arpino, M. Dell'Isola, V.C. Fernicola, A. Frattolillo, L. Rosso, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by D. Zvizdic (FSB/LPM, Zagreb, Croatia, 2004), pp. 635–641