High thermal homogeneity of Flat-Plate Infrared Calibrator

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ABSTRACT

Infrared reference sources such as blackbodies are used to calibrate and test IR sensors and cameras. Because of increasing less noisy and high resolution sensors, very high uniformity of the emissive surface has become crucial for numerous applications. Among those are non-uniformity correction of infrared cameras focused at short distance and simultaneous calibration of a set of sensors for human temperature measurement instruments.

Compared to the state-of-the-art, improving thermal uniformities by a factor of at least two is a key factor to satisfy the operational needs. This implies to achieve a very fine characterization of the sources thermal inhomogeneities and to design very carefully the infrared reference source.

Here, we developed a new temperature control algorithm to reduce the thermal inhomogeneity. Thanks to our uniformity measurement bench and combined the previously developed high accuracy and stability temperature controller, we demonstrate the extremely low non uniformity for low temperature Flat-Plate Infrared Calibrator with rms value below 50 mK at 50°C and below 200 mK at 110°C over a 300mm emissive surface. The vertical gradient, traditionally observed in the Flat-Plate Infrared Calibrator, is removed; the remaining different spatial contributions to the thermal homogeneity are analyzed and the results are compared with thermal simulations. Software/hardware improvement to reduce the global and local non-uniformity pattern are presented.

Keywords: Blackbody, thermal homogeneity, temperature control algorithm, infrared, uniformity, thermal noise

1. INTRODUCTION

Applications of blackbodies requiring a high thermal homogeneity over the emissive surface become more and more frequent. Among these applications are non-uniformity corrections of infrared cameras focused at short distance and simultaneous calibration of a set of sensors facing a large area blackbody. Facing these demanding applications requires to accurately measure the thermal radiation of each point of the emissive surface. For this purpose, HGH has developed a testing bench based on a low noise radiometer mounted of translating stages, thus scanning the emissive surface, and using an exclusive drift correction method [1].

This paper describes how we characterized the different contributions observed in the non-uniformity pattern of this Flat-Plate Infrared Calibrator thanks to this bench and how we consequently managed to improve the homogeneity of this source. The present paper describes thermal simulations of the non-uniformity contributors and presents an experimental elegant way to remove the principal component of inhomogeneities by using multiple sensor and multiple actuators. +We focus in this paper on Peltier-controlled Flat-Plate Infrared Calibrator of large aperture size (typically 300mm) and able to deliver temperature-controlled devices from -5°C to +150°C as a high uniformity specification is particularly critical for this model.

2. SOURCES OF NON-UNIFORMITY

This paragraph lists the possible contributors to the non-uniformity of the Flat-Plate IR Calibrator. These phenomena are expected to be identified during our measurements and to be corrected.

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Electro-Optical and Infrared Systems: Technology and Applications XXII, edited by Duncan L. Hickman,
Helge Bürsing, Ove Steinvall, Philip J. Soan, Proc. of SPIE Vol. 13674, 136740T
2025 Published by SPIE · 0277-786X · doi: 10.1117/12.3069650

2.1 Natural convection

Considering the emissive surface is vertical, one of the most important sources of non-homogeneity on large aperture Flat-Plate IR Calibrator comes from natural convection of the surroundings air on the emissive plate.

Natural convection has been extensively investigated in the past decades and the physical laws describing this phenomenon are given by the heat transfer and the Navier-Stokes equations. From these equations, characteristics of the natural convection for vertical plates can be extracted [2]:

$$Gr = \frac{g\,\beta\,L^3\,(T_s - T_\infty)}{\upsilon^2}$$

$$Pr = \frac{\upsilon}{\alpha}$$

$$Ra = Gr\,Pr$$

$$Nu = \left(\frac{0.825 + 0.387\,Ra^{1/6}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{8/27}}\right)^2$$

$$h = \frac{\lambda\,L}{Nu}$$

$$Q = h\,A\,(T_s - T_\infty)$$

where Gr is the Grashof number, Pr is the Prandtl number, Ra is the Rayleigh number, Nu is the Nusselt number, h is the convective heat transfer coefficient, g is the gravitational acceleration due to Earth, β is the coefficient of volume expansion, T_s is the surface temperature, T_∞ is the temperature of the fluid temperature far from the surface, L the height of the emissive plate, A is the area of the emissive plate, λ is the thermal conductivity of the fluid, ν the kinematic viscosity of the fluid, α the thermal diffusivity.

The Grashof number approximates the ratio of the buoyancy to viscous forces acting on the fluid: for Gr lower than 10^8, the convection can be considered laminar for the boundary layer; for Gr lower than 10^9, the convection is turbulent. As can be observed in the Table 1, the convection is laminar for size below 300mm and temperature below 80°C. The heat transfer coefficient is between 4 and 10 W/m^2/K. The Nusselt number is related to the temperature gradient at the surface of the emissive plate: a high Nusselt number mean a high temperature gradient. Since the Nusselt number increases significantly with the length of the plate, one can expect to observe the highest differences for the largest plate; an increase in temperature is also related to an increase in the non-uniformity due to the natural convection.

Table 1. Characteristics of fluid convection with respect to temperature and length of the emissive plate

	25°C	50°C	80°C	110°C	150°C
L=50mm	Gr= 0.11*10^6 Ra= 0.07*10^6 Nu= 11.09 h= 5.8 W/m^2/K Q = 0.07 W	Gr= 0.61*10^6 Ra= 0.43*10^6 Nu= 17.47 h= 9.1 W/m^2/K Q = 0.68 W	Gr= 1.16*10^6 Ra= 0.81*10^6 Nu= 20.80 h= 10.8 W/m^2/K Q = 1.62 W	Gr= 1.67*10^6 Ra= 1.17*10^6 Nu= 22.97 h= 11.9 W/m^2/K Q = 2.69 W	Gr= 2.27*10^6 Ra= 1.59*10^6 Nu= 25.03 h= 13.0 W/m^2/K Q = 4.23 W
L=100mm	Gr= 0.85*10^6 Ra= 0.06*10^6 Nu= 19.09 h= 5.0 W/m^2/K Q = 0.25 W	Gr= 4.87*10^6 Ra= 3.41*10^6 Nu= 31.02 h= 8.1 W/m^2/K Q = 2.42 W	Gr= 9.29*10^6 Ra= 6.51*10^6 Nu= 37.32 h= 9.7 W/m^2/K Q = 5.82 W	Gr= 13.31*10^6 Ra= 9.33*10^6 Nu= 41.42 h= 10.8 W/m^2/K Q = 9.70 W	Gr= 18.16*10^6 Ra= 12.73*10^6 Nu= 45.34 h= 11.8 W/m^2/K Q = 15.33 W
L=180mm	Gr= 4.93*10^6 Ra= 3.46*10^6 Nu= 31.14 h= 4.5 W/m^2/K Q = 0.73 W	Gr= 28.41*10^6 Ra= 19.91*10^6 Nu= 51.71 h= 7.3 W/m^2/K Q = 7.26 W	Gr= 54.2*10^6 Ra= 37.98*10^6 Nu= 62.64 h= 9.0 W/m^2/K Q = 17.59 W	Gr= 77.67*10^6 Ra= 54.44*10^6 Nu= 69.77 h= 10.1 W/m^2/K Q = 29.39 W	Gr= 105.92*10^6 Ra= 74.25*10^6 Nu= 76.60 h= 11.1 W/m^2/K Q = 46.60 W
L=300mm	Gr= 22.84*10^6 Ra= 16.01*10^6	Gr= 131.5*10^6 Ra= 92.2*10^6	Gr= 250.8*10^6 Ra= 175.8*10^6	Gr= 359.5 *10^6 Ra= 252.0*10^6	Gr= 490.4*10^6 Ra= 343.7*10^6

	Nu= 48.50 h= 4.2 W/m^2/K Q = 1.89 W	Nu= 81.79 h= 7.1 W/m^2/K Q = 19.14 W	Nu= 99.5 h= 8.6 W/m^2/K Q = 46.59 W	Nu= 111.2 h= 9.6 W/m^2/K Q = 78.04 W	Nu= 122.3 h= 10.6 W/m^2/K Q = 124.02 W

2.2 Others sources of non-uniformity

Three others sources of non-homogeneity of temperature can be mentioned:

- Non uniformity due to the discretization of the actuators; in our case, the Flat-Plate IR Calibrator is controlled through a Peltier matrix; therefore, the Peltier pattern is observed on the uniformity map
- Heat losses on the edges of the emissive plate
- Non uniformity due to differences in the emissive painting; here, we refer to the apparent temperature of the Flat-Plate IR Calibrator. We mention this point for completeness, but it is negligible compared to other non-uniformity components and cannot be observed experimentally.

3. THERMAL SIMULATION OF CLASSICAL FLAT-PLATE IR CALIBRATOR

To observe the three main contributions to the non-uniformity mentioned previously, we perform thermal simulations with Elmer GUI software [3]. We model our system in 2D to reduce the size of the mesh so that the calculation can be performed with a standard computer. We choose to simulate our system at 50°C to avoid turbulence instabilities in the calculations. The simulation is stopped after 45s since the temperature profile do not change anymore.

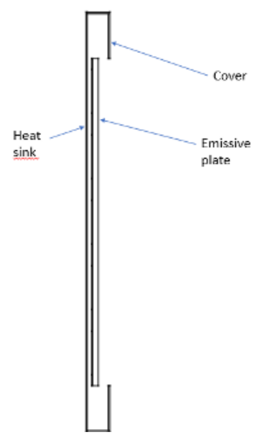

Figure 1. 2D model for the simulation; the emissive plate is equipped by 5-Peltier matrix on the its back face. The emissive plate, heat sink and cover are surrounded by air.

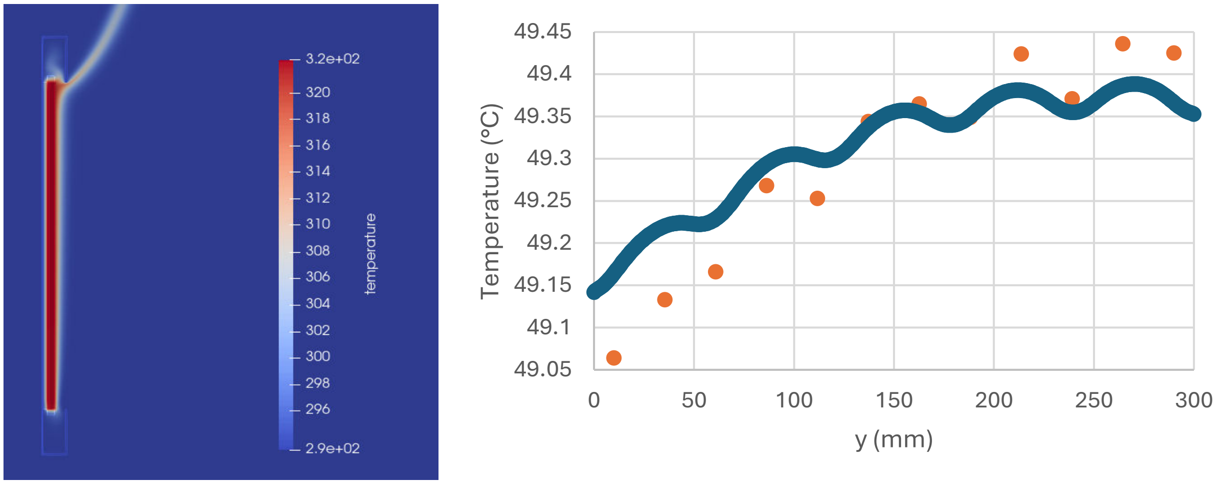

Figure 2. Left: Result of the simulation for the temperature (K); Right: Temperature profile with a vertical plate of 300mm heated at around 50°C (49.3°C) with 5-Peltier matrix and natural convection; Blue: simulation data; Orange: experimental data

In Figure 2, the results of the simulation are presented with a comparison with experimental data. Although the match between simulated and experimental data is not perfect, we can observe similar behavior in the two curves. Three contributions previously mentioned can be observed:

- The Peltier pattern correspond to a sinusoidal curve distributed over the whole plate
- Heat losses on the edges generate a parabolic profile in temperature where the maximum is at the center of the plate
- Natural convection produces an increase in the temperature as the y position increases; the top of the plate is hotter than the bottom

4. EXPERIMENTAL DATA ON CLASSICAL FLAT-PLATE IR CALIBRATOR

Uniformity maps have been measured on Flat-Plate IR Calibrators with different sizes and at different temperature and using the bench described into paragraph 1.

In Figure 3, two temperature uniformity maps are presented where the only difference is the size of the emissive plate. The non-uniformity contribution due to natural convection can clearly be observed; as stated in the previous paragraphs, the natural convection has a higher impact when the size of the plate increases. For a 300 mm plate (right map), the difference between the top and the bottom of the plate corresponds to 1.8°C at 150°C and is the main contribution to the non-uniformity whereas the difference between the top and the bottom is only 0.4°C at 150°C and the main contribution to the non-uniformity is the Peltier pattern.

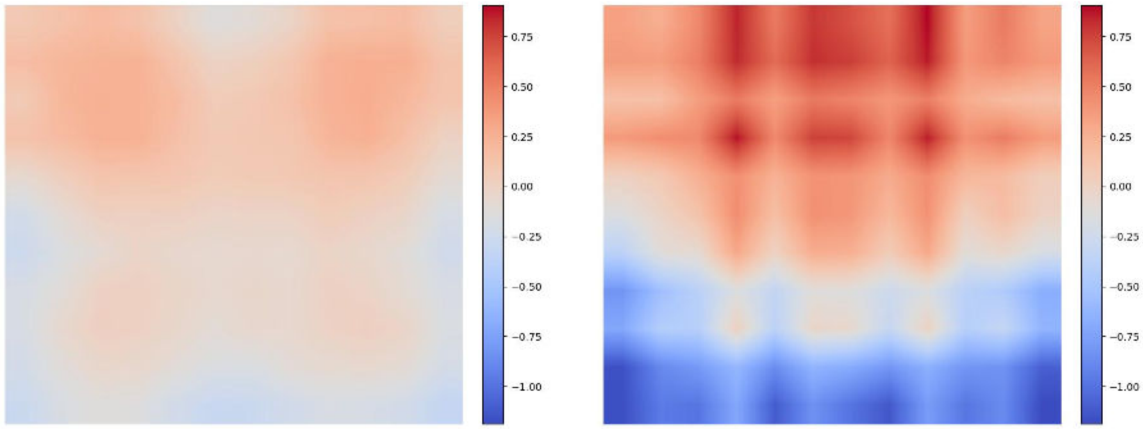

Figure 3. Uniformity map on two Flat-Plate IR Calibrator at 150°C; Left: Length of the plate is 100mm; Right: Length of the plate is 300mm. The mean temperature has been retrieved from the uniformity map and the color scale is the same for the two maps.

In Figure 4, two temperature uniformity maps are presented where the only difference is the temperature of the plate; the length of the plate is 300mm. The non-uniformity contribution due to natural convection can clearly be observed; as stated in the previous paragraphs, the natural convection has a higher impact when the temperature increases. For 150°C (right map), the difference between the top and the bottom of the plate corresponds to 1.8°C whereas the difference between the top and the bottom for temperature of 75°C is only 0.6°C.

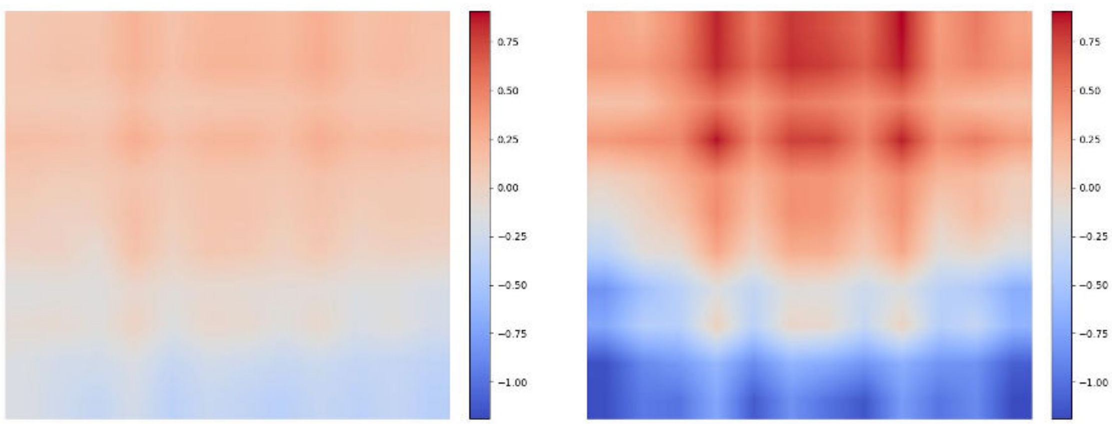

Figure 4. Uniformity map on the Flat-Plate IR Calibrator (300mm); Left: the temperature of the plate is 75°C; Right: the temperature of the plate is 150°C. The mean temperature has been retrieved from the uniformity map and the color scale is the same for the two maps.

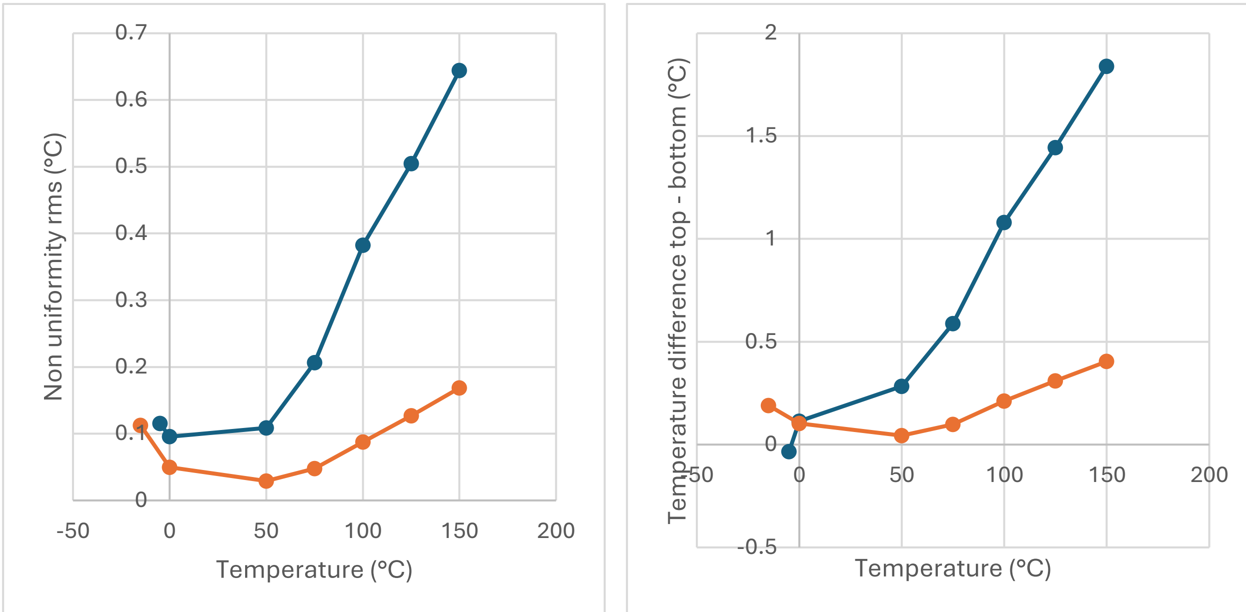

Figure 5. Non-Uniformity rms value and temperature difference between top and bottom for different temperatures; Orange: Height of the plate is 100mm; Blue: Height of the plate is 300mm.

Figure 5 present the non-uniformity rms value and the top-bottom differences for 100 (orange) and 300mm (blue) plates at different temperatures. As intuited, the natural convection produces the largest effect for the highest temperatures and the largest apertures. For this reason, in the following, we have concentrated our effort on Flat-Plate IR Calibrator with length of 300mm.

5. IMPROVEMENT ON THE UNIFORMITY

To remove the vertical gradient coming from the natural convection, the idea was to use two temperature sensors and two independently-controlled Peltier matrices; the power sent to the Peltier matrix is controlled through an electronic controller, including a PID algorithm coupled with a high precision temperature monitoring system in order to achieve high temperature stability in the range of a few mK. The temperature sensor located at the top of the plate is used for the regulation of the upper Peltier matrix (2 x 5) and the temperature sensor located at the bottom for the regulation of the lower Peltier matrix (3 x 5). To achieve the best thermal uniformity, the temperature sensors are calibrated with an uncertainty of 50 mK. To reduce the heat losses, isolation has been placed on the edges of the emissive plate.

Figure 6. Flat-Plate IR Calibrator with two temperature sensors and two Peltier matrices

The measurement was performed at 50, 80 and 110°C; in the Figure 8, the uniformity map at 110°C is shown.

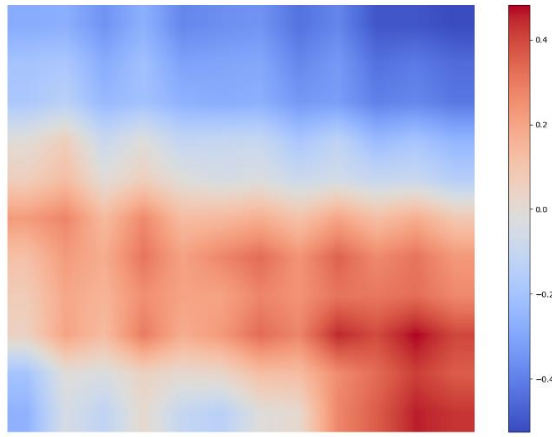

Figure 7. Uniformity map of 12’’ Flat-Plate IR Calibrator at 110°C with two temperature sensors and two Peltier matrices. The mean temperature has been retrieved from the uniformity map and the color scale is the same for the two maps.

Table 2. Comparison of the uniformity rms value and top-bottom temperature difference

Temperature (°C)	Uniformity rms with 2 sensors and two Peltier matrix (°C)	Uniformité with one sensor and one Peltier matrix (°C)	Top-bottom temperature difference with 2 sensors and two Peltier matrix (°C)	Top-bottom temperature difference with one sensor and one Peltier matrix (°C)
50	0.037	0.109	-0.01	0.28
100	Not measured	0.383	Not measured	1.08
110	0.269	Not measured	-0.28	Not measured
125	Not measured	0.505	Not measured	2.00

The result is promising since the most important contribution to the non-uniformity has been removed; the vertical gradient has been clearly reduced and only a hot spot in the middle of the plate can be observed. One can also observed the 5x5 Peltier-matrix pattern on the uniformity map. To reduce these contributions, two changes has been made; the first change was to rearrange the Peltier matrices as indicated in Figure 8 to reduce the hot spot in the middle plate. In the previous configuration, the lower matrix equipped with 3x5 Peltier modules generates more heat transfer than the upper one equipped with 2x5 Peltier modules. By rearranging the matrices, a line of Peltier with lower heat transfer is located at the top of the plate, reducing the temperature at the top.

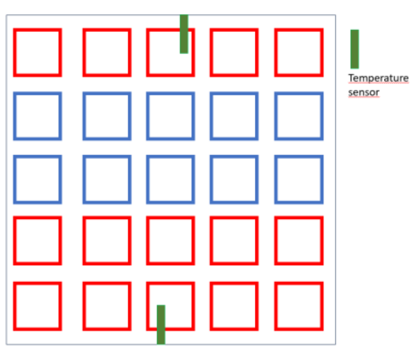

Figure 8. Uniformity map of 300mm Flat-Plate IR Calibrator at 110°C with two temperature sensors and two Peltier matrices

The uniformity maps for the previous configuration and the new configuration are presented in Figure 9. On the right picture, we can clear see that the hot spot in the middle of the plate has been removed. We can still observe the Peltier pattern and some hot zone on the right bottom part of the picture. This area cannot be related to some misconception in our design and our current explanation is that it is due to non-planarity of the plate causing non-uniform contact with the Peltier modules.

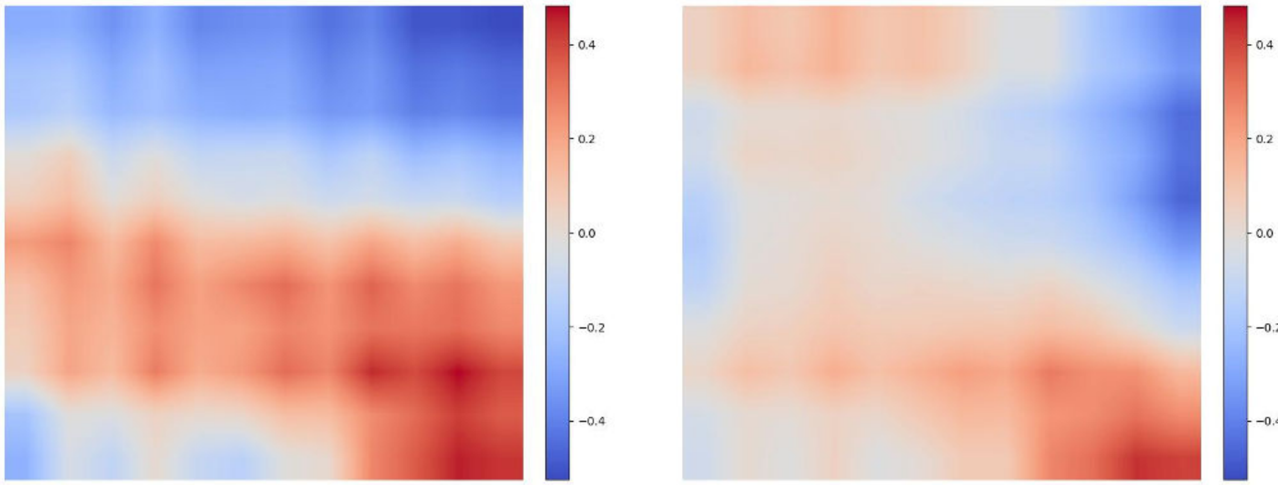

Figure 9. Uniformity map of 300mm Flat-Plate IR Calibrator at 110°C with two temperature sensors and two Peltier matrices. The mean temperature has been retrieved from the uniformity map and the color scale is the same for the two maps.

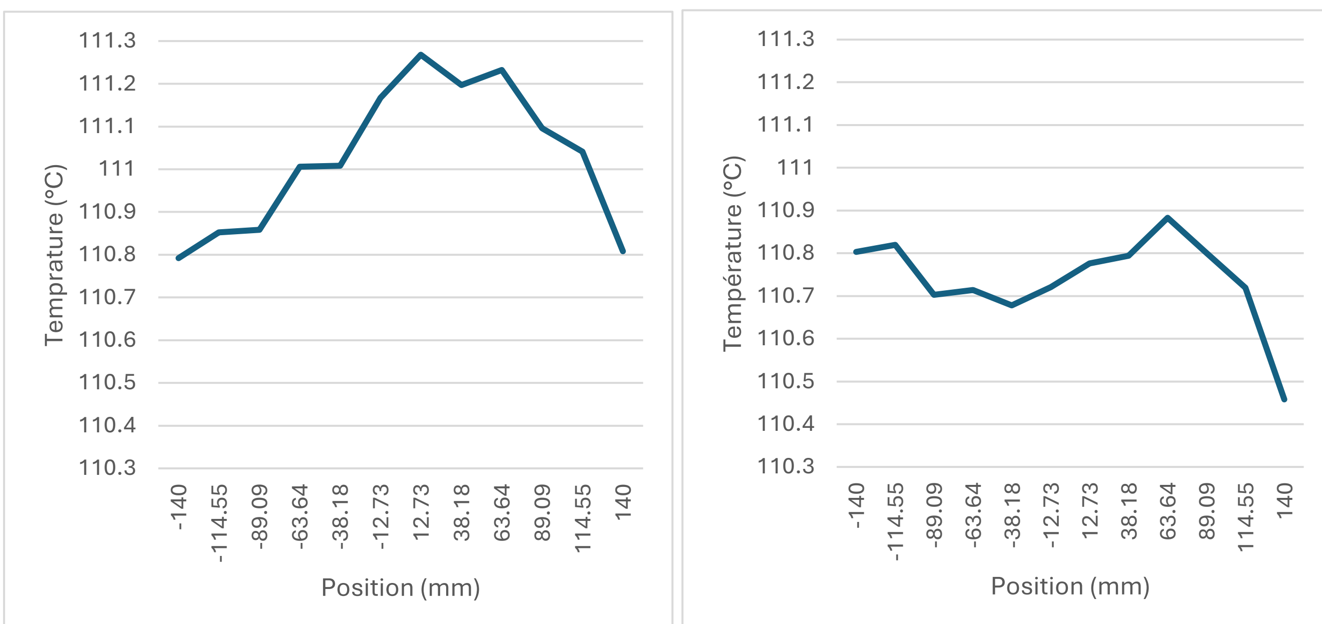

Figure 10. Horizontal profile in the center of the uniformity map and not centered on a line of Peltier. Left: with the initial Peltier matrices; Right: with changes in Peltier matrices

The remaining important contribution is related to the Peltier pattern. To reduce this effect, we introduce a graphite thermal pad; this anisotropic material will diffuse the heat laterally efficiently and will "blur" the pattern. The Figure 11 presents a horizontal profile centered on the central line of the Peltier matrix. The Peltier pattern can be clearly observed with an amplitude of 160mK with the classical thermal pad (blue curve) and an amplitude of 60mK with the graphite thermal pad (orange curve); the component corresponding to the Peltier pattern has been reduced by a factor 2.7.

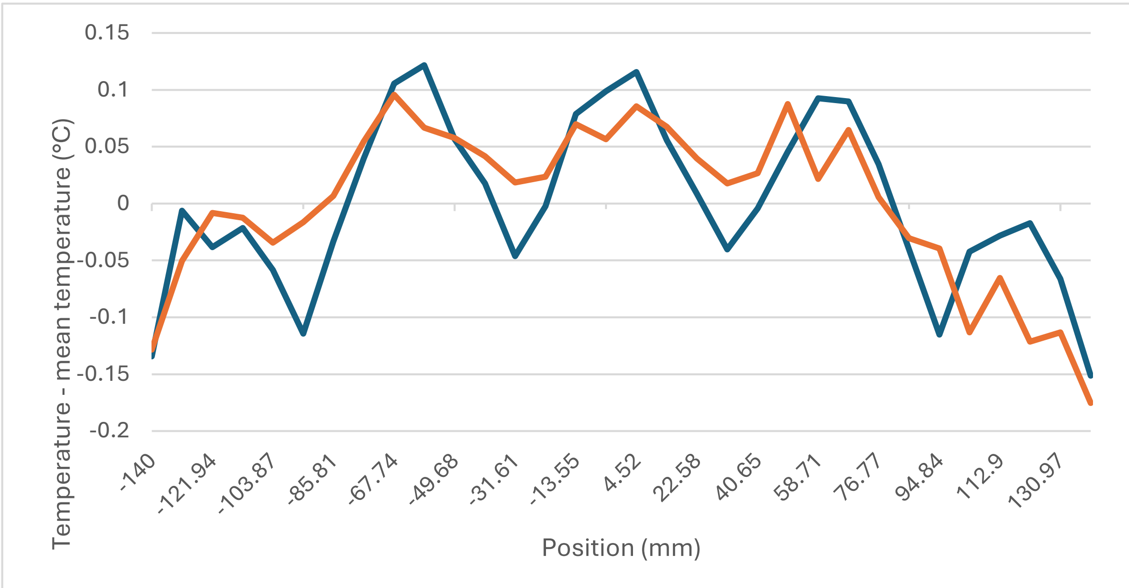

Figure 11. Horizontal profile in the center of the uniformity map. Blue: with the silicon thermal pad; Orange: with graphite thermal pad

The final rms value with the rearrangement of the Peltier matrices and the graphite pad is 0.17°C at 110°C, a factor 2 below the classical configuration with a single temperature sensor and a single actuator and with a silicon thermal pad.

6. CONCLUSION

Contributions to non-homogeneity has been analyzed, simulated, and compared with experimental data. Three main factors impact the temperature uniformity of Flat-Plate IR Calibrator: natural convection, Peltier pattern and heat losses on the edges.

We demonstrate an improvement by a factor 3 at 50°C and a factor > 2 at 110°C in the temperature uniformity of large Flat-Plate IR Calibrator (300mm) by incorporating two temperatures sensors and two independently adjustable Peltier matrices to compensate for the vertical gradient caused by natural convection. The remaining contribution corresponding to the Peltier pattern has been reduced significatively by including an anisotropic graphite thermal pad.

Combining these improvements with other methods to reduce non uniformity like using a thicker plate can even reduce the non-uniformity of the Flat-Plate IR Calibrator, allowing to perform very precise calibration of sensor using large aperture blackbodies.

Further improvement on the comprehension of the non-uniformity contribution might be obtained from simulation with other software optimized for simulation of fluid like OpenFOAM in order to take into account turbulence at higher temperatures.

REFERENCES

[1] Catherine Barrat, Sébastien Violleau, « Evaluating uniformity of IR reference sources », SPIE # 9649-6

[2] https://faculty.utrgv.edu/constantine.tarawneh/Heat%20Transfer/HeatTransferBooklet.pdf
[3] https://www.elmerfem.org/blog/