Thermal modelling of RLCYC 75: a 2kW electrically calibrated laser calorimeter designed for Laser MegaJoule diagnostics calibration

C CRESPY, D VILLATE, M TODESCHINI, A LAVILLE –GEAY, M SOSCIA

1 CEA CESTA, BP2, 33114 Le Barp, FRANCE
2 Laser Métrologie, Z.A. les Romains, 74960 Gran Gevrier, France

E-mail: charles.crespy@cea.fr

Abstract. RLCYC 75 is a new electrically calibrated laser calorimeter especially manufactured by Laser Métrologie to calibrate energy diagnostics of Laser MegaJoule (LMJ). It consists of an optical cavity cooled by a hydraulic system. The system is designed to provide laser power measurements with uncertainty less than 1% at 2kW and traceability to the International System of Units (SI) thanks to electrical calibrations. In this paper, a 3D thermal model is developed to study the thermal equivalence between electrical calibration and optical measurement. The simulation results are crossed with PT100 measurements in order to validate the model. The thermal modelling of the RLCYC 75 calorimeter is a key point to analyse the calorimeter efficiency, thus this work validates the geometrical design of RLCYC 75 calorimeter.

1. Introduction
Electrocaly calibrated laser calorimeters are considered as the most suitable tools to perform laser power measurements. Each calorimeter has to be designed taking into account laser characteristics: wavelength, power, pulsed or continuous, laser beam size...

To calibrate the laser energy diagnostics of Laser MegaJoule (LMJ), a 2 kW laser standard is required. Since current metrology is not accurate enough for this range of power, it has been chosen to develop a new calorimeter called RLCYC 75. RLCYC 75 is designed and manufactured by Laser Métrologie ®.

1.1. RLCYC 75 principle
RLCYC 75 consists of cylindro-inner-cone cavity cooled by a water jacket. The hydraulic cooling system is an under skin turbulent flow. The measurements of the water flow rate (q) and of the water temperature rising (ΔT) provide an estimation of the power absorbed by the calorimeter (P) thanks to the relation:

\[ P = C \cdot \Delta T \cdot q \]  \hspace{1cm} (1)

\( C \) is the calibration coefficient (close to the water thermal capacity). To perform laser power measurement traceability to international system units, electrical calibrations must be achieved. To this
end, an electrical heater has been implemented within the calorimeter. During electrical calibrations a known electrical power (primary electrical standard) is supplied. Thus, the measurement of \( \Delta T \) and \( q \) allow an estimation of the calibration coefficient \( C \). The calibration coefficient is assumed to be constant. This point implies that the variation of water thermal capacity in function of temperature is neglected (actually, the water thermal capacity variation is close to 0.3% when the water temperature ranges from 20°C to 28°C).

The water temperature rise \( (\Delta T) \) is measured using two temperature probes (four wires class A PT100) paired in a Wheatstone bridge. The flow rate measurement is performed using a calibrated magnetic induction ZTN 20-05 turbine. The repeatability of RLCYC 75 measurements (product of temperature rise by flow rate) has been experimentally estimated to be less than 0.2%. During data acquisition, the flow rate is constant and close to 4 l.min\(^{-1}\). In this configuration 2kW laser absorption leads to a temperature rise close to 7 °C.

![Visualization of RLCYC 75](image)

**Figure 1.** Visualization of RLCYC 75

1.2. Thermal equivalence definition
The electrical calibration results can be used for optical power measurement if the amount of thermal losses in the two deposit modes (optical mode and electrical mode) is the same. This point, known as the thermal equivalence between optical and electrical modes, is underlined in many works (see ref. [1], [2] and [3]).

To quantify the uncertainties due to the thermal equivalence, power balance is considered. Because of the thermal losses, a fraction of the power supplied during electrical calibration is dissipated in the environment, and thus, is not measured by the instruments. The fraction of the electrical power transmitted to the water cooling system is called \( D_e \). As in electrical mode, a fraction of the power supplied by laser shots is not transmitted to the water cooling system and, thus, is not measured by the instruments. The fraction of power absorbed by the calorimeter and transmitted to the water cooling system is called \( D_o \). With these considerations, the laser power is written:

\[
P = \frac{D_e}{D_o} C(q\Delta T) = dC(q\Delta T)
\]

The term \( d \) (\( d=D_e/D_o \)) is called the thermal equivalence parameter. The estimation of the value \( d \) parameter is a key point to validate RLCYC 75 measurements traceability to international system of units. If the parameter \( d \) is equal to unity, then the thermal equivalence contribution to uncertainty is zero.

1.3. Aim of the study and contents
The aim of this work consists in estimating the value of the parameter \( d \) by modelling the thermal behaviour of the calorimeter. To this end, the thermal losses in the two deposit modes are computed using a 3D thermal model developed with Comsol Multiphysics. In a first part, the thermal model is
presented (heat source location, boundary conditions...). Then numerical results are compared with temperature probes (PT 100) measurements and the value of $d$ parameter is numerically estimated. In the last section some techniques to reduce the uncertainty linked to thermal equivalence are presented.

2. Thermal model

The aim of the thermal model is to quantify thermal losses during electrical calibrations and during laser power measurements. The simulations are performed in steady state condition. The system discretization consists in a tetrahedral mesh. A refined mesh is used on the important temperature gradient zones (cone and cylinder), a coarser mesh is used for the rest of the system.

2.1. Heat sources

The main difference between electrical and optical modes is linked to the heat source location. In electrical mode the heat source is modelled using a surface heat source condition located on the calorimeter – electrical heater contact (see Figure 1). Concerning optical mode, the heat source strongly depends on the impact of the laser beam within the optical cavity. In order to take into account the influence of light reflections inside the cavity in the thermal model, a 3D ray tracing mode has been implemented. On the cavity walls, the nature of the reflexion depends on incidence ray angle on the cavity wall. If the ray incidence angle is more than 75° specular reflexions are considered. On the other case, isotropic reflexions are considered (cf. Figure 2). In isototropic reflexion case, a Monte Carlo procedure is implemented: the direction vector characteristics are chosen randomly. In order to reduce the numerical uncertainty due to numerical random process, the trajectories of 200 000 rays are computed. The laser beam is a divergent square shaped laser beam. The heat source location is estimated by computing the ray impacts on cavity wall (cf. Figure 3).

2.2. Convective cooling modelling

The turbulent hydraulic cooling is modelled by estimating the convective coefficient and taking into account the temperature rising along the fluid path. The water cooling system consists of a square shaped tube. The convective coefficient value ($h_c$) is estimated using the empirical law defined in [4]:

$$Nu = \frac{h_c D}{\lambda} = 0.027 Re^{4/5} Pr^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14}$$

(3)

Where $Nu$ is the Nusselt number, $Re$ the Reynolds number, $Pr$ Prandtl number and $\mu$ the viscosity, $\lambda$ the thermal conductivity, $D$ the hydraulic diameter. The evolution of the Reynolds number and the convective coefficient as a function of the flow rate is presented in Figure 4 and Figure 5.
It is noteworthy that the flow is turbulent ($Re>10000$) when the flow rate is higher than 2 l.min$^{-1}$. This point enhances the cooling convective coefficient which ranges from 5 000 Wm$^{-2}$K$^{-1}$ to 14 000 Wm$^{-2}$K$^{-1}$ when the flow rate ranges from 2 l.min$^{-1}$ to 8 l.min$^{-1}$.

2.3.  Thermal losses modelling

Thermal losses due to conduction, convection and radiation are considered in the model. Thermal losses due to conduction are very low and are not described here. Radiation losses inside the optical cavity are modelled using a surface to surface radiation simulation. A vertical plate is located in front of the optical cavity in order to quantify the amount of power lost by radiation. The cavity to ambient view factor is close to 1%.

In order to quantify natural convective coefficient, 2D simulations of the air motion around the calorimeter are performed (see Figure 6). It is noteworthy that the calorimeter is located in a rectangular box which reduces the convective losses. Concerning the natural convective cooling inside the optical cavity the 3D air motion are estimated in order to estimate a global convective coefficient (see Figure 7).

It is noteworthy that the effect of internal convection occurs at the cylinder entrance. Thus, the internal convection does not play an important role on the whole internal surface of the cylinder. Both
convective phenomenon are not easy to model, thus the uncertainty on the convective coefficient will be taken into account in the results analysis.

3. Results and analysis

3.1. Temperature fields
The numerical temperature fields within the calorimeter during a 2kW electrical calibration and during a 2 kW laser deposit are presented in Figure 8 and Figure 9 (the flow rate is 4l.min⁻¹).

The main difference between the two deposit modes is linked to the heat source location. The electrical power is supplied within the system, while optical absorption is located on the optical cavity surface. This point leads to very different thermal behaviours.

3.2. Comparison between numerical and experimental results
Eight temperature probes (PT 100) located at different points of the system provide measurements used to validate the thermal model. Sixth probes are located along the cylinder width. The two others are located on the back of the calorimeter. The location of the probes is presented on Figure 10.

The measurements are acquired during a 2kW electrical calibration and during a 2kW optical supply. In both cases the flow rate is close to 4 l.min⁻¹. The results in term of $\Delta T (\Delta T=T-T_{amb})$ are presented on Figure 11 and Figure 12.
Figure 11 and Figure 12 show that the numerical results and measurements are in good agreement (deviation less than 0.6°C). This study validates the water cooling modelling and the geometry of the laser deposit.

3.3. Thermal equivalence parameter estimation

In order to estimate the uncertainty on laser power measurements due to thermal equivalence, the ε parameter is defined:

\[ d = 1 + \varepsilon \quad (4) \]

Figure 13 and Figure 14 show the evolution of ε parameter as a function of the flow rate and the power.

The value of ε has been estimated for different flow rate values for a 2kW supply. The ε value ranges from 0.015% to 0.055% when the flow rate ranges from 2 l.min\(^{-1}\) to 6 l.min\(^{-1}\). The model shows that the fraction of thermal losses is very close in the two deposit modes. The main part of thermal losses is due to convection (70%). To sum up, the geometry of the hydraulic system is sufficiently well to
perform an efficient cooling whatever the heat source location. The difference in term of thermal non-
equivalence when the flow rate ranges from 4 l.min$^{-1}$ to 6l.min$^{-1}$ is less than 0.02%. This point justifies
the use of a 4 l.min$^{-1}$ flow rate for accurate measurements.

3.4. Uncertainty on thermal losses estimation
To quantify the uncertainty on $\varepsilon$ estimation, the sensitivity of model parameters is investigated.
Indeed, some parameters used in the model are not perfectly known: the fraction of power deposited
on the cylinder in optical mode ($R_S$), the convective coefficient value due to water cooling ($h_C$), and
the convective coefficients for natural convection cooling ($h_{cn1}$ for external convection, $h_{cn2}$ for internal
convection). Influence of these parameters is presented on table 1.

| Parameters | Value Range         | Influence on $\varepsilon$ estimation |
|------------|---------------------|---------------------------------------|
| $R_S$      | 10% - 20%           | 0.03%                                 |
| $h_C$      | 6000 - 10000 W.m$^{-2}$K$^{-1}$ | 0.02%                                 |
| $h_{cn1}$  | 2 W.m$^{-2}$K$^{-1}$ - 5 W.m$^{-2}$K$^{-1}$ | 0.05%                                 |
| $h_{cn2}$  | 0 W.m$^{-2}$K$^{-1}$ - 3 W.m$^{-2}$K$^{-1}$ | 0.02%                                 |

With these values the uncertainty on $\varepsilon$ is estimated to be less than 0.1%. Thus, in the following, the
uncertainty due to thermal non-equivalence is considered to be 0.2% (this result includes uncertainty
on thermal non-equivalence estimation).

4. Thermal equivalence improvement
In order to improve the thermal equivalence, many solutions to reduce thermal losses are studied.
Since the convection is the main contributor, it can be envisaged to put the calorimeter in a cylinder
shaped enclosure. This will reduce the air motion around the calorimeter (see Figure 15). The
the evolution of the exchange coefficient between enclosure and the calorimeter ($h_{cn1}$) in function of the
enclosure diameter ($\delta_\phi$) is shown on Figure 16.

![Figure 15](image1.png)
![Figure 16](image2.png)

**Figure 15.** Air velocity fields located between calorimeter and enclosure

**Figure 16.** Exchange coefficient between enclosure and calorimeter in function of the
enclosure diameter ($\delta_\phi$)

The exchange coefficient is due to the conduction within the air slice and to the natural convection.
If the enclosure diameter is less than 0.015 m, the air velocity is zero and the exchange is only due to
the conduction across the air. It appears that this diameter enclosure value is the optimal choice. In this
configuration the natural convective coefficient around the calorimeter is close to 1 W.m$^{-1}$ K$^{-1}$. Thus the thermal losses due to external convection are divided by 3.

Another improvement consists in reducing convection within optical cavity. To this end, a shutter has been designed. The aim of shutter is to reduce the air motion at the entrance of the cylinder without cutting the laser beam. The internal shutter face has to reflect radiations from optical cavity. Thus, the shutter will reduce not only the convective losses but also the radiation.

With these two improvements, thermal equivalence of the calorimeter is predicted to be less than 0.03% (including uncertainty on thermal equivalence estimation).

5. Conclusion
To guarantee the traceability of RLCYC 75 laser power measurements to international system of units, the thermal equivalence of the calorimeter has been estimated. Thus, a thermal model has been developed to quantify the amount of thermal losses during an electrical calibration and a laser power measurement. The key points of the model are the heat source locations (which is the main difference of the two deposit modes) and the thermal losses modelling. Concerning the heat source location in optical mode, a 3D ray tracing model has been developed to take into account the reflexions inside the cavity. Concerning the thermal losses, the main issues are due to the convective phenomena which are responsible of 70% of the total amount of thermal losses. The numerical results show a good agreement with temperature probes measurement. This point validates the efficiency of the cooling system. The thermal equivalence term is estimated to be less than 0.1% with an uncertainty close to 0.1%. This result is very important in term of traceability chain since the systematic error due to electrical calibration is less than 0.2%. Several simple improvements can be implemented to reduce the thermal losses during calibration and measurement. The main aim of these improvements consists in reducing the thermal convection around the calorimeter and inside the optical cavity. The systematic error due to thermal equivalence will be less than 0.03%. In future works the uncertainty due to the other contributors will be estimated (instrumentation, optical cavity absorption, model error).

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