Thermal analysis of Laser MegaJoule calorimeters

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Abstract. For LMJ applications, an accurate procedure for laser pulse energy measurement is a crucial requirement. In this study, the influence of measurement procedure on LMJ calorimeter uncertainty is experimentally and numerically investigated. To this end, a 3D thermal model is developed and two experimental devices are implemented. The metrological characteristics of both devices are presented. As a first step, the model is validated by crossing numerical and experimental results. Then, the influence of a large number of parameters considered as likely uncertainty sources on calorimeter response is investigated: wavelength, pulse duration, ambient temperature, laser beam shape... The final goal is to define a robust and efficient calibration procedure in order to strongly reduce the uncertainty on LMJ laser pulse measurement.

1. Introduction

The Laser MegaJoule (LMJ) at Commissariat à l’Énergie Atomique et aux Énergies Alternatives (CEA) near Bordeaux (France) is designed to achieve fusion ignition of a deuterium-tritium target. It will contain 176 square shaped laser beams having a section of 400x400mm.

The laser pulses energy measurement is a key point in LMJ applications. Indeed, the uncertainty on laser pulse energy measurement has to be less than 2%. Thus, REC (Radiomètre etalon de conversion) calorimeter has been especially manufactured to accurately quantify the energy of LMJ laser pulses. REC is an electrically calibrated calorimeter. It consists of an absorbing glass which is attached to an aluminum plate. The response of the calorimeter is the time dependent temperature profile measured on the rear face of the aluminum plate using an array of Peltier cells. Moreover, electrical heaters are attached to the aluminum rear face to perform electrical calibration. The REC are not absolute: they must be optically calibrated in an out of line lab to give a measurement traceable to the International System of Units. The difference between calibration conditions and LMJ line measurement conditions can lead to important systematic errors. It’s a requirement to quantify the influence of measurement procedure on the calorimeter accuracy. Thus, modeling and analysis of the calorimeter thermal behavior are very important issues.

To this end, two kinds of tools have been developed:
- A three-dimensional model is developed using COMSOL Multiphysics to understand the calorimeter response in the two deposit modes (electrical an optical)
- Two experimental devices have been implemented to analyze the thermal behavior of the calorimeter after an electrical deposit and after laser pulse absorption.
The measurements are used to validate the model, then the influence of some parameters on the calorimeter response is numerically and experimentally studied (wavelength, laser beam size, deposit time).

2. Thermal Model

2.1. Geometry and mesh

The geometry of the REC is presented in Figure 1. Since REC calorimeter is designed for the absorption of a 400 x 400 mm\(^2\) square shaped laser beam, the geometry of the calorimeter is not standard. The absorbing glass is a 400 mm x 400 mm x 7.6mm slice of NG11 (Schott). In Figure 1, the visualization of the rear face of the aluminum plate shows the disposition of the 30 Peltier cells array and the 5 electrical heaters. The energy supplied within the calorimeter is dissipated into the thermal mass through the Peltier cells. The system is modeled using Comsol Multyphiscs. Using symmetry properties of the system only a quarter of the calorimeter is modeled. A refined mesh is used on the important temperature gradient zones (peltier cells and absorbing glass), a coarser mesh is used for thermal mass discretization.

![Figure 1. REC calorimeter (a-profile view, b-rear face of the aluminium plate, c-mesh visualization)](image)

2.2. Energy supply modelling

Energy can be supplied by laser absorption (optical mode) or by Joule effect within electrical heaters (electrical mode). Both modes are modeled. The electrical and optical pulses are considered as temporal rectangle function defined by their duration (\(\tau\)) and the total amount of energy (\(Q\)). Concerning optical mode, a coupled conductive / radiative transfer heat transfer problem is considered (see [Liu’04] [Hahn’97] [Tan’00]). The thermal balance in a material submitted to a transient heat transfer is governed by the energy equation relating the variation of the local temperature to the total heat flux divergence:
\[
\rho C_p \frac{\partial T(x, y, z, t)}{\partial t} = -\nabla q^c + S' (x, y, z, t)
\]

(1)

\[
q^c = -\lambda_c \nabla T
\]

(2)

Where \( \rho \) is the density, \( C_p \) the specific heat, \( \lambda_c \) the thermal conductivity, \( q^c \) the conductive heat flux density and \( S' \) the radiative source term. Since the maximum temperature rise within the system is less than 8°C, the thermal properties are assumed to be independent of the temperature. The radiative source term is defined as the radiative flux divergence. It is estimated using radiative transfer equation (RTE). Since the glass is opaque in the far IR, the radiative own emission can be neglected. By assuming that the laser pulse is monochromatic and that the laser propagation is only directed along \( x \) axis, the ETR in the glass is written:

\[
\frac{1}{\beta} \frac{\partial q'(x)}{\partial x} + q'(x) = 0
\]

(3)

Where \( \beta \) is the glass extinction coefficient and \( q' \) the radiative flux. The radiative source term is defined as the radiative flux divergence:

\[
S'(x, y, z, t) = div(q^c) = \beta(1 - R_f) \frac{Q}{\tau d_o} \left[ e^{-\beta x} + \rho_r e^{-\beta(2L-x)} \right]
\]

(4)

Where \( x \) is the coordinate along the laser propagation, \( d_o \) laser beam side, \( R_f \) the reflectivity of the glass, \( \rho_r \) reflexion coefficient at the interface aluminium/glass, \( L \) the glass thickness.

**Figure 2.** Visualization of the temperature fields for the two deposit mode (because of the symmetry a quarter of the calorimeter is modelled)

2.3. Response and model validation
The Peltier cells constitute the thermal leaks of the system. A Peltier cell consists of 127 couples of semi conductive materials sandwiched between two ceramic plates. The semi conductive junctions are modeled using a virtual material with equivalent thermal properties. Peltier cells provide voltage directly proportional to the temperature difference between aluminum plate and thermal mass. The time dependent voltage profile constitutes the calorimeter response. Since Peltier cells are connected
in series, response is numerically estimated by calculating temperature difference between front and rear faces of the Peltier cells integrated over the 30 Cells. Thus, in the following, the calorimeter response is expressed in term of $\Delta T$ (temperature difference between both faces of the peltier cells) in function of the time.

The comparison between simulated and measured calorimeter response is used to validate the model. The measured and simulated calorimeter responses after electrical energy supply and optical energy supply are shown in Figure 3. The maximum and $rms$ difference between simulated and measured profiles is less than 1% for the two deposit modes. The model error on maximum amplitude signal is close to 0.5%. Thus, the model is accurate enough to study measurement procedure influence on calorimeter response.

![Figure 3. Calorimeter response simulation for the two deposit modes](image)

3. Experimental Devices

Two experimental devices have been implemented to calibrate the REC calorimeter. In both cases the principle consists in supplying a known input energy and to record the calorimeter response. In the first experimental device, the energy is supplied within the absorbing glass by a laser shot (optical device). In the second one, the energy is supplied by Joules effect in electrical heaters (electrical device). The main aim of these experimental devices is REC calibration; nonetheless they can be used for parameter influence estimation.

Concerning the optical device, the uncertainty on laser energy deposit is close to 2% at 2kJ. The standard deviation on REC calorimeter response amplitude signal is close to 0.3% at 2kJ. The evolution of REC calorimeter response amplitude in function to the amount of energy is linear (deviation from linearity less than 1%).

Concerning the electrical device, the uncertainty on energy is close to 1.25% at 2kJ. The metrology characteristics of the experimental device have been estimated during repeatability campaigns. The standard deviation on electrical power is close to 0.15% at 2kJ while the standard deviation on REC calorimeter response amplitude signal is close 0.25% at 2kJ. The evolution of REC calorimeter response amplitude in function to the amount of energy is linear (deviation from linearity less than 1%).

4. Influence of energy supply characteristics on calorimeter response

4.1. Laser beam wavelength and time pulse duration

4.1.1. Wavelength
The study of the wavelength influence is a critical point because laser pulse absorption within the glass is strongly dependent of the wavelength. The radiative source term for $\lambda=351$ nm and for $\lambda=1030$ nm are shown in Figure 4 (x variable is the axe along the laser propagation).

REC is designed to perform energy laser measurement at 351 nm, but the laser used in calibration procedure operates at 1030 nm. Regarding this point, a wrong evaluation of wavelength influence leads to systematic error on REC measurement. Moreover, the influence of this parameter on the signal amplitude can not be experimentally investigated. The numerical results show that the change of the wavelength has an influence on the response shape and amplitude. When $\lambda=1030$ nm, half maximum is reached 5s sooner. This point can easily be explained by the fact that a part of the laser energy reaches the aluminum plate. Moreover, it can be noted that for a same absorbed energy the amplitude is 0.75 % higher when the wavelength is 1030 nm. In order to validate numerical results, measured and simulated normalized responses are presented in Figure 5. The comparison between normalized responses is used to validate the model since wavelength strongly impacts the response shape. The normalized response is written:

$$\Delta T^* = \frac{\Delta T(t) - \Delta T_{\text{MIN}}}{\Delta T_{\text{MAX}} - \Delta T_{\text{MIN}}}$$

(5)

4.1.2. Laser pulse duration

The laser pulse duration is also a key point since it is impossible to reproduce the online measurement conditions (2kJ in 5 ns) during the calibration procedure. The experimental and numerical normalized response for different pulse durations are shown in Figure 6.

Experimental and numerical results show that if the pulse duration is less than 2s it has no influence on calorimeter response (amplitude variation lower than 0.1%). Since the thermal inertia of the calorimeter is very important, the calibration procedure with 1s laser pulse does not involve systematic error.
4.2. Laser beam size and homogeneity

4.2.1. Laser beam size

LMJ laser beam size can be reproduced during calibration procedure. Nonetheless, it is important to know if this parameter is important or if the calibration procedure can be simplified. The numerical and experimental REC responses for two different laser beam sizes (278x278 mm² and 355 x 355 mm²) are presented in Figure 7 and Figure 8.

Experimental results show that the change on laser beam size leads to a time rise 3s longer and a change in amplitude close to 1.8%. Concerning numerical results, the increase on rise time is well predicted, nonetheless, the change on amplitude is only 0.6%.
When the laser beam size is 278x278 mm², a larger part of energy absorbed by the glass is not directly in front of a peltier cell. Peltier cells temperature fields in both cases are presented in **Figure 9** and **Figure 10**.

**Figure 9.** visualisation of the peltier cell array temperature when the laser beam size is 355x355 mm²

**Figure 10.** visualisation of the peltier cell array temperature when the laser beam size is 278x278 mm²

The delay taken by the heat flux to reach the measurement location is longer when the laser beam size is 278x278 mm².

Moreover, if the gain of each Peltier cell is slightly different, the response amplitude and shape will be strongly impacted by the laser beam size. This point can be an explanation for the difference between experimental and numerical results.

### 4.2.2. Laser beam homogeneity

Laser beam homogeneity influence has only been studied numerically. The procedure consists in modeling a non uniform laser source with the presence of a hot spot (10% of the energy on 2% of area). Three different locations of the hot spot have been investigated (see **Figure 11**).

**Figure 11.** Temperature fields visualisation for hot spot influence simulation

The simulation of signal amplitude variation due to non-uniform beam absorption is presented in **Figure 12**.
It can be noted that the hot spot location have an important impact on signal amplitude. The amplitude change due to the hot spot ranges from 0.15% (case#1) to 0.65 % (case#3). This study confirms the conclusions about laser beam size impact. The response amplitude strongly depends on the heat flux path across the calorimeter which is itself dependent on the geometry of the laser heat source.

V Conclusion
For LMJ applications, the need to perform accurate Energy laser pulse measurements is obvious. In this work, influence of likely uncertainty contributors on REC calorimeter response has been experimentally and numerically investigated. As a first step, a 3D thermal model has been developed. To validate model results two experimental devices have been used: an electrical calibration device and an optical calibration device. Since numerical and experimental results are in good agreement, the modeling constitutes a convenient and powerful tool to predict calorimeter response and also to improve our knowledge about REC. This work underlines that the geometry of the laser beam absorption has an important consequence on calorimeter response.

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