Califlux : a heat flux calibration tool for Fast Heating tests

IMEMG FCO Expert Working Group

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Abstract

Many modern munitions are designed to be insensitive to outside influences and external aggressions. In order to classify munitions as insensitive, positive results to standard tests that simulate the effect of varied external environments must be accomplished. One such test is the NATO standard Fast Heating (FH) test to simulate munitions behaviour, when submitted to a liquid fuel fire. As described in STANAG 4240 (edition 2), the FH test requires the munitions to be engulfed in a jet fuel fire. Due to the environmental impact of burning jet fuel, an alternative procedure using a gas fuelled heating source has been introduced in edition 3 of the STANAG. Any test configuration developed to use an alternative fuel shall be properly calibrated and a minimum net absorbed heat flux of 80 kW/m² shall be demonstrated for a valid test fire.
The IMEMG Expert Working Group "Fast Heating Tests" has analysed the impact of such a change. In particular the group worked on the definition of a joint heat flux calibration device to evaluate the net absorbed heat flux as specified in the AOP4240 edition A version 1. Harmonization will secure the quality and consistency of heat flux measurements in fast heating tests. The development of such a device will be detailed in the paper.
The device works as a thermal capacitance and consists of a small steel cylinder with known physical properties, equipped with a thermocouple. The device is designed to be robust, easy to manufacture and easy to use.
In order to ensure the correct setup of the thermocouple, an integration process as well as a simple verification trial have been defined. Solutions for the installation of the device (or series of devices) within the flame are also described. For calibration purposes the number and location of the heat flux measurements shall be consistent with AOP4240 requirements.
A post-processing methodology is defined and validated by finite elements modelling analysis and cone calorimeter trials. An Excel post-processing file enables a quick assessment of the heat flux based on the device temperature measurement.
The device is fitted for calibration phases as specified in the AOP4240 edition A version 1. Thanks to the small size of the device, it may also be installed during an IM test as a simple extension to the usual fire instrumentation with no influence on the response of the tested item. Results obtained on various fire test facilities with this method are presented.

Keywords :

Harmonization, Fast heating test, heat flux measurement, calibration tool

1. Introduction

Many modern munitions are designed to be insensitive to outside influences and external aggressions. In order to classify munitions as insensitive, positive results to standard tests that simulate the effect of varied external environments must be accomplished. One such test is the NATO standard Fast Heating (FH) test to simulate munitions behaviour, when submitted to a liquid fuel fire. As described in STANAG 4240 (edition 2), the FH test requires the munitions to be engulfed in a jet fuel fire. Due to the environmental impact of burning jet fuel, an alternative procedure using a gas fuelled heating source has been introduced in edition 3 of the STANAG. Any test configuration developed to use an alternative fuel shall be properly calibrated and a minimum net absorbed heat flux of 80 kW/m² shall be demonstrated for a valid test fire.

LPG fire
(courtesy of WTD91, Germany)

Propylene gas burners
(courtesy of NEXTER, France)

Fig. 1 Examples of Fuel Burner Fires

The net absorbed heat flux is a sum of the absorbed incident radiative heat flux and the net convective heat flux. Different tools are proposed in the AOP4240 edition A version 1 to measure this heat flux : plate thermometers, differential flame thermometers, differential heat flux sensors and slug calorimeters. The IMEMG Fast Cook Off Expert Working Group is recommending using a joint heat flux calibration device in order to evaluate the net absorbed heat flux as specified in the STANAG. Harmonization will secure the quality and consistency of heat flux measurements.
With this aim in mind a joint heat flux calibration device, named Califlux, has been designed by IMEMG. The development of the device is detailed in the paper.

2. Concept development

Califlux shall enable fast heating facilities calibration as well as fire-to-fire heat flux comparison. The requirements for this tool have been defined as follows : a) Fire heat flux measurement, as requested by AOP4240, b) Easy and cheap to build, c) Small, easy to install in fire, robust, and if possible reusable.

2.1 Design

The device works as a thermal capacitance and consists of a small steel cylinder with known physical properties, equipped with a thermocouple. A ring ensures the good fixing of the thermocouple as well as a sealing of the inner cavity of the cylinder preventing hot gases entry. Once placed in fire, the device is fully engulfed in the flame and thus shall be able to support the high temperatures occurring in fire (typically up to 1100 °C).
The min characteristic dimension of the device has been set to 25 mm.
The cylinder is made of stainless steel (AFNOR 35NCD16) and pre-processed with an oxy-black surface treatment in order to ensure a high and relatively stable emissivity (close to 0,9).

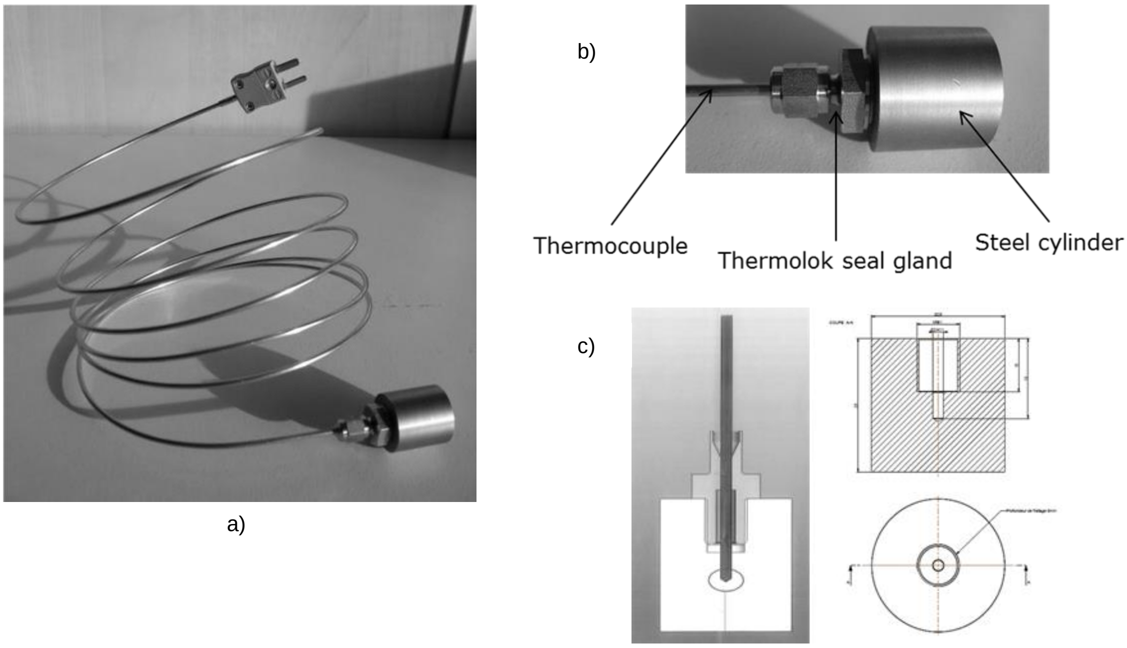

Fig. 2 First prototype design : a) full system, b) sensor part, c) CAD file (courtesy of NEXTER, France)

First trials have been performed with the prototype shown Fig. 2, with metric thread. For further trials, this metric thread will be replaced by a NPT thread in order to simplify the assembly and avoid risks of fusion of the small copper ring present with the metric design. The elementary cost of the device does not exceed 50€ per unit (without thermocouple).

2.2 Post-processing

The net absorbed heat flux, q_{abs} [W/m²], is expressed by :

$$q_{abs} = h.(T_f - T) + \varepsilon.q_{inc} \qquad (1)$$

where h is the convective heat transfer coefficient [W/m²/K], T the wall temperature [K], T_f the hot gas temperature [K], ε the wall emissivity [-] and q_{inc} the incident radiative heat flux [W/m²].

The post-processing method relies on isothermal assumption of the cylinder. In this case, the wall temperature is approximated by the inner temperature of the cylinder, as measured by the thermocouple, and the net absorbed heat flux can be rewritten as :

$$q_{abs} = m.C.\frac{1}{S}.\partial T/\partial t + \varepsilon\sigma T^4 \qquad (2)$$

where m is the mass [kg], C the apparent specific heat [J/kg/K] and S the external surface [m²] of the system {cylinder+ring}, σ the Stefan-Boltzmann constant and $\partial T/\partial t$ the cylinder heating slope [K/s].

2.3 Finite element modelling

A preliminary check of the post-processing method is done based on finite element simulations. Thermal gradients, as well as sensitivity to cylinder dimensions and fire conditions are analysed.

A simplified 2D axi F.E. model of cylinder is built. Different fire type convective and radiative conditions are applied on the external sides of the cylinder, see Table 1. Fire conditions n°1, 2 and 3 are representative of liquid fuel fires while fire condition n°4 is a variant possibly representative of a gas fire.

External conditions	**Fire 1**	**Fire 2**	**Fire 3**	**Fire 4**
Convection	800°C 20W/m²K	800°C 20W/m²K	1000°C 20W/m²K	1000°C 40W/m²K
Radiation	900°C ε_f=1	800°C ε_f=1	1000°C ε_f=1	1000°C ε_f=0.3

Table 1 Boundary conditions

A sensitivity analysis to cylinder dimensions is performed. The following geometrical configurations are investigated :

- diameter of 25 mm, length of 25 mm.
- diameter of 15 mm, length of 15/25/35 mm

Temperature results obtained with the nominal configuration on fire 1 are illustrated Fig. 3. Maximum and averaged temperature evolutions are compared to the temperature calculated at the theoretical thermocouple location “TTC”. All temperatures tend to converge toward an equilibrium temperature comprised between the convective and radiative exchange temperatures (893 °C for fire 1). Thermal gradients calculated for the different configurations are plotted Fig. 4. They logically increase with the cylinder size and can attend 80 K during the transient phase on a 25 mm cylinder (diameter and length). The maximum difference between the average temperature and the temperature calculated at the thermocouple location is about 30 K (i.e. error of 6 %) which confirms that temperature “TTC” provides an acceptable approximation of the cylinder temperature. Based on these observations the characteristic dimension of the cylinder is set to 25 mm in accordance with the minimum value specified in AOP4240 edition A version 1.

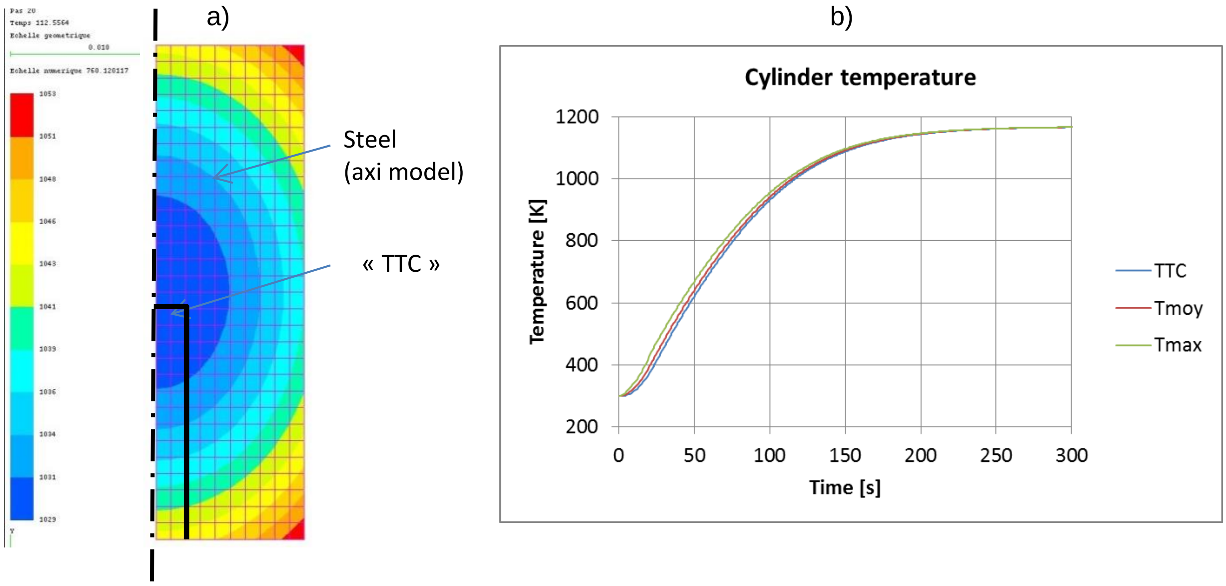

Fig. 3 Cylinder of 15 mm diameter and 25 mm length, “fire 1” conditions
a) Isothermal view at 112s, b) Maximum, average and “TTC” temperatures versus time

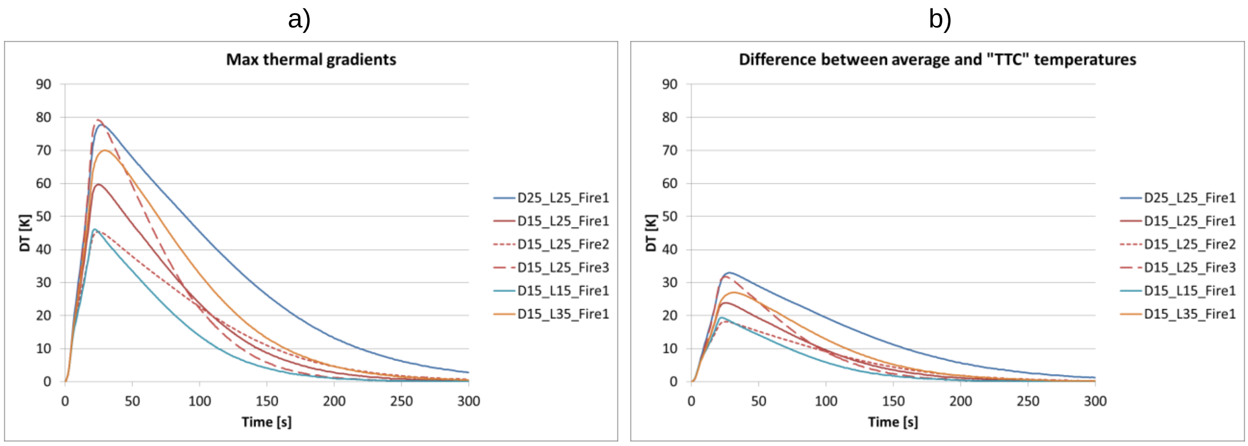

Fig. 4 Thermal gradients versus time
a) Maximum gradients b) Difference between average and “TTC” temperatures

The net absorbed heat flux is estimated from temperature "TTC" using equation (2) and compared to the exact net absorbed heat flux. Results obtained with a cylinder of 15 mm diameter and 25 mm length and fire 1 conditions are plotted Fig. 5. During the transient phase, the heat flux reaches a maximum value which reflects the combined effect of the convective heat flux and the incident radiative heat flux evolutions. Then the net absorbed heat flux progressively stabilizes as the device temperature stabilizes.
Different post-processing methods have been investigated. Results highlight that temperature-dependant specific heat data provide much more accurate results than constant data (see Fig. 5). With the selected time step assumption (dt=1s), no significant effect of the derivation scheme is clearly demonstrated at this point. A centred derivation scheme is selected for the evaluation of dT/dt.

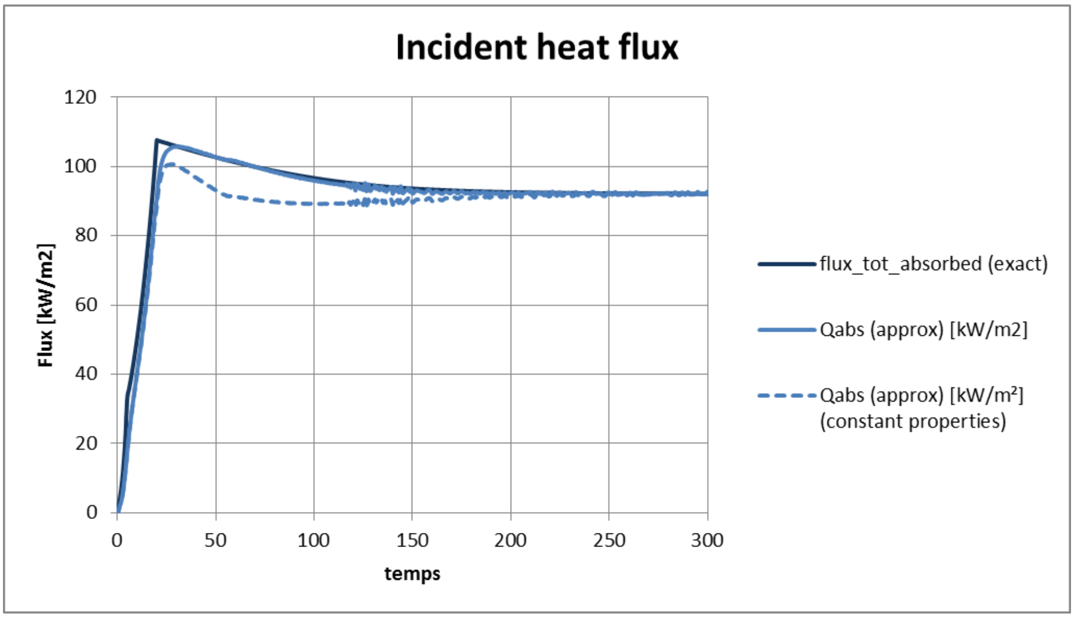

Fig. 5 Cylinder of 15 mm diameter and 25 mm length, "fire 1" conditions - Comparison of exact net absorbed heat flux with calculated solutions

Fig. 6 summarizes the heat flux results obtained for the different configurations (maximum and steady state values). Cylinder dimensions (in the range considered) have no significant effect on the results. On the contrary a strong sensitivity to fire conditions is observed : steady state values are comprised between 50 and 130 kW/m². The lowest value is obtained with fire conditions n°4 where the relatively low flame emissivity assumption (0.3 as expected with gas facilities) significantly reduces the incident radiative heat flux contribution.
Maximum errors on the estimated heat flux do not exceed 3% as reported in Fig. 7. Califlux concept is thus theoretically validated for fire heat flux estimations.

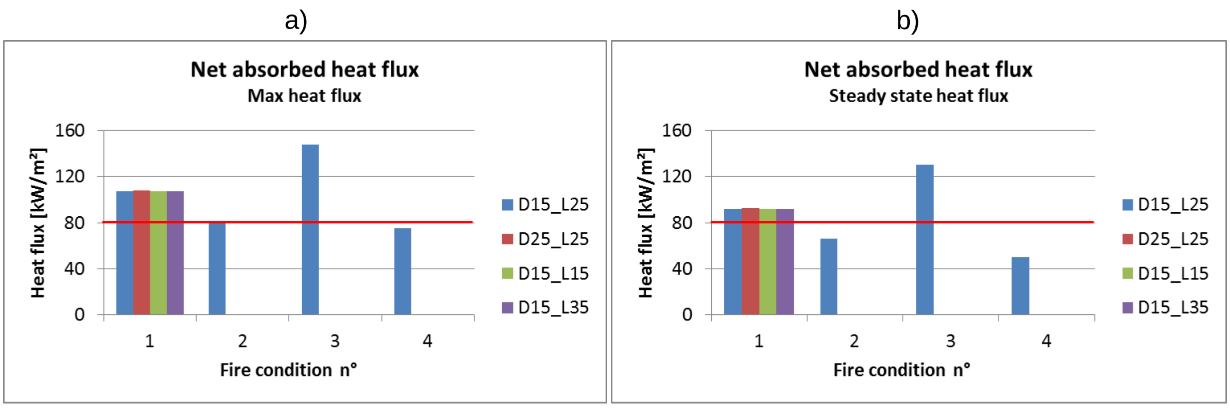

Fig. 6 Net absorbed heat flux results
a) Maximum heat flux b) Steady state heat flux

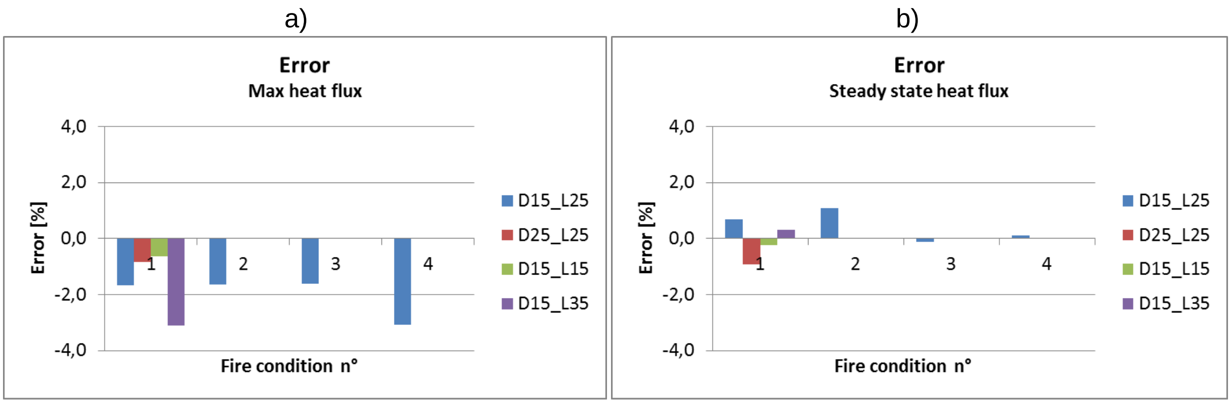

Fig. 7 Maximum error on net absorbed heat flux
a) Maximum heat flux b) Steady state heat flux

2.3 Calibration trials

Calibration trials are performed with a cone calorimeter setup in order to further validate the device. This setup is usually used for heat release rate measurements. Well-known incident heat flux conditions are applied on the specimen. Here the cylinder is heated on its plane surface and other walls are insulated in order to limit heat losses (see Fig. 8).

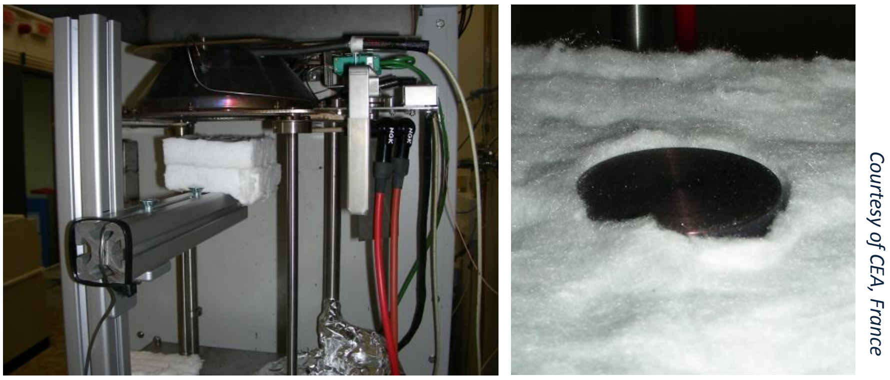

Fig. 8 Cone calorimeter setup

The post-processing is adapted to the configuration, i.e. incident heat flux is calculated by :

$$q_{inc} = \frac{1}{\varepsilon}.(m.C.\frac{1}{S}.\frac{\partial T}{\partial t} + \varepsilon\sigma T^4) \qquad (3)$$

with S the surface of the disc exposed to heating [m²]

Two conditions of incident heat flux are tested : 50 kW/m² and 80 kW/m². The uncertainty of the conical calorimeter is about 1 %.
A good correlation between the heat flux applied in test with the conical calorimeter flux meter “Qinc (trial)” and the estimated heat flux with the device “Qinc (estimated)” is achieved and presented tab. 2. The delta is lower than 3% taking into account the cylinder and the sealing ring weights.

Qinc (trial)	Qinc (estimated)	Delta
50 kW/m²	49 kW/m²	-1%
80 kW/m²	82 kW/m²	+3%

Table 2 Cone calorimeter trials – Heat flux results

3. Assembly verification

A good contact between the thermocouple and the cylinder is essential for the good operation of the device. In order to ensure the correct setup of the thermocouple, a detailed integration process has been defined.
The recommended torque value for the sealing ring is about 3 or 4 N.m. It is evaluated by progressively increasing the tightening torque until thermocouple failure is observed (cf. Fig. 9).

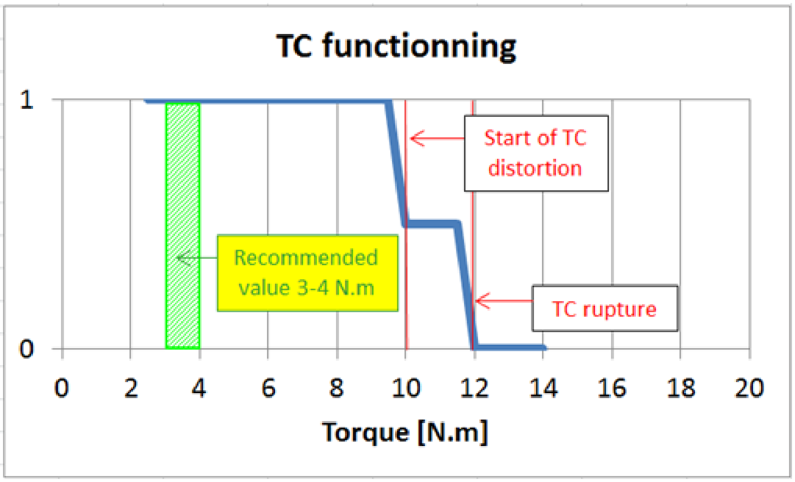

Fig. 9 Sealing ring torque

In addition an elementary trial is elaborated in order to facilitate the verification of the thermocouple setup. The trial consists in immersing the device in pure boiling water during one minute and checking the thermocouple response with the reference data provided on Fig. 10 : yellow curves correspond to water temperature measurements and blue curves to the expected cylinder temperature with acceptable tolerances.

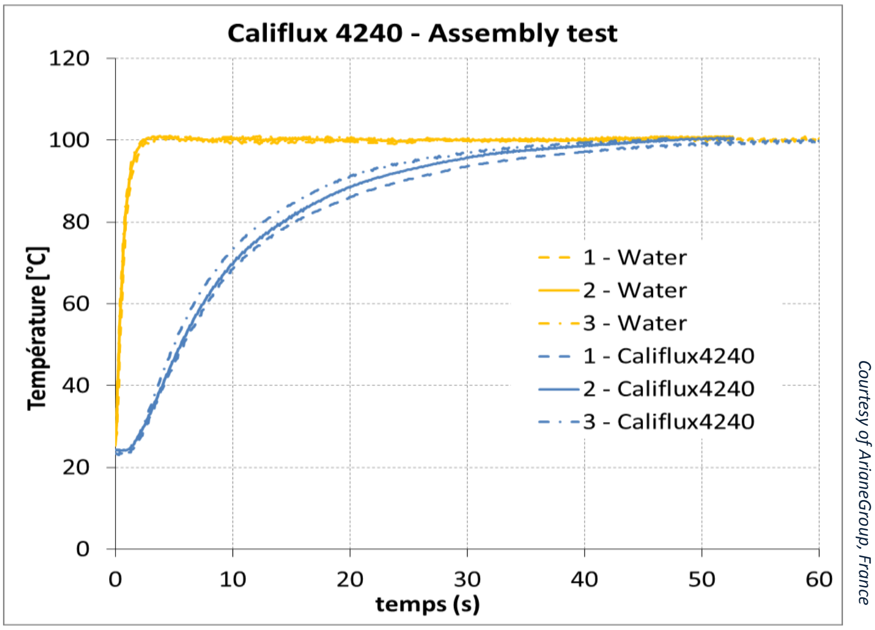

Fig. 10 Elementary assembly test results

4. Preliminary fast heating tests results

A first trial campaign was performed by Diehl Defence with a slightly different cylinder design (length 30 mm, diameter 30 mm). The test facility consists of a parametric setup of gas burners for calibres up to 155 mm. A dozen cylinders are placed in line in the flame and instrumented with a type K thermocouple. Heat fluxes calculated at different location in the fire are illustrated Fig. 11. Values comprised between 95 and 130 kW/m² are obtained. These values are largely compliant with the AOP4240 edition A version 1 requirements and highlight the spatial dispersion which is likely to occur in gas fire.

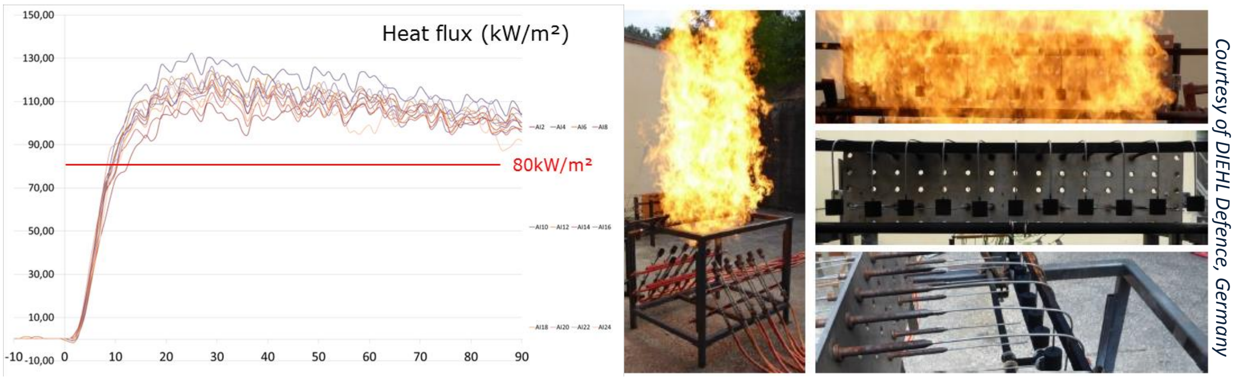

Fig. 11 Parametric setup for calibres up to 155 mm (Diehl Defence)

The device has also been tested by NEXTER during the development phase of a propylene gas burner setup (demonstrator for small calibres 20-155 mm). Sensitivity to burner parameters is investigated. Results highlight the strong impact of mass flows conditions on the heat flux assessments, as well as the significant temporal variations observed on the results. As an example, Fig. 12 shows the results obtained with low mass flow conditions ("Mes A") and higher mass flow conditions ("Mes B").

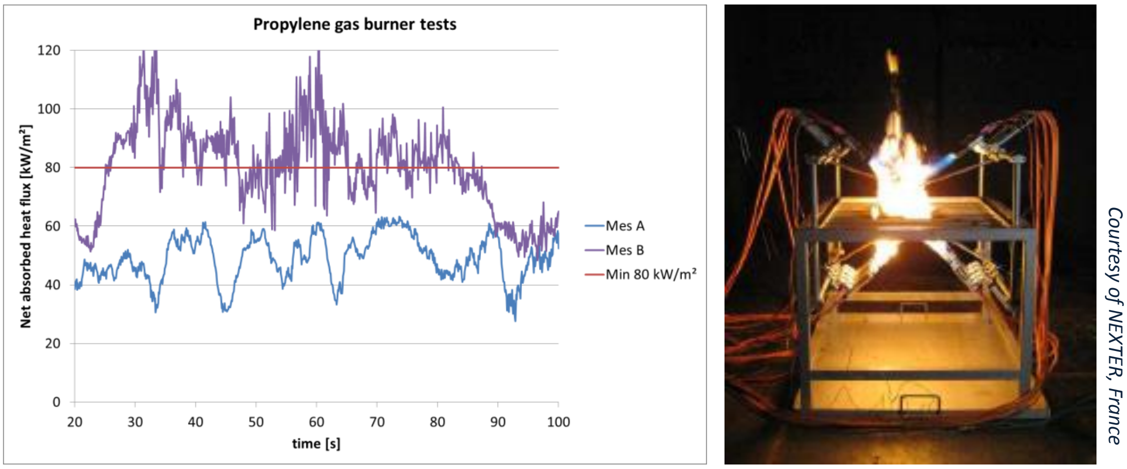

Fig. 12 NEXTER propylene gas burner tests – Sensitivity to mass flow conditions

Fig. 13 shows the sensitivity to the time step assumption. On Fig. 13 a), the net absorbed heat flux is estimated assuming an acquisition rate of 1s while a rate of 0.1s is considered on Fig. 13 b). Results highlight that a 1s time step is much more appropriate (important noise obtained on 0.1s assessment. From a thermal point of view, a frequency of 1 Hz is largely sufficient to correctly capture the cylinder heating and enables to smooth undesirable fluctuations on the heat flux estimation.

a) dt=1s b) dt=0.1s

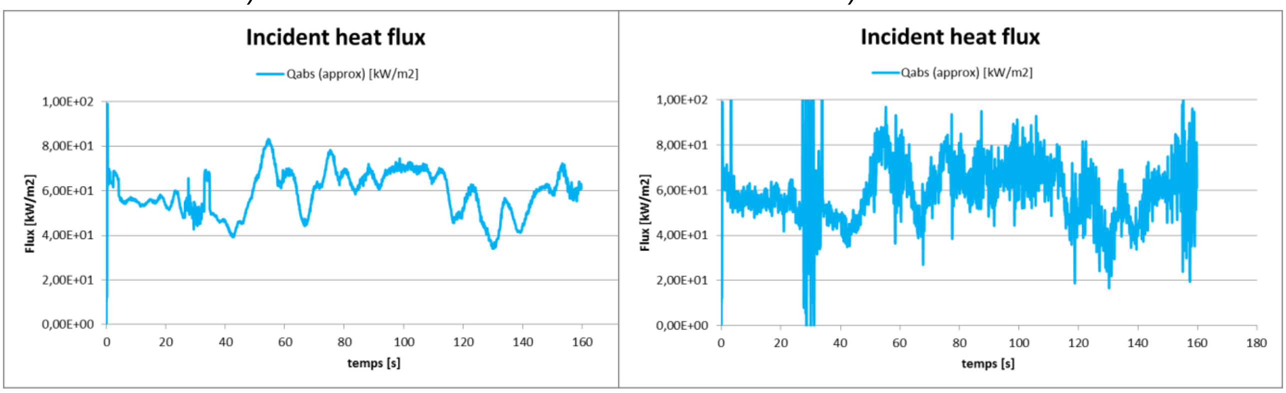

Fig. 13 NEXTER propylene gas burner tests – Sensitivity to time step (test C)

Overall these preliminary fire test results show a good response of the tool and its ability to evaluate locally the net absorbed heat flux. Thanks to the relatively small size of the device, several Califlux can be placed in a fire at the same time, enabling an efficient spatial and temporal characterization of the fire heat fluxes.

5. Conclusions and perspectives

CALIFLUX is a heat flux measurement device developed by the IMEMG FCO expert working group in response to the need to have a better characterization of fire heat fluxes for fire trials on munition. It is designed for net total absorbed heat flux determination in hot environments such as fire situations or fast heat heating experiments (liquid fuel fire, gas fire, etc). The device is operational, affordable and easy to use.

Further analysis of the tool response will be conducted. In particular additional fire tests will be performed (liquid fuel fires and gas fires). Results will support the final validation of the device as well as the assessment of ageing effects and reuse capabilities. The data pack will be made available on the IMEMG website in order to facilitate the use of Califlux by other companies and test centres.

Acknowledgment

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