Inverse Heat Conduction Method for Surface Heat Flux Prediction for Ramjet/Scramjet Application

Vincente Cardona[1], Thierry André[2], Victor Vernoux[3]

Abstract

Ramjet and scramjet are engines whose interest in the supersonic and hypersonic applications is always as strong over the world, due to their great specific impulse. However, a high engine efficiency is needed to be truly of interest. To improve the engine efficiency, several parameters may be investigated such as the fuel type, the injection method, the geometry of the engine, among others. In this study, the investigation is focused on the thermal losses in the combustion chamber. This paper presents a preliminary study on an inverse heat conduction method that enables to evaluate the heat flux and thus the thermal losses of a combustion chamber, with a simple wall temperature. As a first use case, the method was applied to experiments conducted with metallic models, located at the exit of a study ramjet, and suffering important heat fluxes. The mathematical method will be exposed, and applied to experimental results. Results will be discussed, highlighting the advantages and constraints of the method, leading to the next steps of the presented work.

Keywords : *inverse heat conduction methods, surface heat flux, thermal losses, ramjet/scramjet*

Nomenclature

CFD – Computational Fluid Dynamics
IHC – Inverse Heat Conduction
IHF – Inertia Heat Fluxmeter
TC – Thermocouple
Cp – Heat capacity, J.K^{-1}
d – Depth of thermocouple, m
h_{conv} – Convection coefficient, W.m^{-2}.K^{-1}
P_i – Total pressure, Pa
$q(0,t)$ – Surface heat flux, W.m^{-2}
r – Regularization parameter, s
T_i – Total temperature, K
$T(x,t)$ – Temperature, K
t – time, s
x – position (depth from heated wall), s
λ – Thermal conductivity, W.m^{-1}.K^{-1}
ρ – Density, kg.m^{-3}

Subscripts
c – calibration
e – experiment

1. Introduction

1.1. Context and object of the study

Ramjet and scramjet engines are widely used in supersonic and hypersonic applications due to their great specific impulse. Their general structure, without any moving part, can make one think that they are easily designable. However, contrarily to their external simplicity, many parameters affect the performances of these kind of engines. From the aerodynamic and thermodynamic of the internal flow to the fuel injection performances, every details of the physics need to be understood so that the working range can be broadened, allowing a crucial improvement of performances.

Amongst the various parameters of influence, one topic is recurrent: thermal effects. Indeed, according to Bondaryuk [1], total efficiency of an ideal ramjet engine may be conceived as the product of thrust efficiency with thermal efficiency. Thus, in the case of a non-ideal ramjet application, thermal losses are to be considered in thermal efficiency and so in the total efficiency of the engine. In this context, the present work is part of a preliminary study that focuses on the evaluation of thermal losses in a

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ramjet combustion chamber. The characterization of these losses over the surface of interest during the engine operating time is the result of local surface heat flux measurements. To be representative of what is really happening in the combustion chamber, it is wished to map it in terms of surface heat flux measurement.

One important question remains: measurement method to be used. Many methods allow to measure the surface heat flux, in particular: the use of fluxmeters, bulky and expensive; or the use of thermocouples which imply to perfectly know both the heated wall properties and the thermocouples location and characteristics. An alternative solution is the use of inverse heat conduction method that does not have the aforementioned issues but contains an important non-stability of the calculations. However, the analytical approach has been revised, described and demonstrated by a research team from University of Tennessee, showing a good stability and encouraging results [2][3]. This is the method chosen for this work.

The use of this method implies that only convection and conduction are taken into account. In the context of ramjet combustion chamber, this means that a strong hypothesis is taken: the flame in the combustion chamber is transparent, thus opposite walls thermal radiation are equivalent, and so, cancel each other out in the global solution of thermal losses.

The presented work is a preliminary study on the inverse heat conduction method previously cited and that will be more widely described in section 1.2. As a first use case, the method was applied to experiments conducted with metallic panels, located in the plume of a study ramjet, and suffering important heat fluxes. The mathematical method will be applied to experimental results and discussed, highlighting its advantages and constraints, leading to the perspectives given by the present work.

1.2. Inverse heat conduction method

The inverse heat conduction (IHC) method applied in this study is based on the work of Frankel, Keyhani and Elkins [2][3] who developed a surface heat flux prediction through physics-based calibration. The proposed method allows the calculation of surface heat flux, with the measurement of a unique temperature via a thermocouple, without, in theory, the need of knowing the properties of the heated surface nor the characteristics of the thermocouple.

In most cases, inverse heat methods are ill-posed, which means that one problem admit several solutions. In the present case, this means that an evolution in temperature can be the consequence of different heat flux variations. Here, the method is based on the ill-posed Volterra integral of first kind to which was applied a regularization parameter that enables to stabilize the problem in an equation of second kind described in Eq.1.

$$q_e(0,t) = \frac{\int_{u=0}^{t+r} q_c(0,u) T_e(x,t+r-u)du - \int_{u=0}^{t} q_e(0,u) T_c(x,t+r-u)du}{\int_{u=0}^{r} T_c(x,r-u)du} \quad (1)$$

The regularization parameter, or future time parameter, r must be chosen such as: the mathematical term $\int_{u=0}^{r} T_c(x,r-u)du$ is not zero; its value is equivalent to the delay during which the information comes from the heated surface to the thermocouple, taking into account, among other things, the conduction time of the material and the response time of the thermocouple. This way, the regularization allows to obtain a unique solution of the surface heat flux, constructed for each time step of the experiment.

Eq.1 describes how the heat flux density $q_e(0,t)$ suffered by a surface is calculated thanks to the measurement of a unique temperature $T_e(x,t)$ inside a heated wall (or on its cold surface). This calculation is enabled by a calibration phase that relates a known calibration surface heat flux $q_c(0,t)$ to a measured temperature response $T_c(x,t)$. Explicitly, this means that the previous method needs to be applied following two steps: first, the calibration; then, the experiment.

Even though the experiment is of great importance, thermic results are not entirely usable without a great calibration method. Ideally, the calibration phase should be experimental, applying a known flux to an unknown surface that, later, will be put in the experimented case. Indeed, this would eliminate errors originating from uncertainties in wall properties (thickness, material thermophysical properties and 3D effects), thermocouple placement and response time, ….

However, the experimental calibration being currently under development, a numerical calibration is realized with an internal 1D thermic model based on the Crank-Nicholson schemes. The experimental set-up is numerically recreated by modeling the plate presented in section 1.3 (with its theoretical thermophysical properties), and placing measurement at the experimental thermocouple depth. Numerically, a calibration surface heat flux varying in time is applied at the surface that will later be experimentally heated. With the wall properties and surface heat fluxes, the model gives the resulting calibrated temperatures (at theoretical depth) as a function of time.

Since the calibration cannot be realized in the exact same conditions as in the experiment, different uncertainties are to be considered. To estimate the order of magnitude of the general uncertainties of the method, a parametric study is needed, and results will be presented in section **Erreur ! Source du renvoi introuvable.**.

1.3. Experimental set-up

In order to obtain thermic data close to the conditions of a ramjet combustion chamber, a first simple experiment was set-up to learn about the measurement methods. As so, a metallic plate is placed at the exit of a study ramjet, perpendicularly to the exit section, as shown in Fig 1.

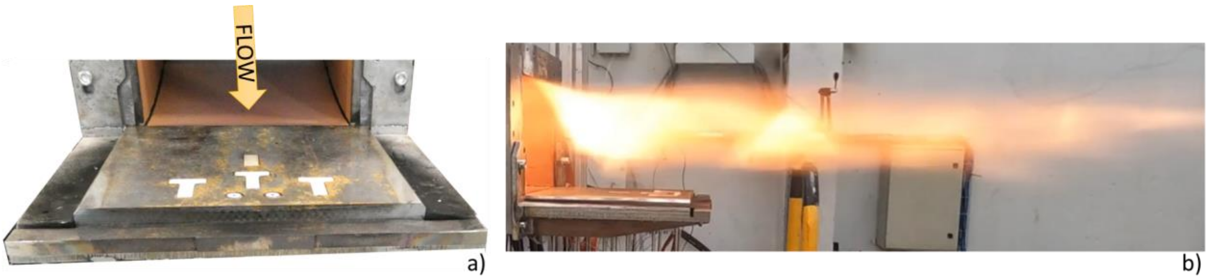

Fig 1. Experimental set-up – rear view a); side view with engine on b)

The study ramjet is alimented by a wind tunnel ignited 40s before beginning the engine sequence, ensuring stable alimentation flow of the ramjet. At the exit plan of the study ramjet, flow conditions are those given in Table 1.

Table 1. Flow condition at ramjet exit plan

P_i (bar)	3.42
T_i (K)	1070
γ	1.32
Mach	1.85
Mass flow (kg/s)	13.8

The plate is in stainless steel (17-4PH) with a thickness of 25mm. It is instrumented, among other things, with 17 thermocouples and 2 fluxmeters as illustrated in Fig 2.

Type K thermocouples (TC) are inserted in the plate through unclogged holes at a depth (distance from the heated surface) of $\mathrm{d}_{TC} = 10\ \mathrm{mm}$, at the exception of TC7 and TC8 which are respectively at a depth of $\mathrm{d}_7 = 15\ \mathrm{mm}$ and $\mathrm{d}_8 = 5\ \mathrm{mm}$. Their positioning is insured with 1/16 NPT inserts.

The fluxmeters are both convective IHF-1400E allowing to resist the estimated heat flux representative of our experiment (for 15 seconds, they are able to endure up to 15MW/m²). NexTherm Sensing, with whom a co-working is realized, makes these fluxmeters. Indeed, due to the extreme thermal conditions in ramjet/scramjet engine, some arrangements, such as material modification, coating addition or conception were needed. This instrumentation still being under development for such conditions, quantitative results can be discussed, but their global functioning ensures trustable responses.

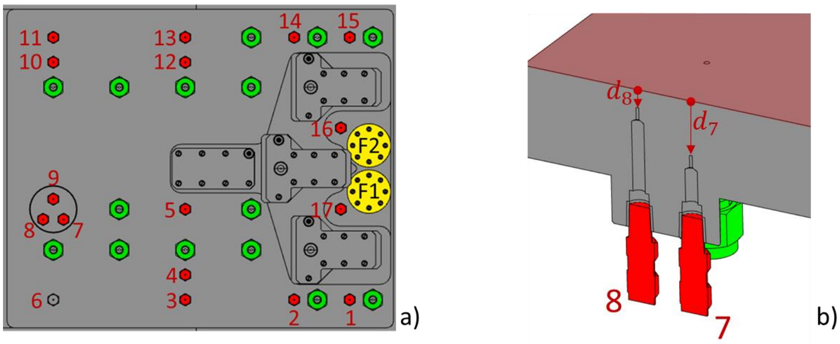

Fig 2. Instrumentation plan – bottom view a); section view b)

2. Results and discussion

As previously exposed, some uncertainties reside in the results obtained with the IHC method. First, the regularization parameter will be investigated demonstrating a variation in stability leading to a data smoothing that needs to be controlled. Then, a focus will be put on the numerical calibration method by studying different calibration surface heat flux tendencies and values, adding uncertainties on the location of the thermocouple, and modifying the wall thermophysical properties.

2.1. Regularization parameter

The IHC method, presented earlier, is stabilized thanks to the regularization parameter r. For a given calibration, Fig 3 shows the results of the IHC method applied to measured temperature values, with different r.

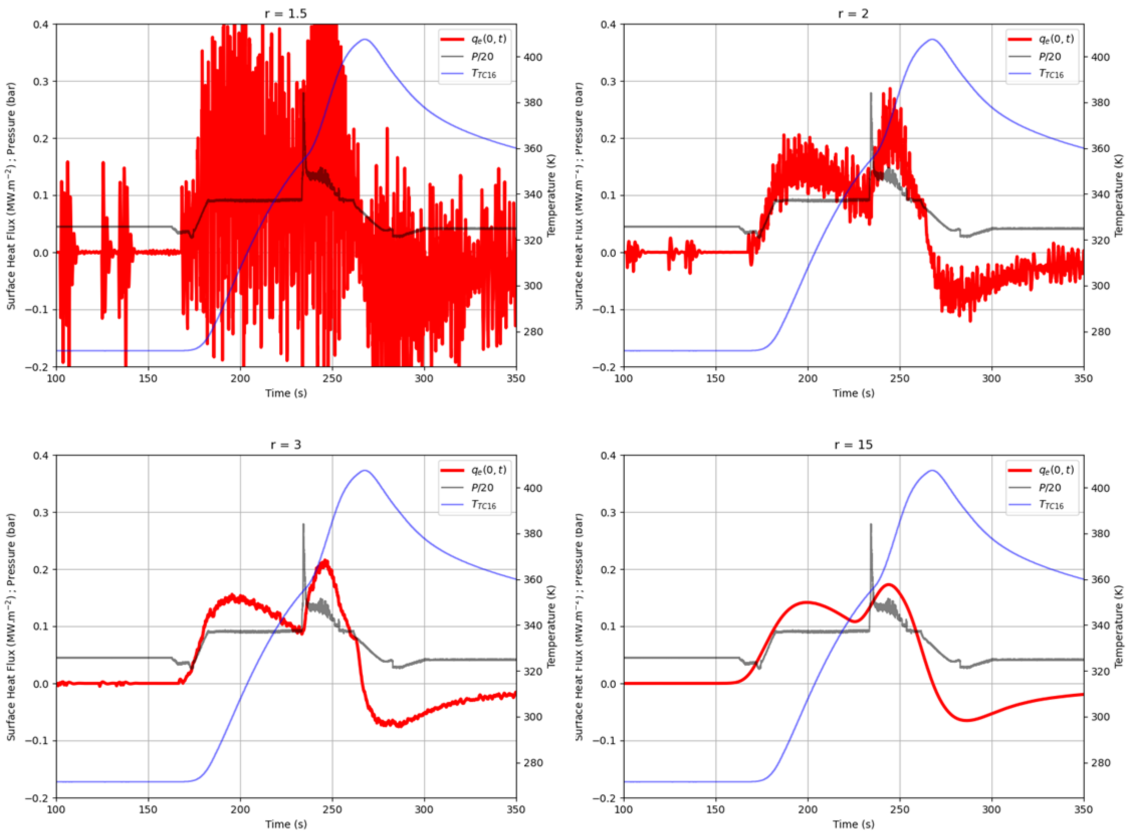

Fig 3. Impact of the regularization parameter r on the IHC results

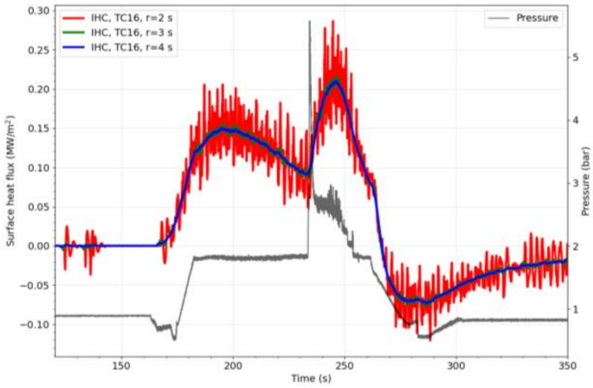

Fig 4. Superposition of results from same calibration but variation of r

As it can be seen, by increasing r the calculation surface heat flux is smoothed, which is the result of the convolution product working as a filter. The difficulty resides in choosing the best values for r. Indeed, in our example, no tendency can be discussed for the case $r = 1.5\ s$ since the result is noisy. On the contrary, for $r = 15\ s$, the results are so smoothed that values are distorted and not trustable. Thus, a compromise has to be made between keeping the veracity of values, and the possibility to read the results. Here, both cases $r = 2\ s$ and $r = 3\ s$ can be considered for an analysis. Indeed, as it can be observed, surface heat fluxes vary in accordance with the plotted pressure, measured in the engine. The heat fluxes response will be discussed in the section 2.3, showing a certain confidence in the results tendencies.

When superposing the results obtained for $\boldsymbol{r = 2\ s}$, $\boldsymbol{r = 3\ s}$ and $\boldsymbol{r = 4\ s}$, as seen in Fig 4, one can see that the three cases are comparable to a moving average of one another. Thus, for the rest of our study, it has been chosen to work with $\boldsymbol{r = 4\ s}$, which seems not to remove the tendency singularities observed, for example, at 180 s or 265 s. This case is also easier to read in curves comparison graphs. Note that this regularization parameter needs to be adjusted according the studied thermocouple.

2.2. Numerical uncertainties

Now that the choice of the regularization parameter is explained, it was wished to establish the impact of the numerical calibration. The calibration corresponds to a couple established as follow: to one calibration surface heat flux function of time, the 1D thermic model gives one calibrated temperature function of time.

First, it was wished to estimate the impact of the tendencies and values of the calibration heat flux on the IHC results. To this end, different calibrations were established and applied to the IHC method (with a fixed regularization parameter) to the values of one thermocouple (TC16). Some of the studied calibration heat fluxes are exposed in the upper graphs of Fig 5, while their corresponding IHC results are shown in the bottom graphs.

For calibration 1 to 9 (left graphs), the calibration surface heat fluxes are of same global tendency, but with different slopes and initial values. The resulting IHC surface heat flux calculated for TC16 shows differences inferior to $7{,}8.10^{-3}$ $MW.m^{-2}$, even at local minimums or maximums. These small differences can be due to the calibration heat fluxes applied or to the regularisation parameter, set to 4 for this study, and that can gently smooth the result since it works as a filter. Anyway, at this stage of the study, the calculated heat fluxes highlight that there is no major dependence of the result on the choice of the slope or the initial value if keeping a function shaped as $\frac{1}{t^n}$, $0 < n < 1$.

However, regarding calibration 9 to 11 (right graphs) where the maximum value of the calibration heat fluxes have been temporally shifted, one can observe that the calculated heat fluxes seem to lose stability. This point is also remarkable since the value of regularization parameter had to be modified for calibration 10 and 11, for which $r = 24\ s$. If the curves of the resulting surface heat fluxes are globally of same tendency, the bottom right graph shows more sinusoids and lower values with a different repartition of the maximums, which are also slightly delayed in time.

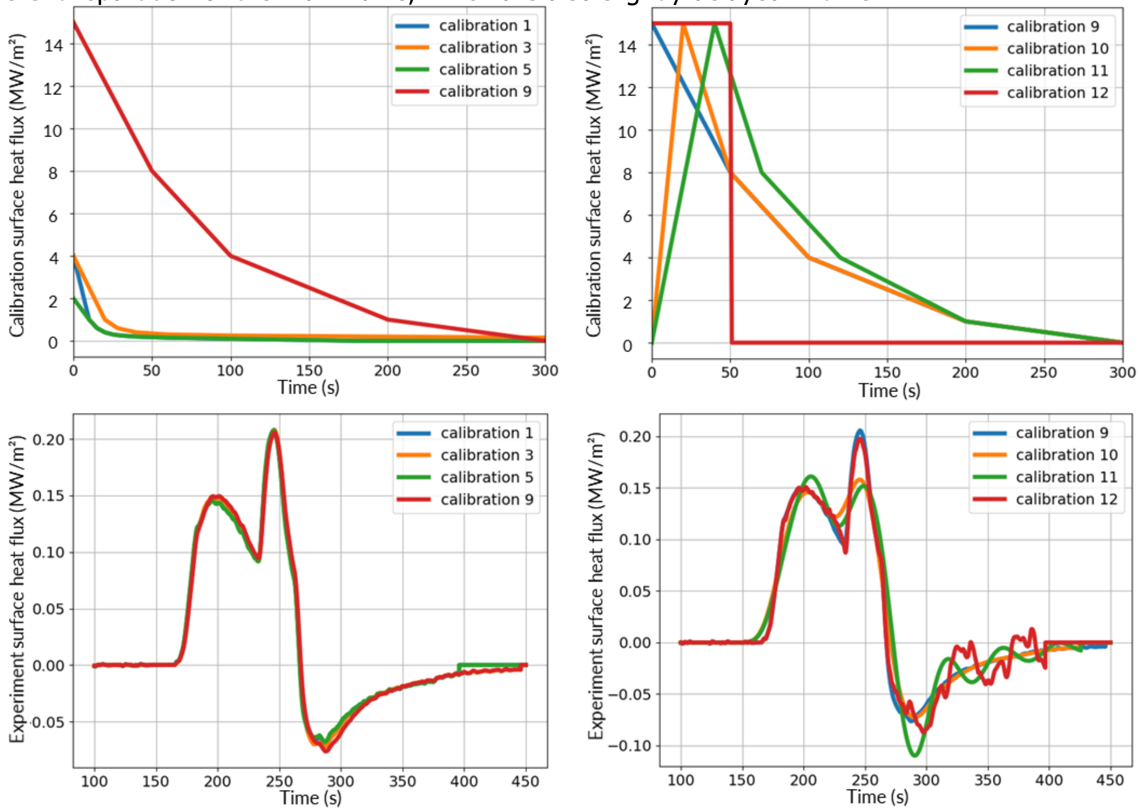

Fig 5. Impact of the calibration on the results of the IHC method. Upper graphs: calibrated heat fluxes applied; Bottom graphs: Resulting calculated surface heat fluxes

Concerning calibration 12, results are comparable to calibration 9 (itself comparable to the calibration in the left graphs). However, no stability of the calculation has been obtained beyond 270s, even when increasing the regularization parameter, which was smoothing the rest of the curve. These numerical biases are not favourable to obtain repeatable results, which lead to the elimination of calibrations 10 to 12.

In the rest of the study, calibration 3 has been retained, but every other calibration from 1 to 9 could have been used.

Since the calibration used is numerical, uncertainties are to be explored. Due to the 1D model used, every parameter cannot be broached, but a focus will be put on the localisation of the thermocouple in the wall of the heated plate, and on the thermophysical properties of the material.

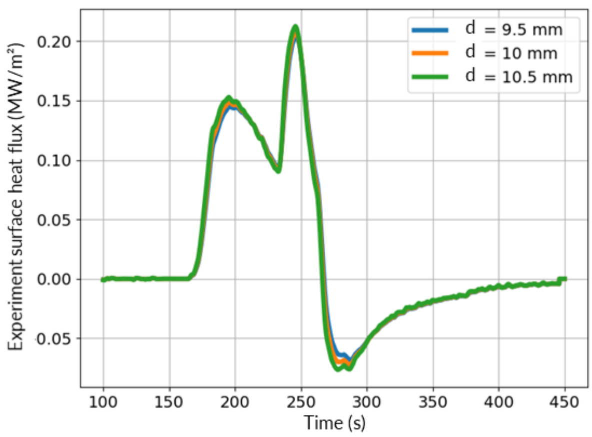

Fig 6. Impact of thermocouple location on the results of the IHC method

In order to estimate errors that could be generated by a mislocation of the thermocouple in the wall, calibration 3 has been recalculated with temperature measured at +/- 0.1mm, +/-0.2mm and +/- 0.5mm. Results of the IHC method for 0.5mm location uncertainty of the thermocouple are given in Fig 6. With those comparisons, a mean difference of 0.00134MW.m^{-2} is observed for each 0.1mm depth difference. A maximal value of 3% difference is found at the minimum value around 280s for the maximum depth difference calculated. These uncertainties are of same magnitude than those observed for the calibrations 1 to 9. Thus, it can be acceptable to work with a depth of +/- 0.5mm considering that the resulting uncertainties are inferior to the calibration uncertainties.

The wall properties are now explored by voluntarily modifying the thermophysic properties in the calibration 3. A derivation of +/- 10% was applied to the density, the thermal conductivity and thermal capacity. As shown by the surface heat fluxes resulting from the IHC method in Fig. 7, results are mainly impacted when changing the density or the thermal capacity. For these two parameters, the difference between the nominal value and the impacted ones is of about +/- 10% for the maximum differences. Beware that the +/- 10% derivation applied to the nominal properties have been taken without considering the actual standard deviation of the material properties. Indeed, the material certificate does not give these properties, so it would be necessary to characterize each material before use. Thus, the resulting uncertainties, presented in this section, are not representative of the actual derivation of the present experiment. Here, the idea was simply to highlight the importance of material calibration.

Of course, many other major uncertainties come from the numerical calibration. In particular, the 2-dimensional and 3-dimensionnal effects resulting from the conductivity of a heated surface, and not a heated point, are not considered with the 1D-model used for the calibration. Therefore, the heat fluxes calculated with the IHC method are underestimated.

Without being able to properly evaluate the global uncertainties generated by the numerical calibration, this preliminary work on the IHC method still gives interesting results that are exposed in the following section 2.3.

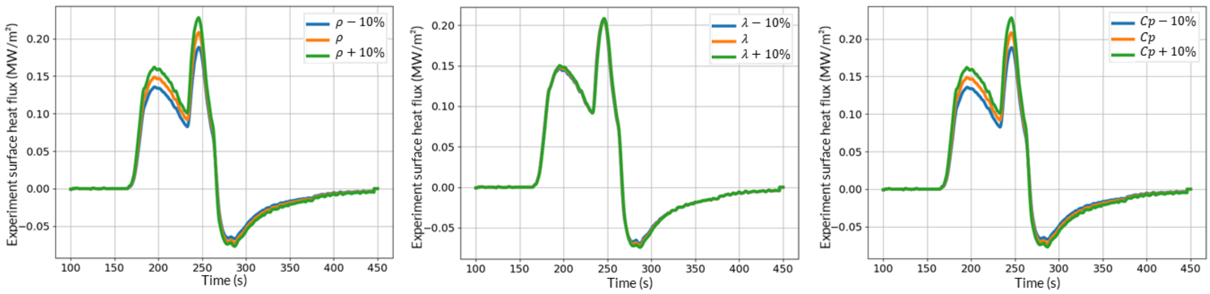

Fig 7. Impact of the wall properties on the results of the IHC method. From left to right: density, thermal conductivity, thermal capacity

2.3. Methods comparison and results discussion

The following results were obtained with calibration 3, $r = 4\ s$, and no uncertainties taken into account.

In Fig 8 are presented a comparison between the two thermocouples and the two fluxmeters supposed to endure similar heat conditions, due to their proximity on the metallic plate. The left graph gives the four surface heat fluxes, and enables to notice the gap between values. While the thermocouples results are consistent with each other, one can observe that FM1 gives lower values than FM2 from 240s. During the experiment, the thermal insulator of FM1 was partially extracted from its normal position in the fluxmeter, preventing the sensitive elements to see the full surface heat flux.

Even though magnitudes are different, the dimensionless results exposed in the right graph of Fig 8 demonstrate a certain similarity of the curves, with a slight delay between the two measurement methods. The reading of the curves explained below is based on the engine pressure plotted on the graph.

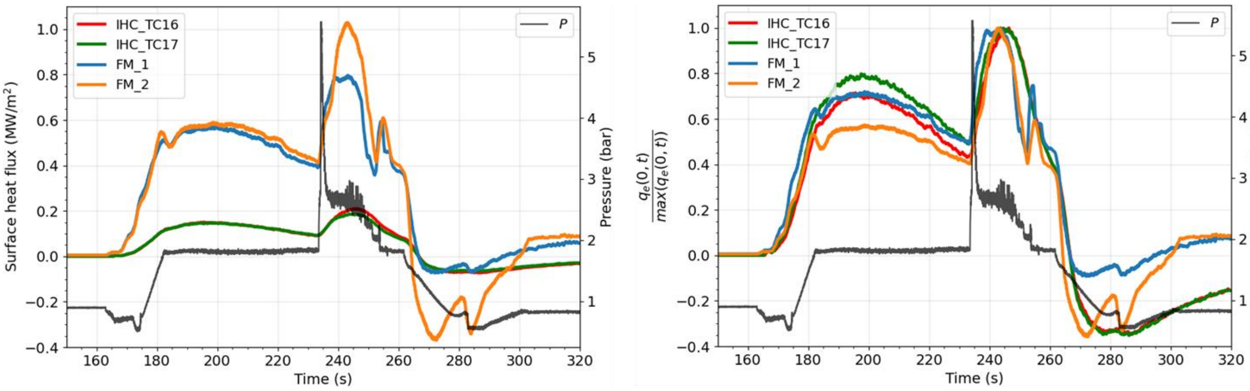

Fig 8. Comparison of the IHC results and the fluxmeters measurements

At the beginning of the experiment, the heat fluxes are null since there is no heat input in the flow. From 185s, the wind tunnel is started which brings a first heat wave. Thus, the plate, placed behind the engine, receives an important heat flux, which then decreases as the wall temperature increases, reducing the temperature difference with the flow. Around 230s, the pressure peak corresponds to the ignition of the study ramjet. Therefore, the flow is highly heated, and the heat flux strongly increases until the wall temperature starts rising in temperature at around 245s. Then, the injection of fuel is slowly reduced until 260s. During that period, one can observe a difference of behavior between the two methods: the IHC shows a constant decrease, while the fluxmeters first decrease but suddenly rise in a peak. This difference can be due to the responsiveness of both method or to calibration uncertainties. After the ramjet and wind tunnel stop, the flow is colder than the wall so the heat fluxes drastically decrease, even inversing the thermal exchange from 265s, where the values become negative.

With this reading, results of both methods seem broadly in accordance with the physics. However, the fluxmeters look more responsive to brief events such as those observed at 180s, 255s and 280s. Moreover, one important point remains: the difference of magnitude between methods. Due to the thermophysical properties of the material conducting the temperature to the thermocouple – 17-4PH for IHC method and copper for fluxmeters – the temperature of the hot wall of each surface is different. Thus, the perceived surface heat fluxes are supposed to be different according the material. To verify the consistence of the results, they need to be read in terms of convective coefficient h_{conv}, as described in Eq.2.

$$h_{conv}(t) = \frac{q(0,t)}{T_{flow} - T_{wall}} \tag{2}$$

For the IHC method, the wall temperature can be calculated using the 1D thermic model previously used for the calibration; for the fluxmeters, the wall temperature is the measured temperature of the instrument. In a first approximation and since both sensors are close, the flow temperature is taken equal to T_i. Results are shown in Fig 9, demonstrating a real gap between magnitudes of both methods. In consequence, the difference of methods does not only resides in a wrong reading of the results due to the nature of the material that conducts the information to the thermocouples.

This last result indicates that the values of surface heat fluxes are impacted by a way more important parameter, and the first that comes in mind is, once again, the calibration method.

For the IHC method, the point already has been discussed and it has already been said that the surface heat flux estimations are underestimated. The question of fluxmeters calibration has not yet been approached; however, it has its importance too. As previously said, the used fluxmeters are still under development and a discussion with NexTherm is set to adapt fluxmeters to the ramjet/scramjet needs. In particular, a subject regularly comes back: their calibration. At the time of the present experiment, fluxmeters were calibrated such as they were not taking into account thermal radiation passing through the thermal insulator nor the conductivity between the hot wall of the plate and the lateral wall of the fluxmeters. For these two principal reasons, the fluxmeters results are overestimated. Today, the co-working allows to progressively reduce uncertainties.

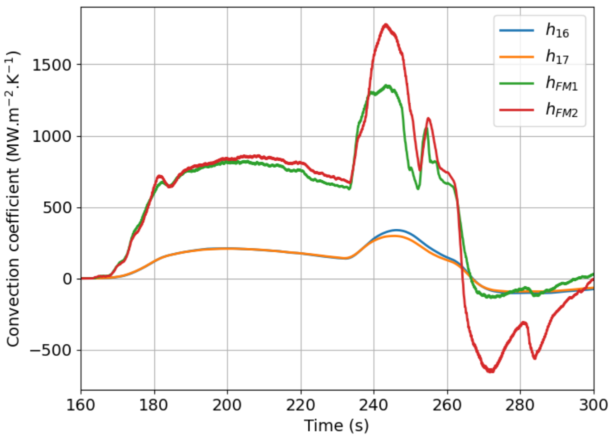

Fig 9. Calculated convective coefficient

In parallel, and to better understand the present results, CFD were realized with the same flow conditions. CFD surface heat fluxes give a maximal value of 0.27MW.m^{-2}, with only the wind tunnel working, before the engine starts, which corresponds to the time between 185s and 230s. For this period, in the IHC case the maximum is of 0.15 MW.m^{-2} while it is of 0.55MW.m^{-2} according fluxmeters values. In both cases, one underestimates the fluxes and the other overestimates them, which is in accordance with our previous paragraph.

If the IHC method is not yet completely exploitable, the fluxmeters also show a certain inaccuracy. Those problems are related to the extreme conditions in which measurement are realized. Yet, this preliminary work shows encouraging results on the developed methodology.

3. Conclusion and Perspectives

Results of the IHC method are greatly encouraging, demonstrating results broadly in accordance with the physics of the experimented flow. Moreover, the dimensionless analysis allows to show that heat flux tendencies are comparable to those obtained with thermal fluxmeter. However, the heat flux values obtained with the inverse method are lower than those of the thermal fluxmeter, but both results are to be taken with caution. Thanks to the different sets of calibration applied to the method, it is shown that results are much sensitive to the properties of the material. This highlights the importance of improving the calibration method, and specifically to set-up an experimental calibration method applicable to each model.

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