Development and Qualification of Conventional and Novel Industrial Combustion Test Probes

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1. Introduction

With the access to ENEL combustion facilities at Livorno, the IFRF is in a position to continue the generation of in-flame measurements [1], which are required for assessing technologies and validating predictive tools. The IFRF Members’ Research Programme includes semi-industrial for different scientific and technological objectives, such us development of oxy-combustion technology, advanced burner design, bio-fuel applications in power generation. The experimental campaigns have been thought to fulfil the needs of new experimental data on semi-industrial scale facilities for mathematical models and, at the same time, start the development of new instruments for further flame investigations [2,3]. The activities described in the work will report the status of industrial in-flame measurement programme, i.e. :

- New 5 hole pitot tube design and calibration for in-flame flow field characterisation;
- Development of new probe and FTIR system for enhanced gas sampling and in-flame analysis (CO, CO₂, nitrogen species, hydrocarbons)
- Local and overall radiative flux measurements;
- New system of optical analysis of the flame;

The research is also aimed to quantify the uncertainties in in-flame/furnace measurements as a first step to providing validation data for CFD codes and sub-models.

2. New 5 holes pitot tube design and calibration for in-flame flow field characterisation;

In-flame velocity measurements have been performed in the latest years with several techniques: Laser Doppler Velocimetry, Hot Wires, and Multi-Hole probes. IFRF choose to enhance and develop the 5-holes pitot techniques because of the relatively low costs, the high resistance of the apparatus and the probes that makes this system more suitable for industrial application and the new features of this technique provided by modern technology.

The most common multi hole probe is the well-known Pitot-static probe, which can provide flow speed information, but only if the flow direction is known beforehand. Three-hole pitch or yaw probes can provide information on one flow angle in addition to the flow speed, but only to a flow angles where the centre port ceases to exhibit the highest pressure of the three ports. Five-holes probes have been used extensively to provide velocity magnitude and direction (i.e. the velocity vector) and the local total and static pressures. Unfortunately the range of this instrument is limited to velocity vectors inclined by less than 60° with respect to the probe axis. The new IFRF 5-holes pitot system provided by Aeroprobe bypasses this limitation with a flow finder algorithm that helps the investigators to put the probe in the best position so that the flow is within the view angle of the instrument. In addition this probe has an the extremely high...
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accuracy thanks to the advanced calibration algorithm of Aeroprobe (see fig. 1) in different speed range (5 m/s, 10 m/s, 20 m/s, 40 m/s)
The 5-holes pitot can be used in hot and cold conditions and it represents the state of the art of gas velocity measurement.

<table>
<thead>
<tr>
<th>Data</th>
<th>Standard deviation</th>
<th>Units</th>
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<tbody>
<tr>
<td>Pitch/Cone</td>
<td>0.1465</td>
<td>deg</td>
</tr>
<tr>
<td>Yaw/Roll</td>
<td>0.1815</td>
<td>deg</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.3426</td>
<td>%</td>
</tr>
</tbody>
</table>

Fig. 1 Average standard deviation of a number of experimental tests with the 5-holes pitot

Fig. 2 5-holes pitot probe tip

Fig. 3 Absolute velocity error in percent on the absolute velocity of the gas measured by the 5-holes pitot. Mean error:0.116, max error:0.370, standard deviation: 0.0862

3. Development of new probe and FTIR system for enhanced gas sampling and in-flame analysis (CO, CO2, nitrogen species, hydrocarbons)

IFRF is developing a new sampling probe that can guarantee that the gas brought to the analyser is representative of the gas inside the flame.
To achieve such result the probe has been designed with a quartz tip so that no reaction can occur within the sampling duct and the gas while the latter is still hot. In addition several thermocouples have been placed in the sampling duct in order to monitor the rapid cooling of
the gas below 300°C and the subsequent temperature of the fluid that must be kept above 150°C to avoid water condensation. With this probe the operator can directly affect the temperature of the gas by changing the length of the cooling water/sample gas heat exchange section (see fig.4) or by setting the resistances placed all along the sampling duct.

![Fig. 4 Tip of the quartz probe with adjustable cooling section.](image)

The probe is connected to a Gasmet FTIR (Fourier Transform Infrared Spectroscopy) analyser and a paramagnetic O\(_2\) analyser. The key advantages of FTIR spectroscopy include multicomponent analysis capability, good sensitivity, excellent specificity, speed and simplicity of calibration. An FTIR spectrometer is an instrument that measures the qualitative and quantitative infrared spectrum and provides information about the molecules present in a given sample. This system will be able to provide in real time the information of concentration of the following components in the sampled gas: O\(_2\), CO\(_2\), H\(_2\)O, CO, N\(_2\)O, NO, NO\(_2\), SO\(_2\), NH\(_3\), HCN. All these quantities will be measured with a relative error within 5%.

![Fig. 5 Example of the output spectrum provided by the FTIR analyser.](image)

4. **Local and overall radiative flux measurements**

The most important instruments used to measure heat fluxes in industrial flames are the total heat flux radiometer and the ellipsoidal radiometer. IFRF used these probes extensively in its history and thus has a great experience with these measuring techniques. In the latest years this experience has been recovered and enriched by studies on the accuracy and error assessment.
4.1. Ellipsoidal Radiometer
The ellipsoidal radiometer is used to measure the total radiative flux incoming from the medium facing the tip of the radiometer. The information obtained using this instrument is of interest whenever the distribution and magnitude of radiative heat transfer is required near the boundary of combustion chamber. Traversing measurements through the flame are also possible and provide additional information on the flame radiative properties.

The instrument consists of a water cooled ellipsoidal cavity having an aperture at one focus and a thermopile at the other. The ellipsoidal cavity has the optical property of focusing all the radiation entering the orifice onto the surface of the thermopile. In order to minimize the radiation loss by absorption at the surface of the ellipsoid, the latter is plated with a 0.5mm gold layer. The thermopile is a heat flow plug of stainless steel with two thermocouple junctions at each end (constantan wire) which produces an e.m.f. proportional to the energy absorbed at the pellet. A protecting window is mounted in the ellipsoidal cavity to avoid damage to the thermopile and errors due to the convection. A purge flow of dry nitrogen (35-50 l/h) is injected on the orifice side of the window in order to prevent the entry of combustion gases.

The response time of this instrument is long relative to the frequency of fluctuations of the total radiative flux, so that only steady state measurements are possible.

4.2. Total Heat Flux Meter
This instrument is designed to measure the total heat transfer (conduction + convection + radiation) from the combusting flow to its front surface. The principle of the total heat flux measurement is based on the measurement of the temperature gradient through a steel plug of known thermal conductivity mounted at the tip of the probe. The total heat flux meter consists of a central stainless steel plug surrounded by two guard rings of the same material, cooled at the rear face only, so that radial heat exchange is negligible. Two Ni-NiCr thermocouples inserted inside the plug and separated by a known distance are used to measure the axial temperature gradient within the plug. The conduction flux through the plug is proportional to the time needed to reach steady state condition. The proportionality constant can be determined by calibration of the total heat flux meter in a blackbody furnace.

Since, in combusting flows, conduction is negligible if compared to convection and radiation, the total heat flux meter may serve to complement the information obtained using the ellipsoidal radiometer. With measurements of the radiative heat flux (ellipsoidal) and total heat flux (total heat flux meter) and knowledge of the emissivity of the receiving surface of the latter instrument, the convective contribution to the total heat transfer can easily be determined. The
range of operation and response of this meter is similar to that of the ellipsoidal radiometer. The
response time for this instrument is in the order of 10 minutes.

![Diagram of Total Heat Flux Meter scheme]

**Fig. 7** Total Heat Flux Meter scheme

![Graph of Total heat flux profile along the wall of the furnace FOSPER in air-gas combustion]

**Fig. 8** Total heat flux profile along the wall of the furnace FOSPER in air-gas combustion

5. **New system of optical analysis of the flame;**

IFRF is actually setting up a research programme with ENEA to test and develop the
application of the ENEA ODC (Optical Diagnostic of Combustion) system [4] to
semi-industrial scale flames. The ODC is based on photodiodes, resolving up to 10 MHz and
over. The whole emission spectrum is sampled (within the sensor spectral response) and no
filter is posed in front of the photodiode. This technique is on-line, very economic and
absolutely not intrusive because it needs only a hole to introduce an optic fiber.

The ODC system consists of a photodiode, a computer that performs data analysis, a DAQ and
a charge amplifier. The photodiode samples the radiant energy or chemiluminescence emitted
by the flame.

The programme, that is starting in June 2010, will include the design and construction of a
water cooled probe for the sampling crystal, the test of the system in a small furnace (Isothermal
Plug Flow Reactor) both in air and oxy-fuel conditions, and finally a full campaign on the 3
MW furnace (Fo.Sper.- Furnace #1) on oxy-gas and oxy-coal conditions.

6. **Uncertainties quantification in in-flame measurements as a first step to providing
validation data for CFD codes and sub-models.**

A prerequisite for model validation in Computational Fluid Dynamic is represented by the
determination of the level of confidence in the experimental results.
In the last years IFRF carried out several studies aimed to establish a procedure for the
determination of the total error in the experimental data, with particular reference to the
experimental campaigns undertaken on Fo.Sper. semi-industrial furnace. In particular, the
experimental error associated to the measurements was determined by estimating all the
possible sources (i.e. conductive heat transfer, suction velocity, radiation, thermocouple, ...)
and considering their contributions to be additive. Moreover, the total experimental error band
was augmented by an estimate of the statistical error, consequent to the random fluctuations of
the measurements in a turbulent environment.
The conclusion of these studies stated that, in all the investigated cases, both experimental and
statistical uncertainty significantly affected the total confidence in the experimental data. This
confirmed that all the possible sources of uncertainty must be taken into account to provide
experimental data sets really suited for model validation. Finally, a methodology for the
quantitative assessment of the level of agreement between experimental data and numerical
simulations was proposed, by means of validation metrics based on the knowledge of the total
uncertainty in the experimental data. Such approach for model validation will be adopted as a
standard in the future IFRF validation activities.

Fig. 9  Temperature measurements at 1620 mm from the burner and corresponding 98%
confidence intervals augmented with the total experimental error. Different scales are
used for the scalar values and the estimated confidence interval.

7. References
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