Electron Beam Fluorescence (EBF) experiments in the LBK wind tunnel

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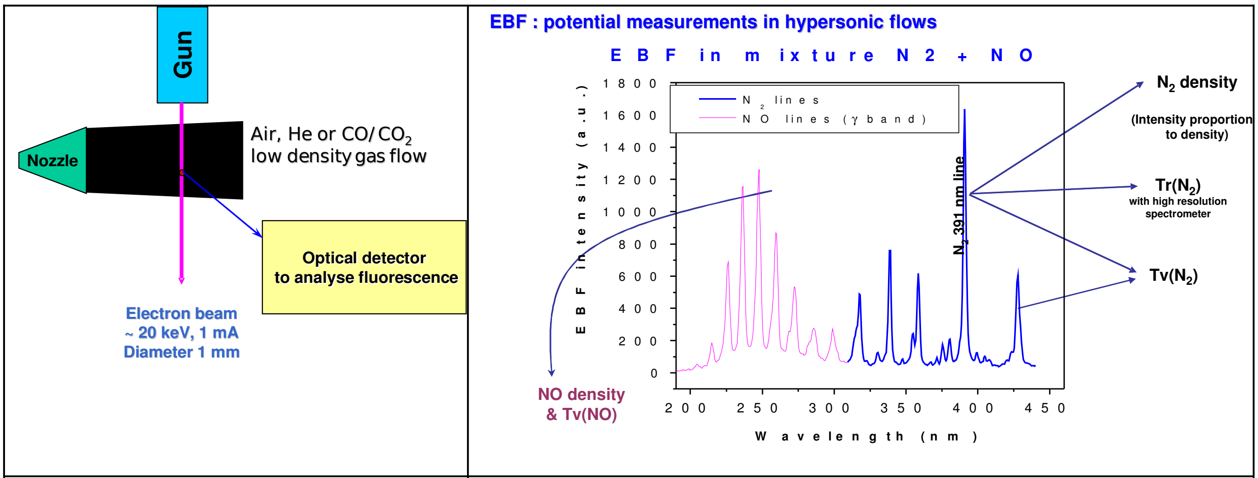
Abstract

The Electron Beam Fluorescence Technique has been recently applied in the DLR LBK wind tunnel to check the feasibility of such a technique for in-flight measurements in the shock layer of a re-entry demonstrator. Measurements of rotational and vibrational temperatures of N_2 as well as the densities of N_2 and NO have been attempted through different tests with a dedicated model. The latter has been built in such a way to allow testing an in-flight configuration with an electron beam emitted from the model as well as fluorescence observation through a sapphire window implemented on the model equipped with PM1000 thermal protection material.

1. Introduction

Previous work in Europe on Hermes, crew capsules and the X-38 lifting body highlighted the need for hypersonic and atmospheric entry flight data, in order to benchmark the aerothermodynamics computer predictions and design tools. Due to the lack of similarity in wind tunnel test facilities and validated CFD-codes it is mandatory to investigate a number of aerothermodynamics phenomena in a real flight environment, having simultaneously all relevant loads. Among other phenomena, these are -flap efficiency and heating; -shock wave/boundary layer interactions; -boundary layer transition; -high-temperature and gas chemistry effects; -gas-surface interaction effects. The present project aims at checking the feasibility of the Electron Beam Fluorescence (EBF) Technique which has a high potential in providing in-flight local measurements in the flow field around a vehicle designed to study these aerothermodynamics phenomena.

EBF is well established to perform local and non intrusive measurements of density, vibrational and rotational temperatures and velocities in low density (less than 3×10^{-16} molecule per cm^3) hypersonic flows (air or CO2 based flows) in ground facilities [1,2,3,4,5,6,7,8,9] (Figure 1). In a low density gas flow, the impact of high energy (about 20 keV) electrons on molecules induces broadband fluorescence ranging from X-ray to the infrared. Each molecular or atomic specie has its characteristic EBF signature in the form of characteristic vibrational bands or rotational emission lines from which measurements specific to that specie can be performed. For chosen lines the emission intensity is proportional to gas density and beam current.



a) Typical setup	b) Typical EBF spectrum for N2+NO

Figure 1 - EBF Technique in a ground facility

For in-flight measurements aboard a re-entry vehicle (Figure 2), the objectives can be to measure simultaneously the vibrational and rotational temperature of N_2 and the densities of N_2 and NO. For a Martian re-entry, the objectives can be the simultaneous densities of N_2, CO and CO2 as well as the corresponding vibrational or rotational temperatures.

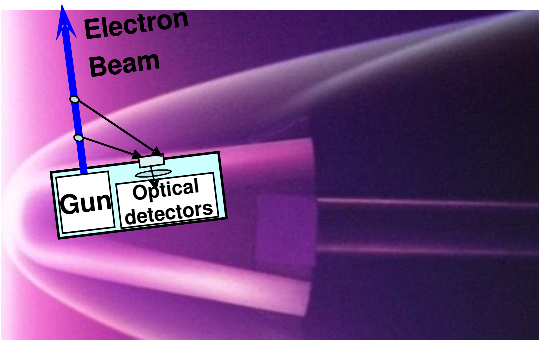


Figure 2 - Envisioned EBF in-flight measurement

Up to now, EBF measurements have been performed using classical heated filament or Pseudo-Spark[5] electron guns. One of the main difficulties for onboard operations with a classical gun lies in the high vacuum (10^{-4} Pascal) requirement for emission of electrons from the heated filament[7,8,9]. To circumvent this difficulty, ONERA has developed a new type of gun, based on secondary emission principle[10]. The present prototype has a working pressure of a few Pascal and therefore requires only a primary pumping scheme. It actually can deliver a self-focused beam of diameter 6 mm and of current up to 10 mA at 20 keV. The diameter of the beam has been easily reduced to 1mm with the help of a magnetic lens. Another major advantage is that the new gun is also quite miniature (cylinder 120 mm long with a diameter of 100mm) which will greatly facilitate the implementation of the EBF technique aboard a re-entry demonstrator.

However, before embarking such a new instrument aboard a vehicle, it is crucial to perform a thorough ground validation. This ground validation must be carried in successive steps:

- in the laboratory,
- in a low pressure-low enthalpy wind tunnel and
- in a wind tunnel with enthalpy and background radiation which resemble the closest to the expected conditions in flight.

Most of the work for the first two validation steps has already taken place but there is low experience for the third step which is an obliged passage to flight. In this project, the L2K test leg of LBK wind tunnel[11,12] has been chosen as it offers the best conditions from all the wind tunnels prospected in Western Europe. It has sufficiently low density for EBF to operate in good conditions together with high enthalpy conditions presenting high chemical disequilibrium (high dissociation with presence of N, O and NO and high vibrational temperatures for N_2 and NO). It presents also luminous background (radiating shock layer) similar or superior to what is expected during flight operation; this is useful to find the appropriate filtering solutions for the flight situation. The principal advantage of using this wind tunnel (compared to other blow down high enthalpy facilities) is its continuous operation over hours which will greatly ease the optimization of the instrument, and allows an estimation of the thermal loading of the gun and a check of the optical window transmission at high temperature.

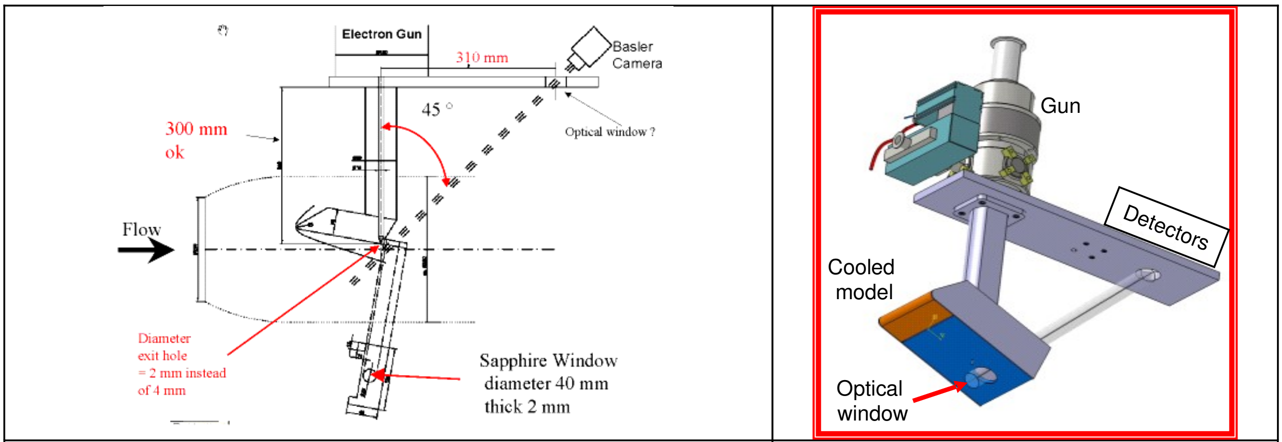
2. Experimental objectives and setup

1. Set up of an integrated EBF 'measurement box' and which can operate inside a wind tunnel low pressure test section (Figure 3).
2. Feasibility test in a wind tunnel simulating high enthalpy re-entry conditions around a model producing realistic shock layer and wall temperature. The set up must allow to observe through an optical window placed on a model equipped with PM1000 to verify also if there can be window pollution or fluorescence disturbances with ablated particles from such TPS material.

The tests have been performed in the arc heated facility LBK, which consists of two test legs L2K (1.4 MW) and L3K (6 MW). The test leg L2K is equipped with a Huels type arc heater and allows achieving cold wall heat flux rates up to 2 MW/m^2 at stagnation pressures up to 150 hPa. The different combinations of throat diameters of 14 mm, 20 mm and 29 mm with exit diameters of 100 mm, 200 mm and 300 mm of conical nozzles with a half angle of 12 ° provide Mach numbers between 6 and 8 at Reynolds numbers up to 10000/m. Models with a size of 150 mm (W) x 250 mm (L) x 70 mm (H) can be tested in a homogeneous hypersonic flow field of this facility. A detailed description of the facility can be found in several documents[11, 12].

For most aerospace applications of the LBK facility air is used as a working gas. But there is also continuous and substantial experience in operation with different gases. Argon, Nitrogen and Carbon dioxide have been used intensively during the recent years. The facility includes components for storage and supply of those gases and the corresponding operational parameters are well known.

The application of non-intrusive diagnostic tools, in particular optical diagnostic techniques for the characterisation of high enthalpy flow fields, has a long tradition at LBK. Emission spectroscopy, absorption spectroscopy, diode laser absorption spectroscopy and laser induced fluorescence spectroscopy of NO and two photon laser induced fluorescence on oxygen atoms have been applied to the flows providing valuable information about the flow properties. By application of these techniques rotational and vibrational temperatures, densities, flow velocities and shock standoff distances have been measured. The techniques are permanently available and continuously used at the arc heated facilities LBK. Pitot pressure sensors and several heat flux sensors are available for flow field characterisation. In addition to the spectroscopic tools, pyrometers and IR cameras are used for model surface temperature measurement at LBK [11, 12].

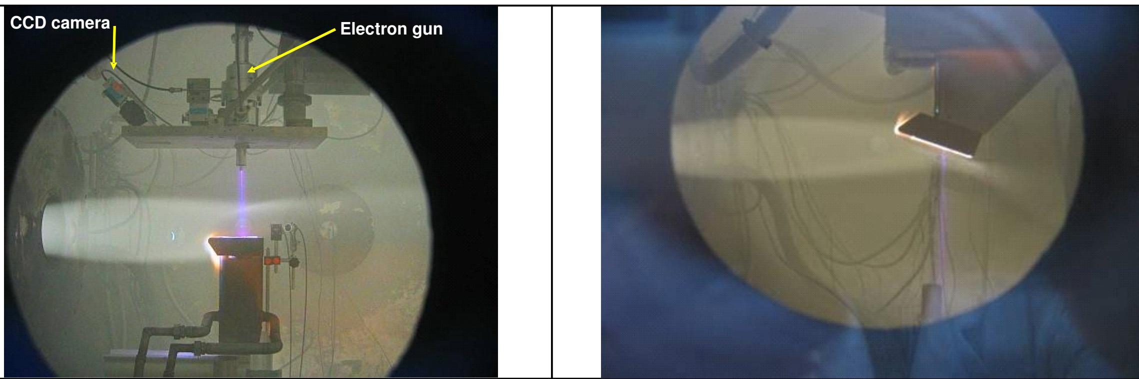


a) Side view	b) Perspective view

Figure 3 - Setup in LBK

The experimental campaign at LBK (Figure 4) was split in two phases:

1. Without any model to check feasibility of an electron gun operation in LBK where magnetic field can disturb electron beam propagation
2. With a dedicated model to mock a set up for in flight measurements.



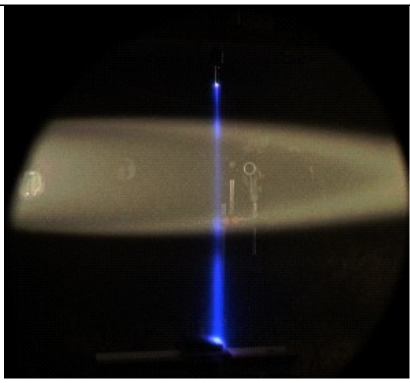
a) 1st campaign : Observation from outside model	b) 2nd campaign: dedicated model with to allow observation from 'inside' model through a sapphire window and PM100 on leeward.

Figure 4 - Configurations tested in the DLR LBK wind tunnel

3. Results and interpretation

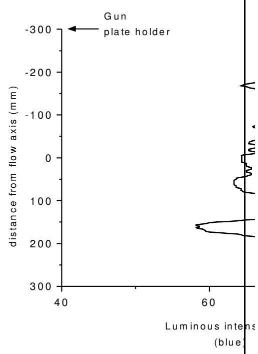
3.1. Density profile

Figure 5 presents the luminous intensity profile which can be extracted from a segment of the fluorescent electron beam. This will lead to a density profile across the flow with proper calibration processing.



(30_11_2005- 18h35)

a) Image extracted from Sony camera film

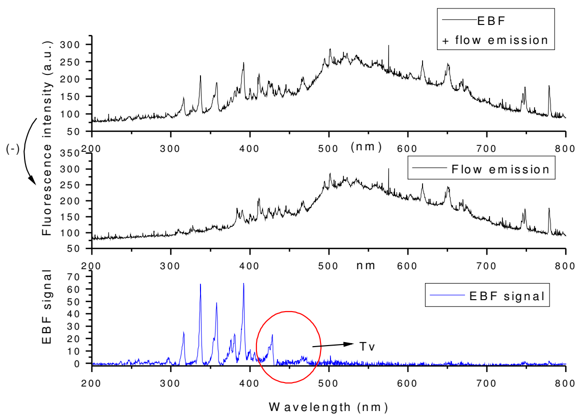


b) Luminous profile along electron beam

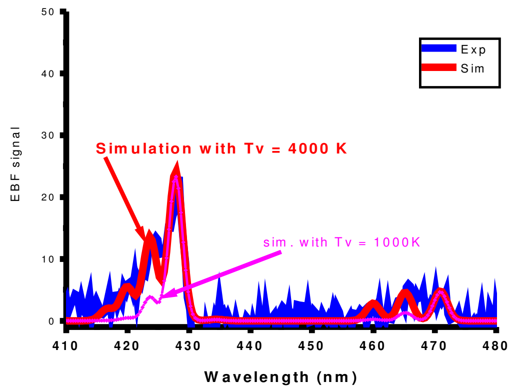
Figure 5 – Density profile (uncorrected)

3.2. Vibrational temperature Tv

The miniature spectrometer operating in the test section near the electron gun allows acquiring N_2 vibrational spectra in the spectral range 200 to 800 nm. Figure 6 presents some results on vibrational temperature Tv extraction from such spectra.



a) Low resolution spectrum

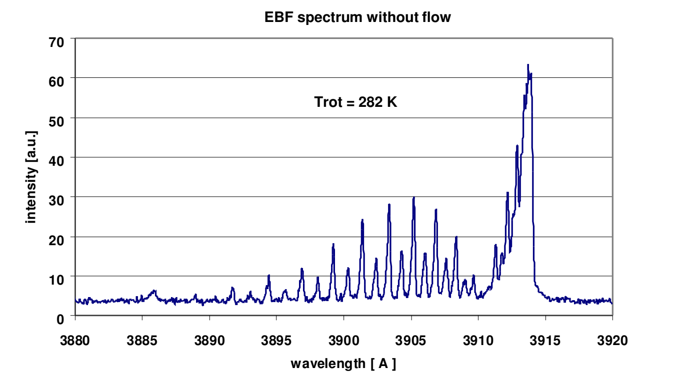


b) Tv extraction through camparison with simulated spectra

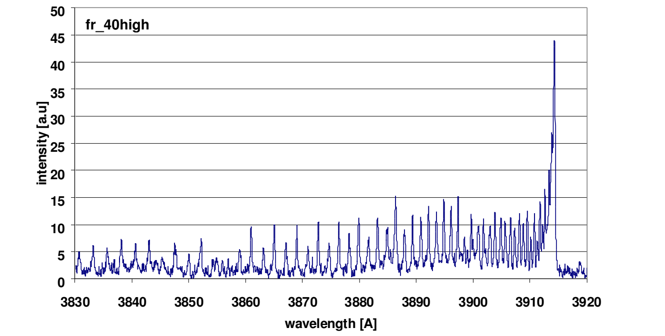
Figure 6 – Low resolution spectra for Tv measurements

3.3. Rotational temperature T_R

Figure 7 presents some high spectral resolution spectra obtained at LBK from which rotational temperature is extracted.



a) In static gas at 282 K



b) High temperature flow (~1000 K)

Figure 7 - EBF Rotational Spectra in LBK

The up to now derived EBF results allow observing high temperature effects in the flow. Data reduction is still underway and results as well as comparison with CFD will be published soon.

3.4. NO detection

The NO γ bands (Figure 8) have been acquired with a spectrometer (from Ropper) equipped with a low resolution grating (300 grooves/mm) set to view the spectral window between 200 to 500 nm. The NO γ bands are more intense in the free flow outside the shock layer. Flow emission is important only above 400 nm.

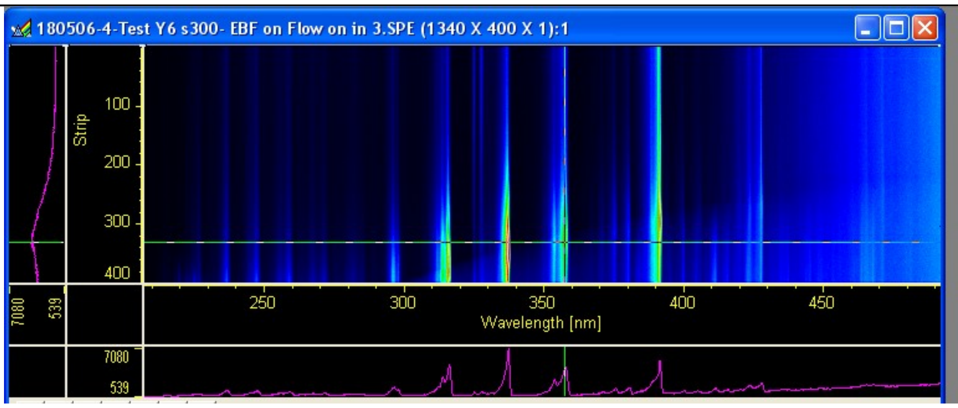
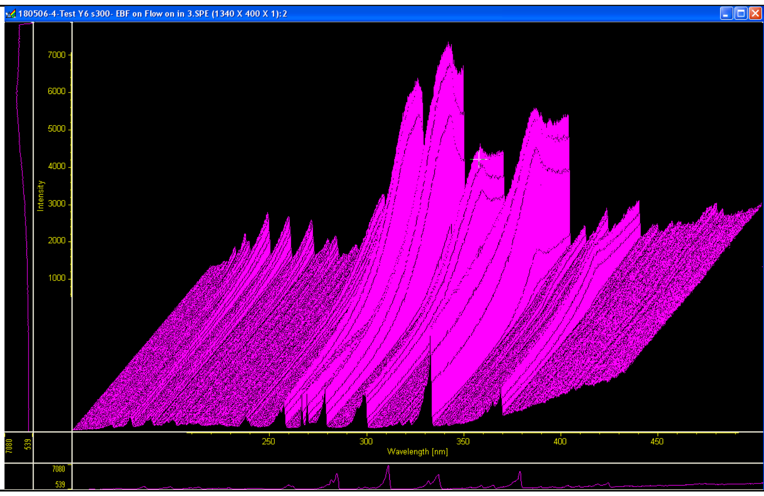
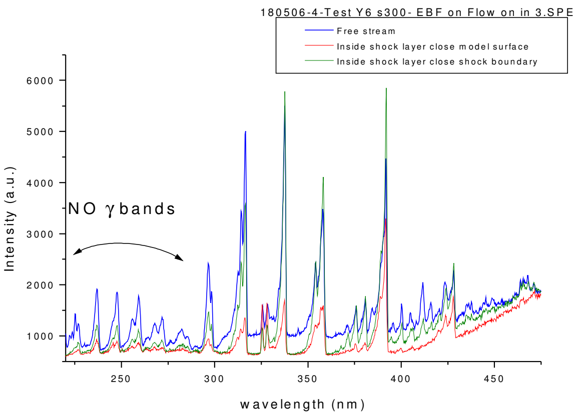
<table>
<tr><td>
</td><td>a) Example of spectra during a medium enthalpy run. The horizontal line marks the shock position, with the corresponding intensity profile</td></tr>
<tr><td></td><td>b) 3D graph of image presented above.</td></tr>
<tr><td>
</td><td>c) Examples of 3 spectra extracted from image presented above to show the differences in the intensities of the NO γ bands at different locations in and outside the shock layer.</td></tr>
</table>

Figure 8 – Low resolution EBF spectra with Roper spectrometer (grating :300 grooves/mm)

4. Conclusion

The electron beam setup has been integrated and tested successfully in L2K with hypersonic re-entry flow conditions. The sapphire window is suitable for spectroscopy and imaging through the high temperature wall. There is no pollution of the spectra from the PM1000 thermal protection under the tested flow conditions.

Concerning the measurements on electron beam fluorescence, the latter is found to be strong enough to be detected against the luminous flow of the L2K wind tunnel. Spectra have been acquired at low and high resolution. Preliminary data reduction shows that temperature measurements are feasible. A large amount of data collected in new conditions for this technique and data reduction is still underway.

Thus the project attained its main objective of checking that the EBF technique is feasible under high enthalpy conditions. The acquired results and experience during this study are now being used to derive the driving and scaling parameters for an embarked instrument with up to date information on requirements or specifications on environmental parameters (EMC levels, pressure limits etc).

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1 References

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