Recent Activities in Italy on MHD Interaction for Hypersonic Flow Control

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Introduction

- Plasma in aerospace an aeronautical applications

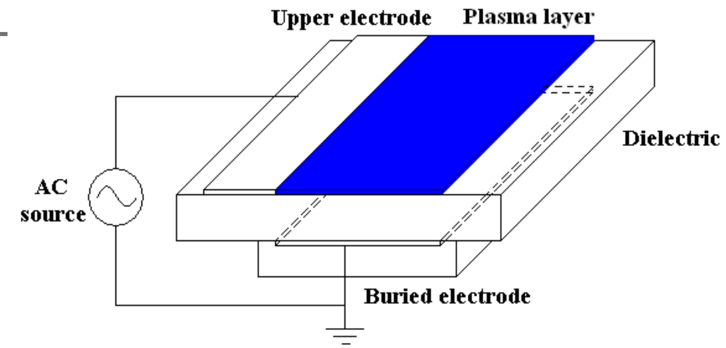
  - Electric space propulsion

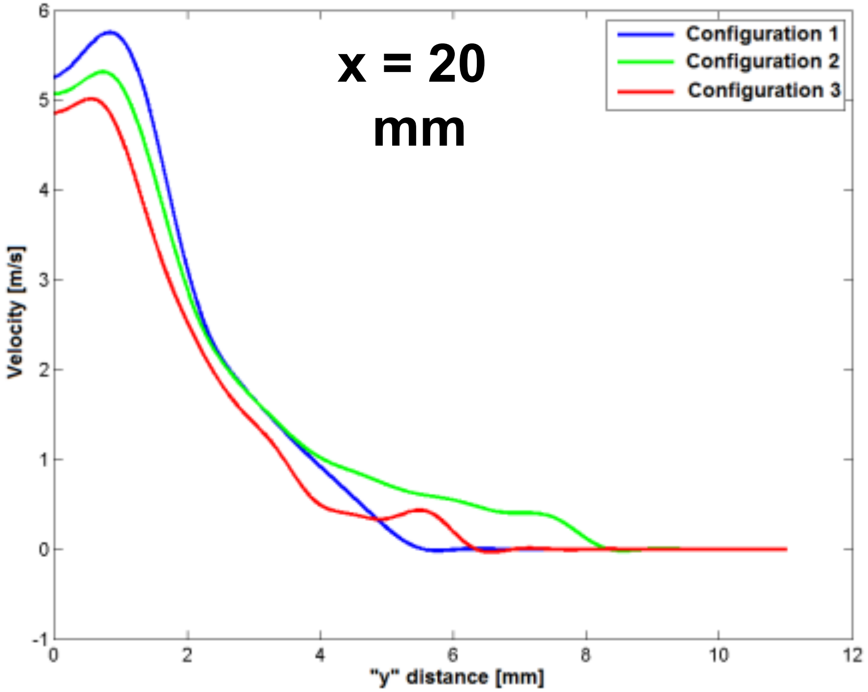
  - Plasma actuators
    - Stall recovery
    - Drag reduction
    - Transition to turbulent regime delay
    - Noise reduction

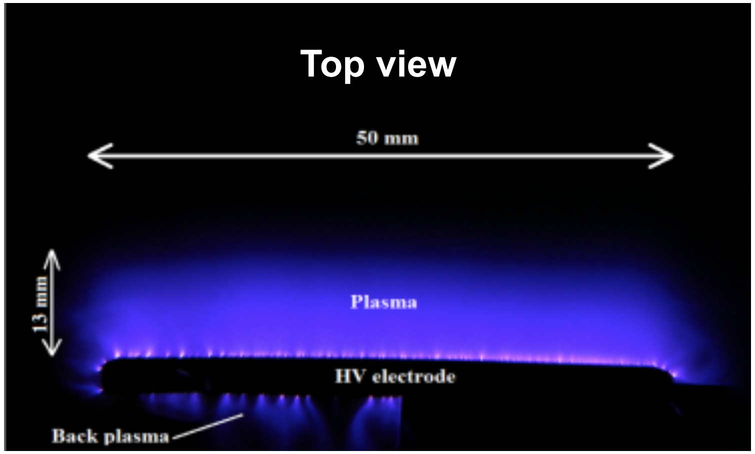
  - MHD
    - Thermal fluxes mitigation during planetary re-entry
    - Trajectory control
    - Vehicle attitude control
    - Mitigation of RF blackout
    - Scramjet inlet and outlet control

DBD actuators

- Plasma actuators are based on the Dielectric Barrier Discharge phenomenon
- Two electrodes separated by a dielectric barrier
- Voltage: some 10s kV
- Frequency: some 10s kHz





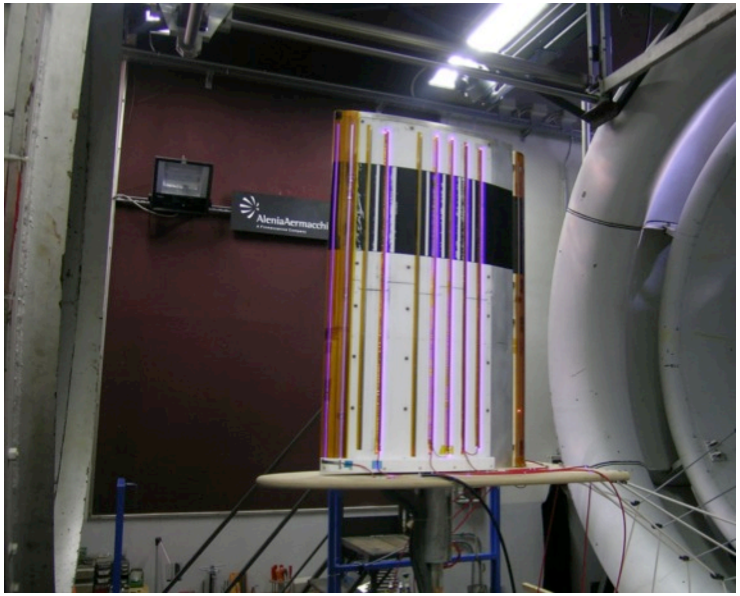


Cooperating on this subject:

- ALENIA AERMACCHI
- Università di MILANO BICOCCA
- Università di Bologna

Aerodynamic Effects

- **Active/Passive Flow Control through non mechanical devices (Plasma Actuators)**
  - Lift enhancement (CL-AoA curve slope and CLmax)
  - Stall delay
  - Drag reduction at low AoA, around CDmin point
  - Control surfaces effectiveness improvement



2-D aerodynamics WT Model

3-D aerodynamics WT Model

The activities were carried out in the projects "PNRM 03.06" and "PNRM a2010.63", funded by the Italian Defense Ministry in the framework of the Military Research Programs

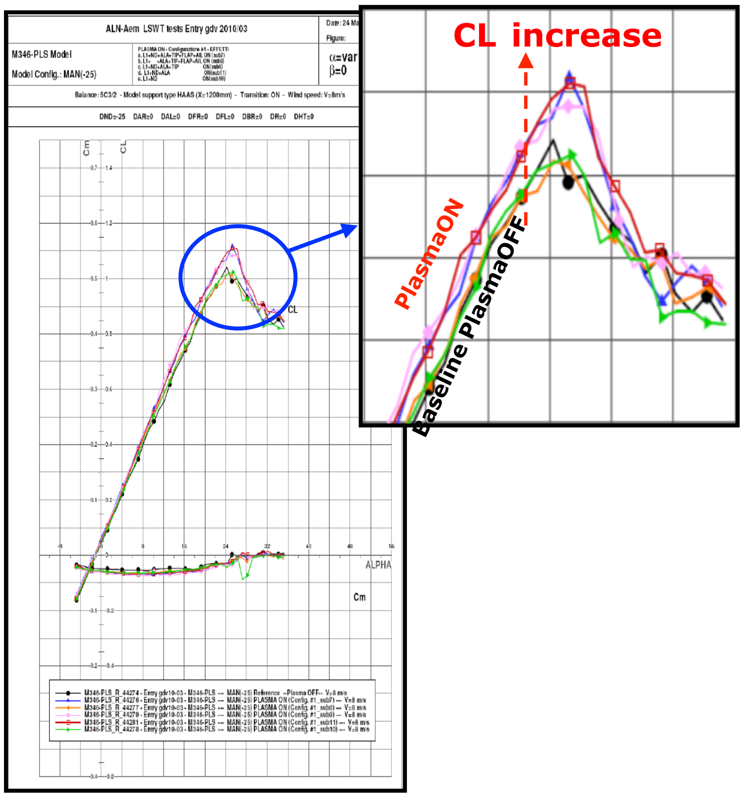
Wind Tunnel Tests Results
Low Speed

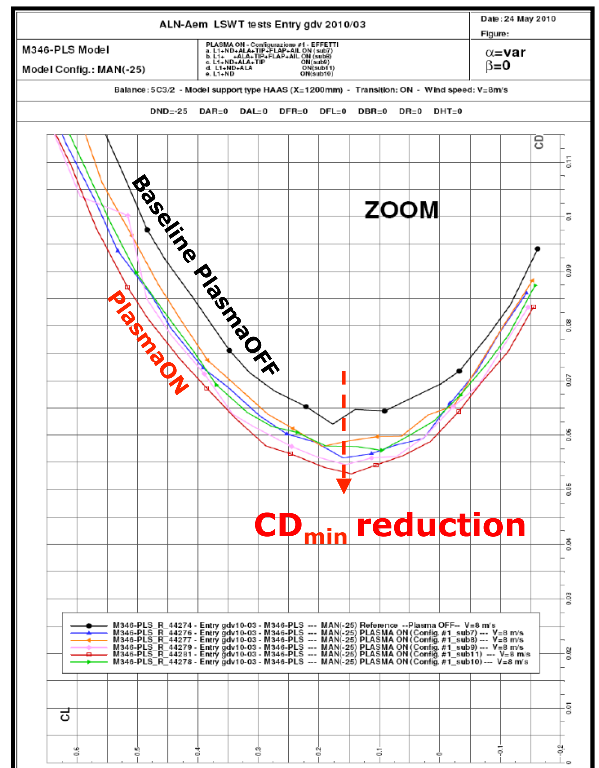
LIFT ENHANCEMENT

- The correct application of Plasma actuators allows to generate an increase of the CL-AoA curve slope and of the CLmax as well. In the most cases, CLmax values grown of more than 10% with respect to the PLASMA OFF test case

DRAG REDUCTION

- In the best tested cases, the CDmin reduction has been quantified in roughly 15% with respect to the PLASMA OFF condition





MHD Interaction in Hypersonic Flows

- **The activities has been carried out in the framework of several Research projects**

  - **2003 Agenzia Spaziale Italiana project "Interazione MHD in Flussi Ipersonici",**
  - **PRIN 2004 (national coordinator) "Sviluppo di un Ambiente Modellistico-Numerico Finalizzato al Progetto Magnetogasdinamico di Veicoli Ipersonici"**
  - **2006 European Space Agency project "PS-JUST" (Validation and Developments of Integrated Plasma and Fluid Dynamics Solvers)**
  - **2007: Agenzia Spaziale Italiana project "CAST" (Configurazioni Aero termodinamiche *innovative* per Sistemi di Trasporto spaziale)**
  - **2007 European Space Agency project "HPF" (Feasibility Study of Advanced Flow Control in a Hypersonic Plasma Flow)**
  - **2009 European Space Agency project "MHD-AFC" (MHD test for Advanced Flow Control)**

- **Italian institutions involved in the Research**

  - **ALTA-SpA**
  - **CIRA**
  - **CNR-IMIP**
  - **Politecnico di Torino**
  - **Università di Bologna**

Motivations

- To demonstrate the effectiveness of the MHD interaction in modifying the flow and in mitigating thermal fluxes
- To acquire basic knowledge on the magnetic and electrical configuration to be utilized for optimizing the effect of the MHD interaction
- To acquire a better insight in the relevant physical phenomena
    - Plasma kinetics
    - Hypersonic fluid dynamic
    - Electrodynamic
- Numerical code has been developed and implemented
- Experiments has been carried out
- The experiments was designed in order to:
    - Have a simple geometric configuration, in order to focus on the basic physical mechanisms
    - axis-symmetric Hall configuration of the test body
    - produce experimental results to be utilized for the validation of numerical codes
    - Working gas:
        - argon – atomic gas, easier to ionize
        - Air – closer to real application, complex plasma kinetics

The Facilities

•Alta High-Enthalpy Arc-heated Tunnel (**HEAT**) is a pulsed hypersonic wind tunnel operative since 1996 at ALTA (Pisa).

- 260 kW arc heater.
- total specific enthalpy up to 6 in air/nitrogen

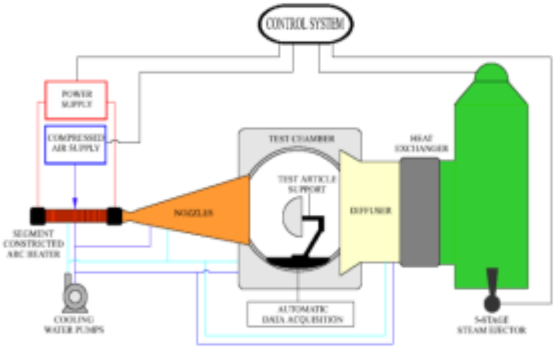
• **GHIBLI** is a hypersonic high enthalpy arc heated continuous facility owned by CIRA.

- 2 MW segmented arc heater
- Sub-scaled w.r.t. Scirocco

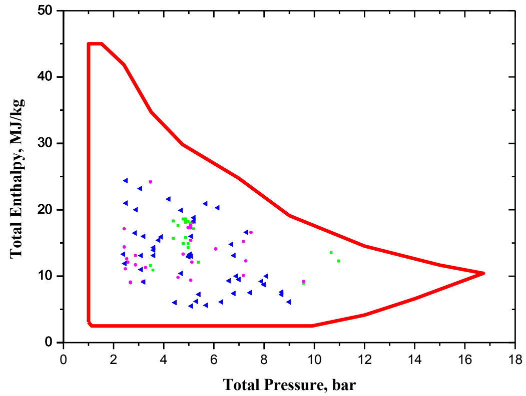
•The CIRA **SCIROCCO** facility is a hypersonic plasma wind tunnel operative since 2001.

- 70 MW segmented arc heater

HEAT nozzle



SCIROCCO functional scheme

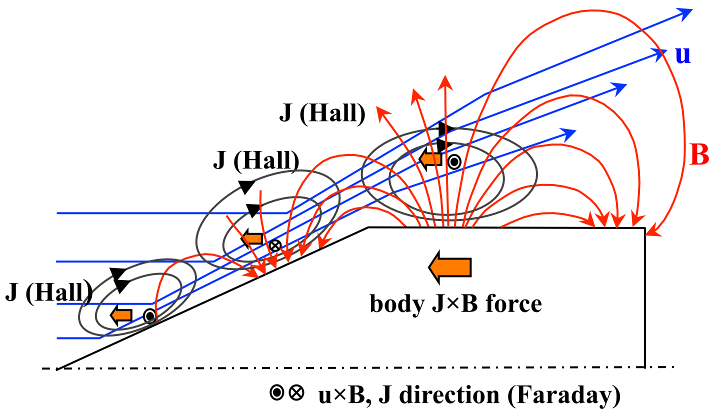


SCIROCCO Performance Map

GIBLI

Sharp Model in HEAT (PS-JUST, HPF, CAST)

Experiment concept

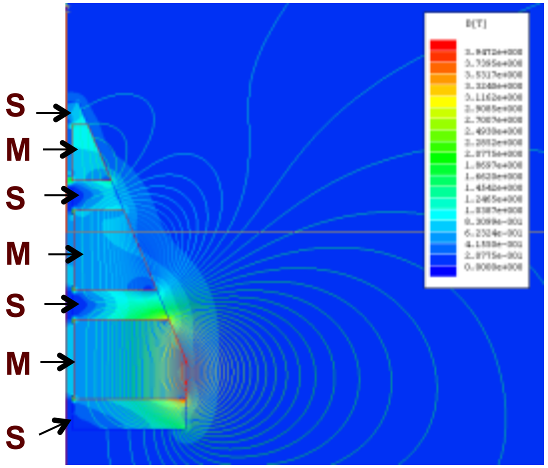


Permanent magnets

Miniaturized piezo-resistive fast pressure transducers

Physical Principle

- A device, internal to the test body, generates a B field perpendicular to the flow velocity.
- An electric field u×B exherts a force on the free charges transported in the flow causing a current density J
- A body force J×B is generated.
- Faraday component of the current density is weakened, as well as the body force J×B by Hall current.



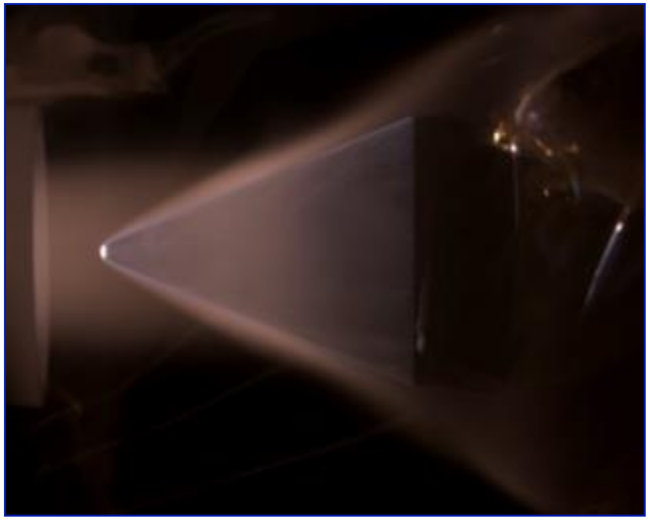
B field distribution M = magnets
S = steel element

Sharp Model in HEAT (PS-JUST, HPF, CAST)

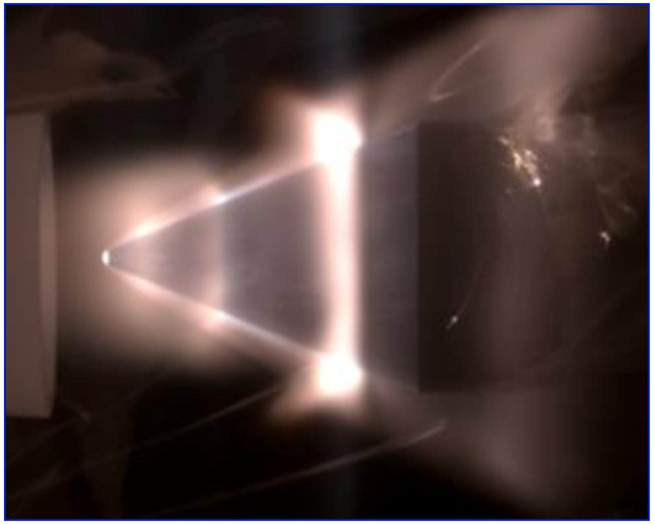
Summary of experimental conditions for the test cases

Working gas: Argon

Cond.	Mach no.	Mass flow rate, [g/s]	Stagn. pressure [mbar]	Stagnation temperature [K]	Electron density ($\times10^{18}$) [m^{-3}]	Electron temperature, [eV]
1	6.16	4.46	523	4455.7	75.11	0.216
2	6.19	5.34	589	3850.4	58.4	0.221
3	6.10	7.027	653	3344.2	24.68	0.227



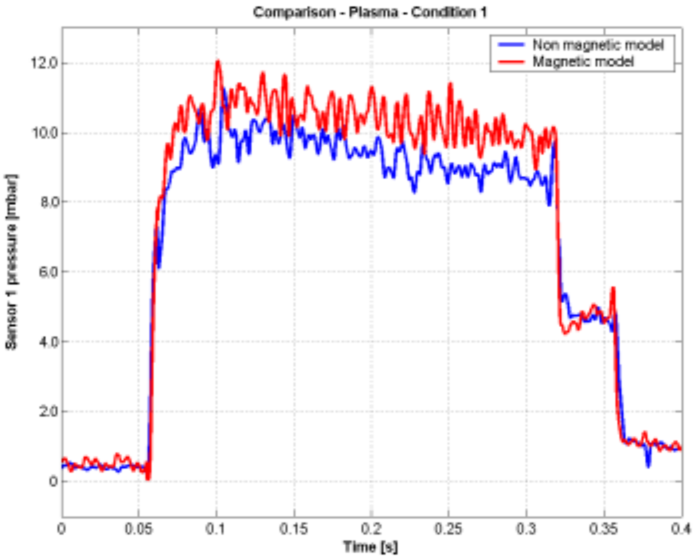
NO MHD (Cond. 3)



MHD (Cond. 3)

Sharp Model in HEAT (PS-JUST, HPF, CAST)

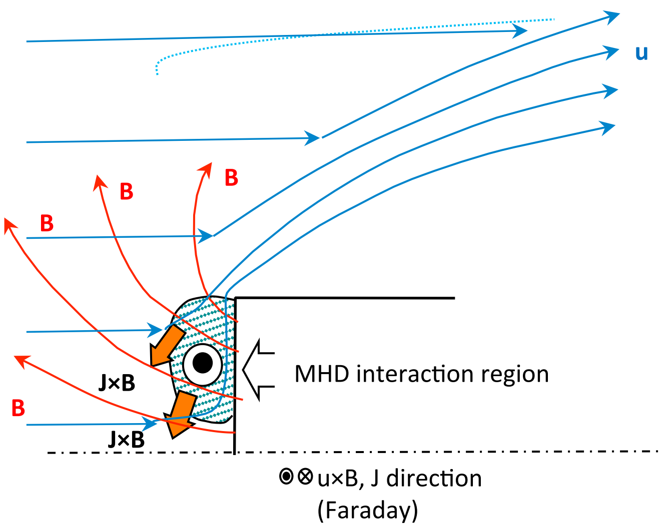
Experimental Results



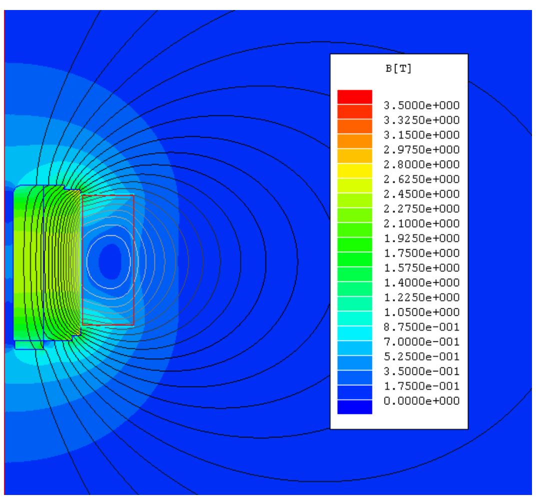
Condition 1: average pressure for the non-magnetic case is 9.01 mbar - MHD interaction case is 10.34 mbar (14 % increase)

Condition	Pressure in non-magnetic runs [mbar]	Pressure in MHD interaction runs [mbar]	Pressure increase [%]	Cp in non-magnetic runs	Cp in MHD interaction runs	Pressure coefficient increase [%]
1	9.01	10.34	14.78	0.344	0.390	13.44
2	10.31	11.68	13.31	0.343	0.388	13.27
3	11.77	12.97	10.16	0.343	0.366	6.88

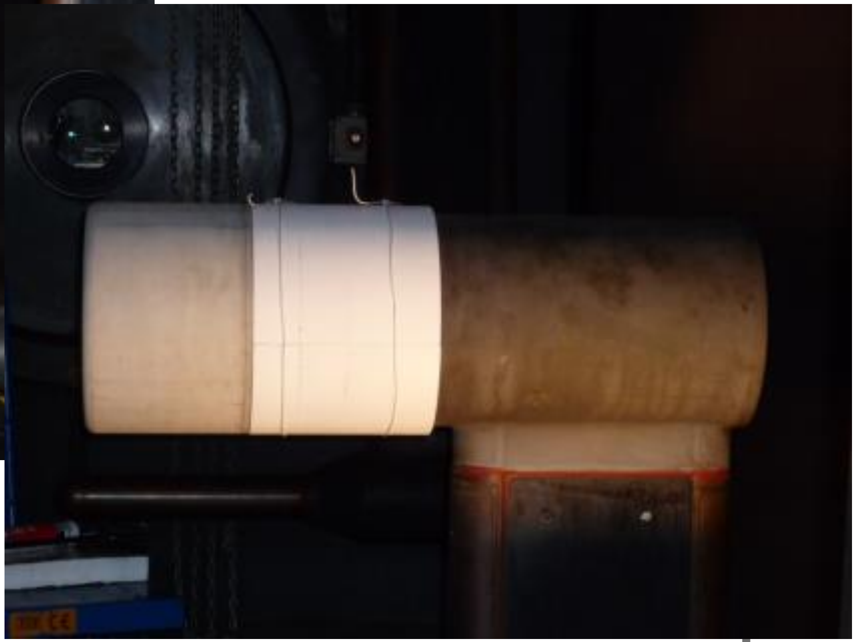
Blunt Body in SCIROCCO (MHD-AFC, CAST)



- Big size. Nozzle exit diameter: 2 m - Model diameter: 30 cm → Maximize ionization, maximize B for a given current density
- Air flow without seeding → representative of re-entry conditions
- Electromagnet → testing different magnetic fields in the same shot
- Long test → cooled model
- Diagnostics:
  - ➢ Plasma characterization at the nozzle exit
  - ➢ 5 pressure taps over the flat face (not only in the stagnation point, where no effect was expected)
  - ➢ Wall temperature measurements by means of thermography

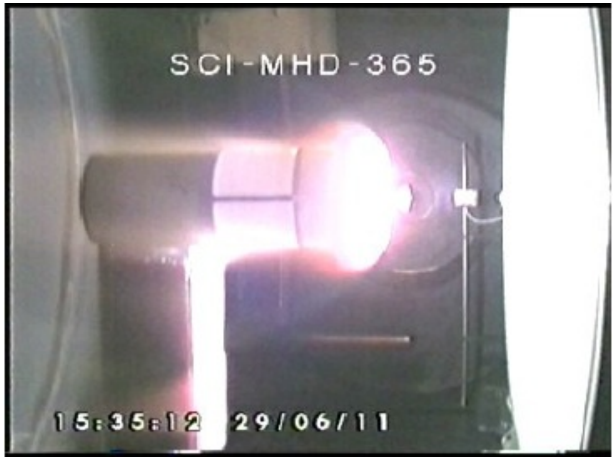


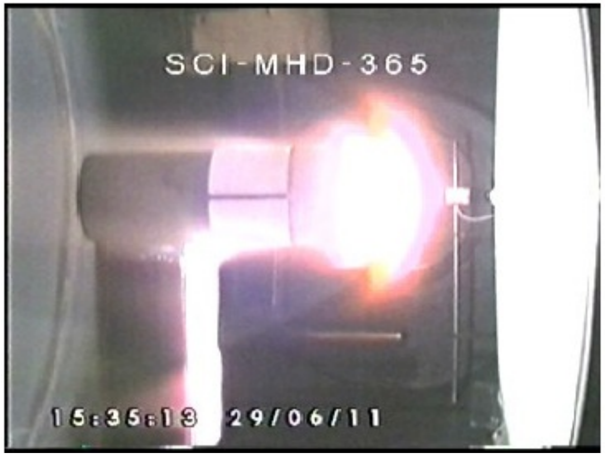
Blunt Body in SCIROCCO (MHD-AFC, CAST)



Blunt Body in SCIROCCO (MHD-AFC, CAST)

Operating Conditions

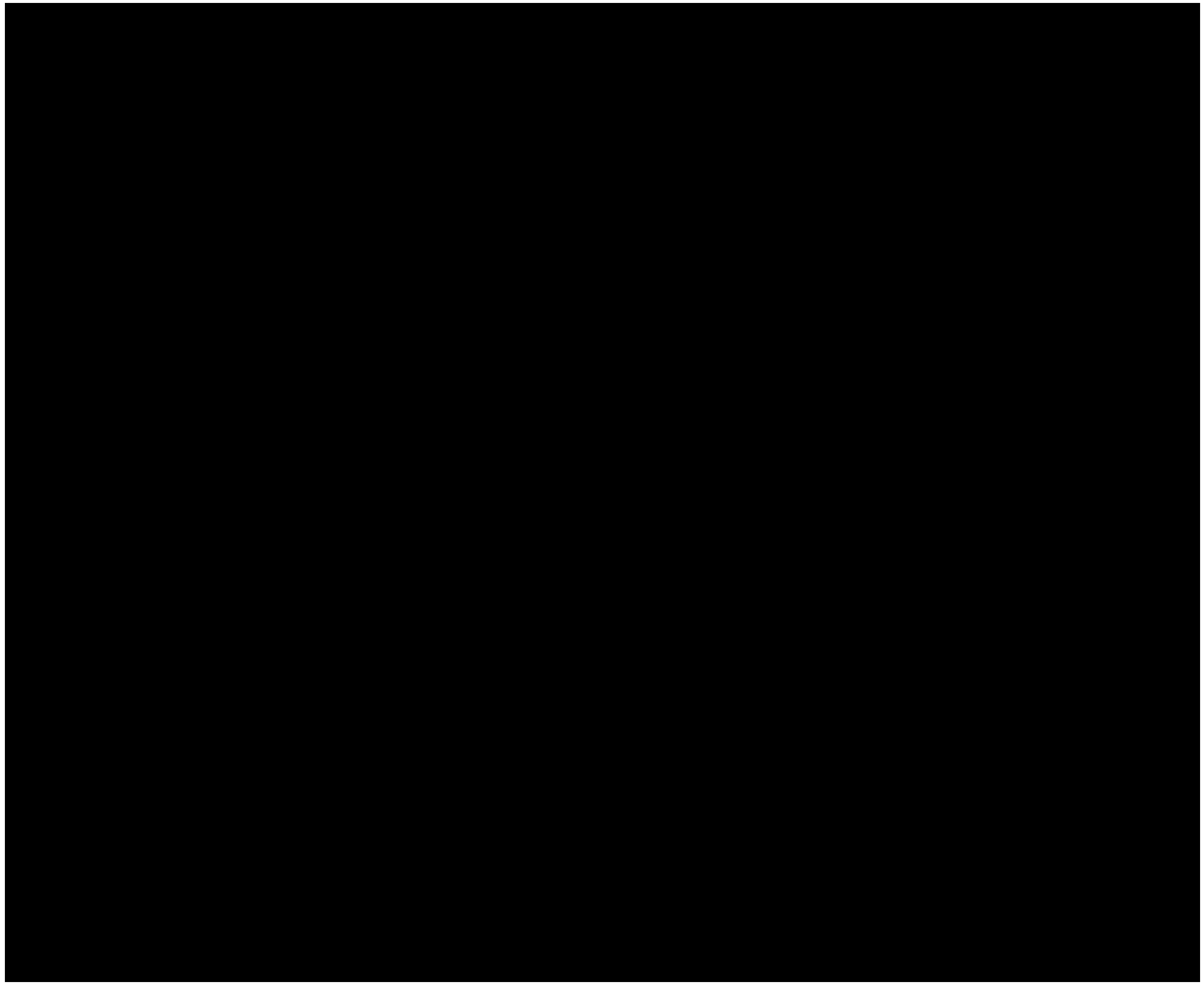




Test Id.	Date	Electromagnet current (I)	H0 (MJ/kg)	P0 (bar)
SCI-MHD-365	29/06/2011	40, 60	12	2.3
SCI-MHD-368	30/06/2011	40, 60, 80	16	2.5

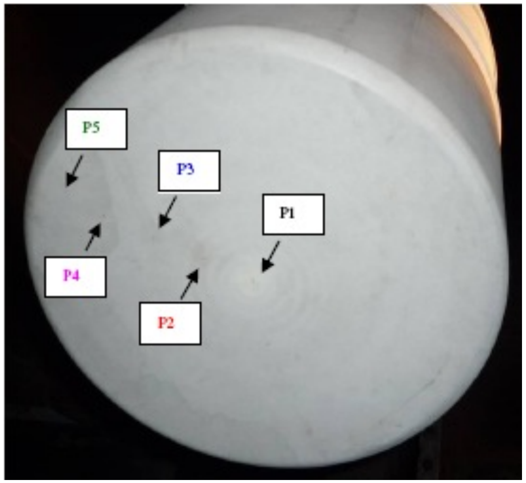
Blunt Body in SCIROCCO (MHD-AFC, CAST)

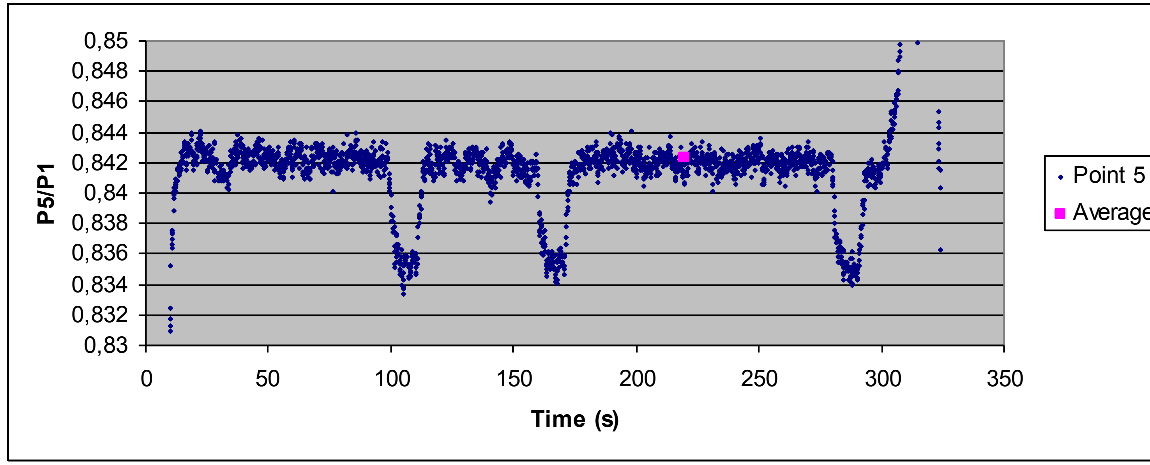
Test video

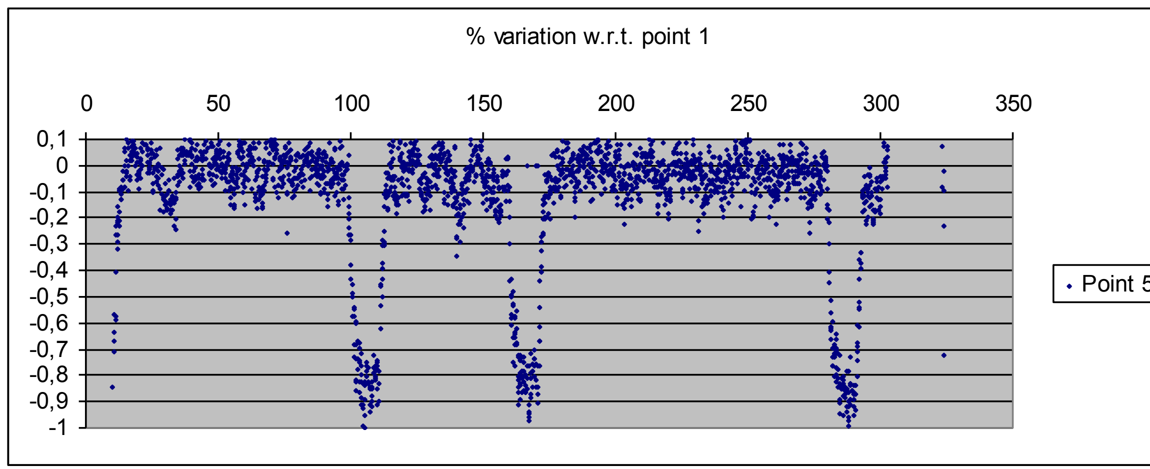


Blunt Body in SCIROCCO (MHD-AFC, CAST)

Pressure measurements – Point 5 (H0 = 16 MJ/kg)





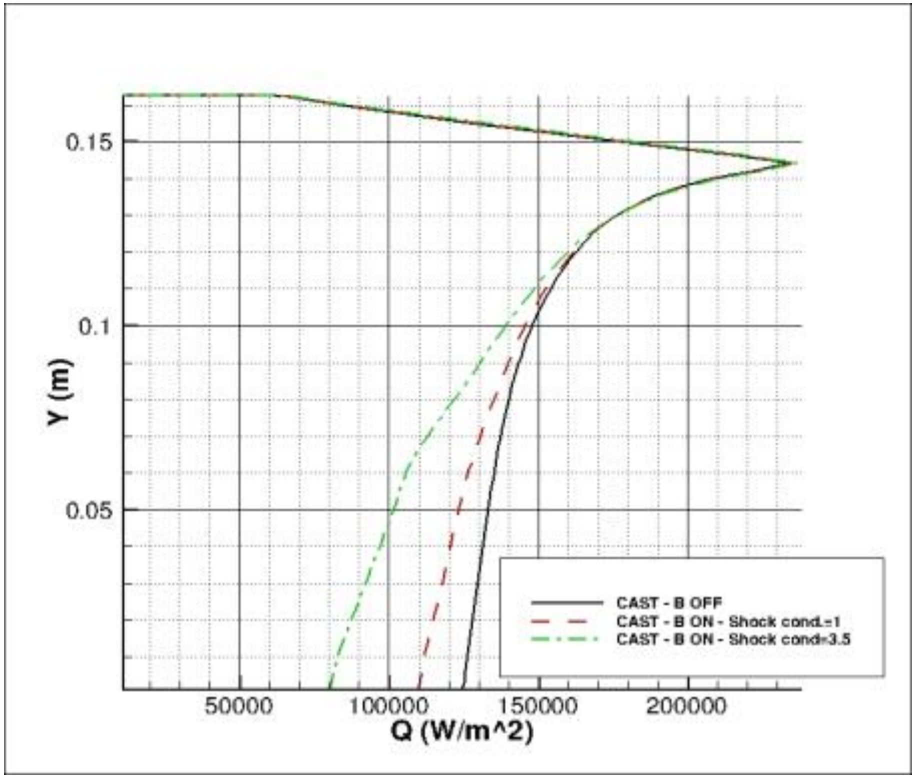


Point 5 exhibits a percentage decrease of 1 % with respect to the stagnation point

Blunt Body in SCIROCCO (MHD-AFC, CAST)

MHD effect on wall heat flux

- Copper TPS prevented a reliable measurement of the thermal fluxes
- Thermal fluxes have been evaluated numerically
- For the most reliable numerical results the wall heat flux was computed
- It can be observed that, also if one considers σ_{shock}=1, a 10% decrease of the heat flux is predicted



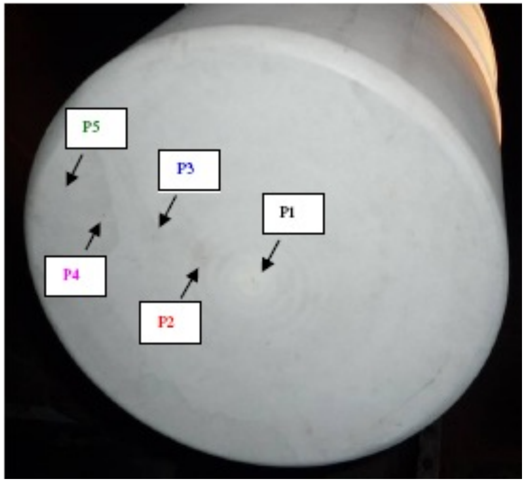
CAST. Wall heat flux

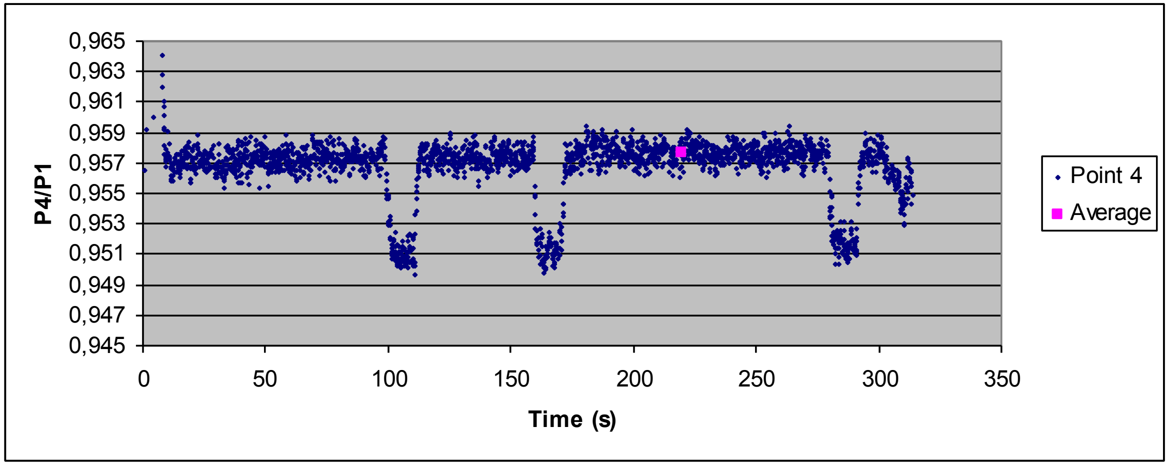
Conclusions

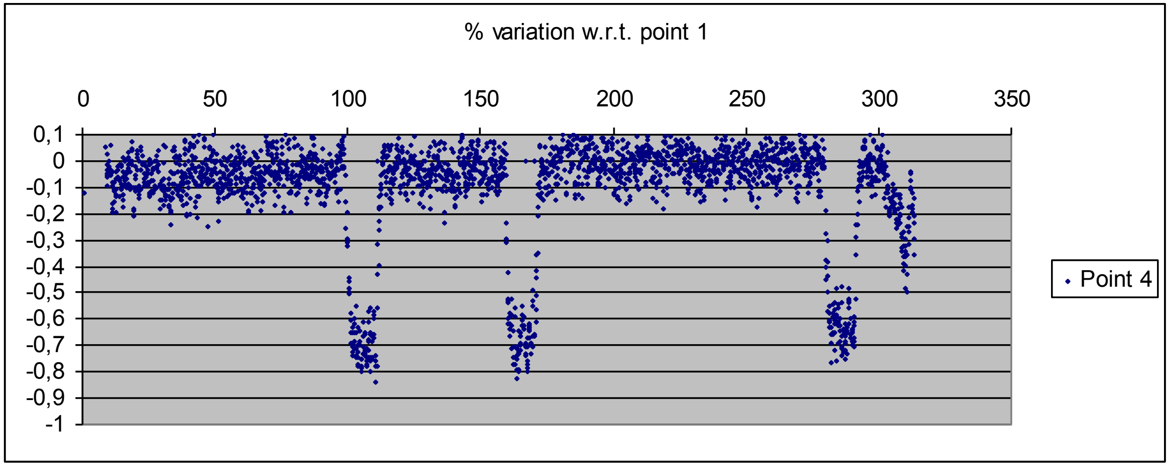
- **The MHD interaction in a hypersonic flow was experimentally investigated in various conditions.**
- **Experiments have been performed on sharp and blunt test bodies in an argon flow at Mach 6 and 15.**
- **Pressure variation**
- **A Mach 11 air flow has been utilized to investigate the MHD interaction around a blunt body in SCIROCCO.**
- **Small but clear effect on wall pressure was obtained in Scirocco test campaign**
- **The pressure effect is not influenced by the intensity of the magnetic field for the tested conditions**
- **The effects on the thermal fluxes are not evident (because of the copper TPS)**
- **MHD phenomena become evident outside the shock layer, due to the ionization in the incoming flow**
- **A significant effect on heat flux is predicted by numerical rebuilding (> 10%).**

Thank you for your attention!

Pressure measurements – Point 4 (H0 = 16 MJ/kg)

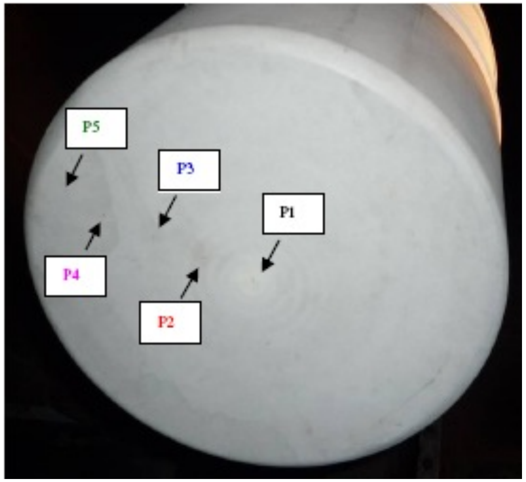


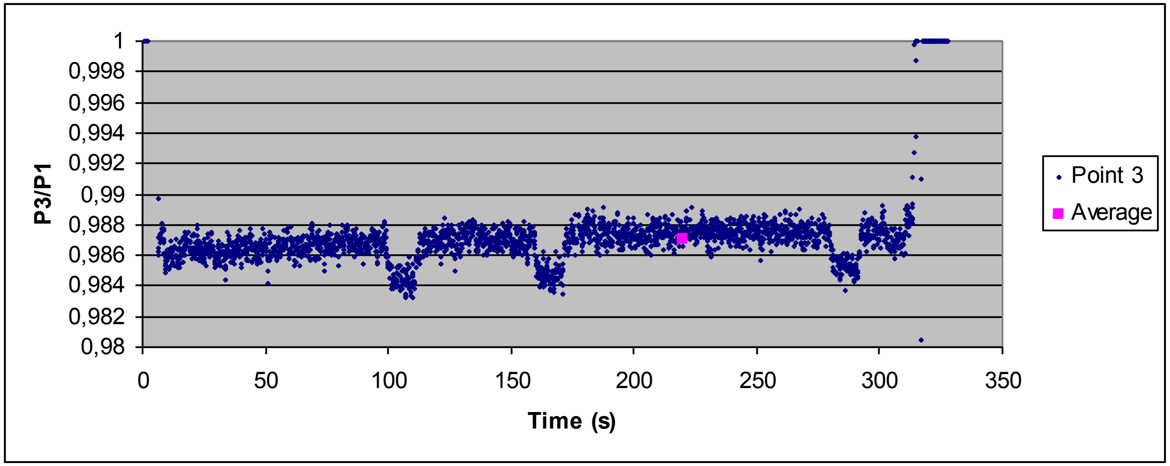


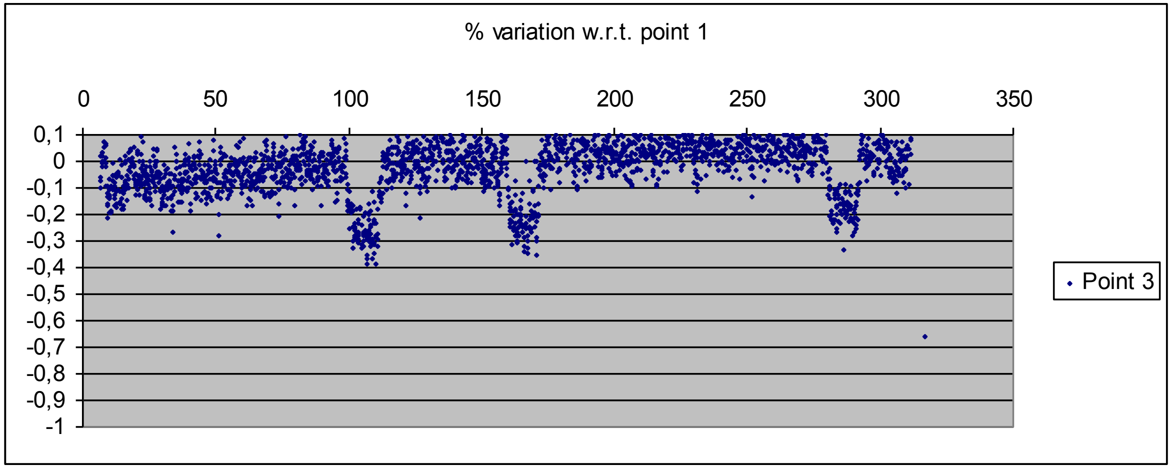


Point 4 exhibits a percentage decrease of 0.8 % with respect to the stagnation point

Pressure measurements – Point 3 (H0 = 16 MJ/kg)

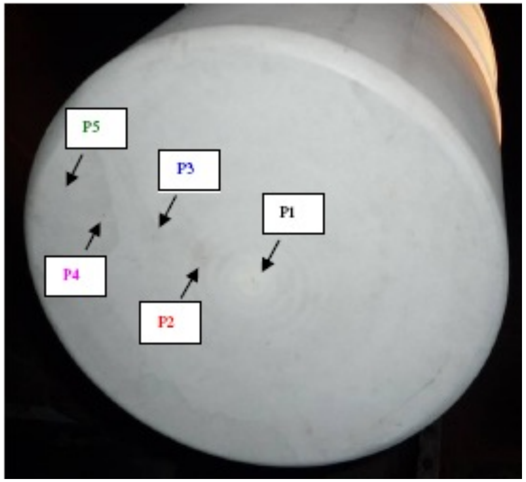


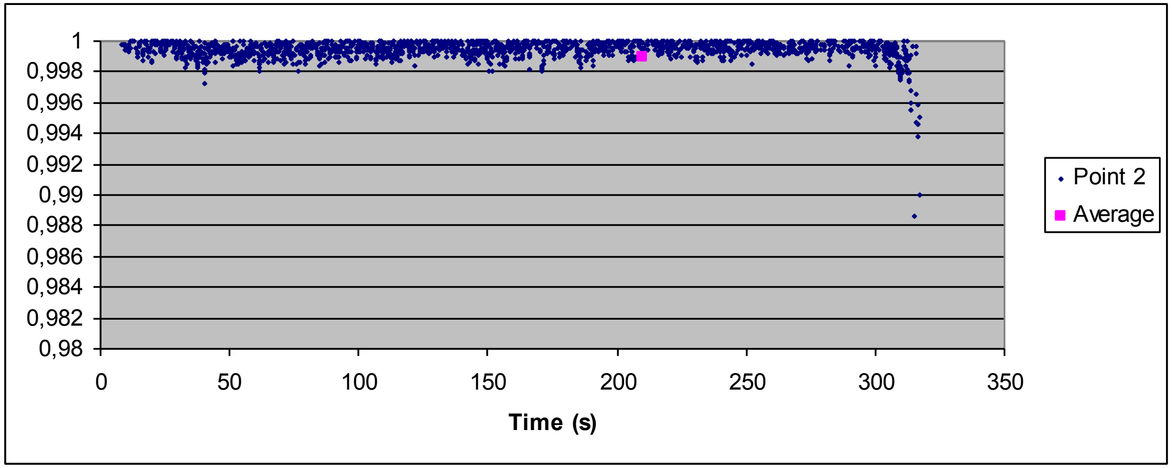


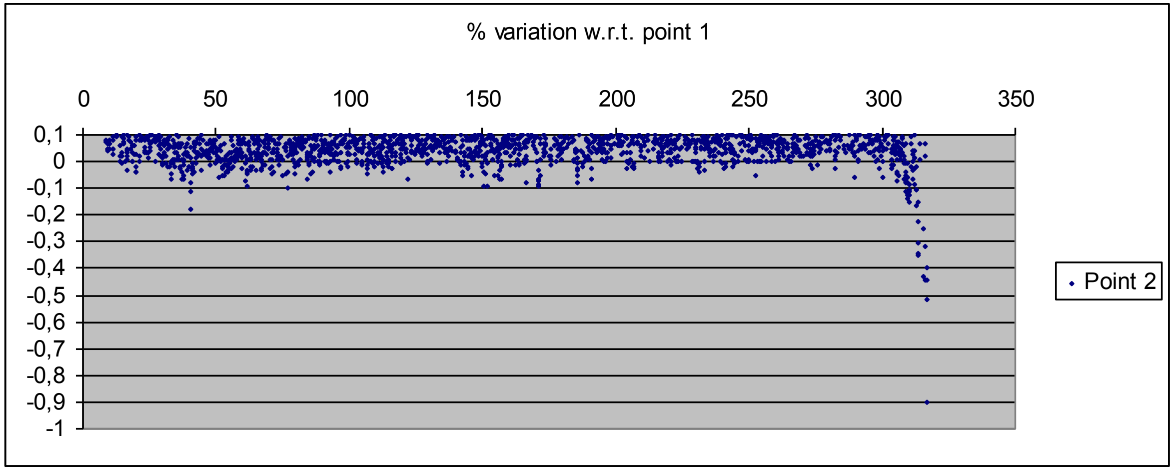


Point 3 exhibits a percentage decrease of 0.4 % with respect to the stagnation point

Pressure measurements – Point 2 (H0 = 16 MJ/kg)

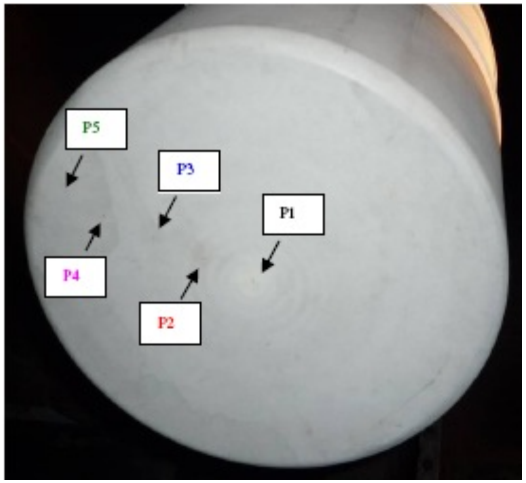


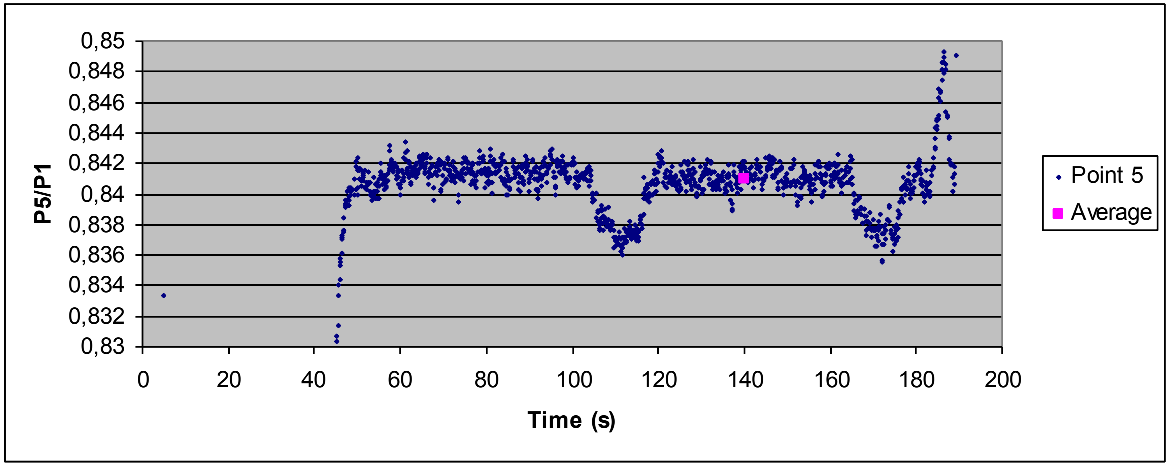


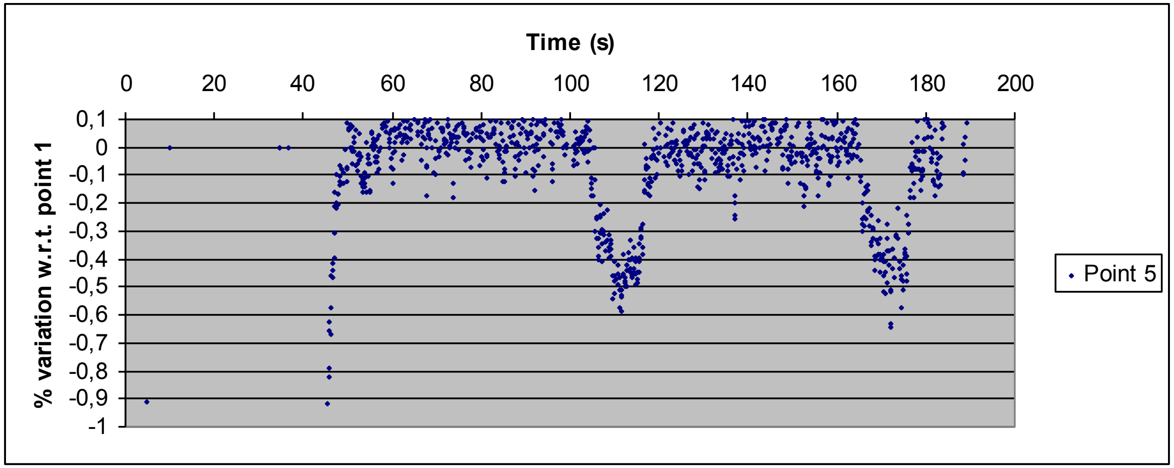


Point 2 does not exhibit significant differences with respect to stagnation point

Pressure measurements – Point 5 (H0 = 12 MJ/kg)







Point 5 exhibits a percentage decrease of 0.5 % with respect to the stagnation point