The Gas Injection Control and Diagnostic System for the ESTHER shock Tube

Bernardo B. Carvalho, Mário L. da Silva, and Sérgio Dias

***Abstract*–A fully automated remote control system for the gas filling system has been developed for the ESTHER shock-tube using technologies and software tools, e.g. PLC, EPICS, CS-STUDIO, similar to the ITER CODAC I&C architecture for slow control. The system also comprises also a fast data acquisition for the combustion chamber diagnostics.**

I. INTRODUCTION

THE European Shock-Tube for High Enthalpy Research (ESTHER) is a combustion drive shock-tube that is now being installed at IST/CTN campus where experimental research on plasma radiation of high-speed (>10km/s) shocked flows will be carried to simulate the high pressure and temperature conditions of spacecraft re-entry in different atmosphere conditions. The shock wave will be driven by the deflagration of a stoichiometric H_2, O_2 gas mixture diluted in Helium with up to 100 bar filling pressure inside a 50 liter combustion chamber. The ignited mixture rises the pressure up to ~600 bar which breaks a disposable diaphragm at the end of the combustion chamber creating the resulting wave front. An industrial partner, Air Liquide, installed the gas filling hardware for the combustion chamber including 15 pressure transducers, 22 controlled valves and 3 mass-flow controllers. The respective control system was developed entirely by the IPFN team using the open software EPICS [1] and CS-Studio [2] SCADA environment, embedded Linux computers and standard industrial automation programmable logic controllers on a configuration similar to the ITER CODAC I&C architecture and software technologies for slow control [3] that was previously evaluated in a local test setup [4].

The control system is responsible for handling the gas purge and injection, preparation for ignition, and exhaust burned or unburned mixtures assuring a safe, reliable and reproducible shock tube operation. The system includes an archiving and browsing system for the most important pressure, flows, filling volumes and temperature parameters and also embraces the connections to the independent security gas (H_2, O_2) alarm system, laboratory door-locking and audible warnings. A number of CS-Studio/BOY graphical user interface (GUI) panels were created both for mimic panels and the gas system operation. Finally a data acquisition system is able to acquire the signals from a fast piezoelectric pressure sensor inserted in the camera and from an inductive sensor measuring the current flowing on the copper-nickel ignition wire.

II. THE ESTHER SHOCK-TUBE EXPERIMENTAL SETUP

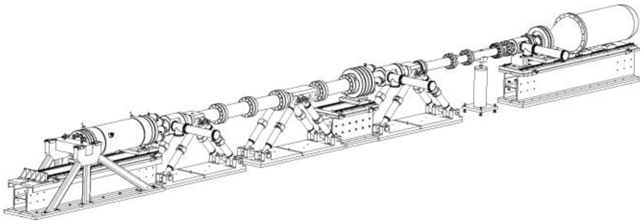

Fig. 1. General view of the Esther Shock Tube, showing the combustion chamber on the left, the intermediary compression tube and the shock-tube and finally the dump tank on the right.

The ESTHER shock-tube assembly (Fig. 1) is composed of a 50 liter combustion chamber designed to deflagrate a gas mixture from up to 100 bar to approx. of 600 bar. Ignition is achieved through a three copper-nickel (constantan) 0.13mm diameter wire system, ignited through a high-intensity electrical current that can be programmed from 50V to 1300V in 10V increments and duration from 1 to 50 ms in 1 ms steps in a specialty built ignition power supply based in a capacitor bank. The intermediary compression tube with a 130 mm internal diameter pre-filled with low pressure Helium is connected to the combustion chamber through a metallic diaphragm designed to burst at defined pressure and accelerated the front wave to speed in excess of MACH 10. Finally the 80 mm internal diameter shock-tube is connected to the compression tube through a second bursting diaphragm. The shock tube include a series of fast pressures sensors along the path and a test section equipped with lateral windows for time-dependent spectroscopic diagnostics. The end section on the shock-tube is connected to a dump tank planned to absorb the wave energy and to recover the burned gases flowing in the wake of the wave.

To validate the design of the main ESTHER combustion chamber and the ignition system a smaller 3 liter test chamber ("bombe") closed at both ends has been constructed. It was already tested in more than 100 pulses in diversified conditions. The ESTHER sock-tube and all the gas filling system are

---

Manuscript received May 30, 2016. This work was developed under support the European Space Agency from contract 23086 "Kinetic Shock-Tube for Planetary Exploration, and from Fundação para a Ciência e Tecnologia through project UID/FIS/50010/2013.

The authors are with the Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal (e-mail: bernardo.carvalho@ipfn.tecnico.ulisboa.pt).

installed on a semi buried and explosion proof and ATEX rated “bunker” contained within a building complex specially constructed for the new Hypersonic Plasmas Laboratory of IPFN-IST. The building includes a remote control room and a diagnostic hall.

III. GAS FILLING SYSTEM

The gas filling system was designed and supplied by Air Liquide. It has been designed for being capable of supplying an arbitrary (He/ H_2/O_2) mixture to either the test bombe or the final ESTHER combustion chamber for a maximum filling pressure of 100bar. All the H_2 lines are completely segregated and use only pneumatic control valves. The four valves directly connected to the camera/bombe were custom built by Maximator GmbH and withstand a 1600 bar overpressure. The system include a set of three of digitally controlled Mass Flow Controller (MFC) for the precise measure of the inserted gas masses.

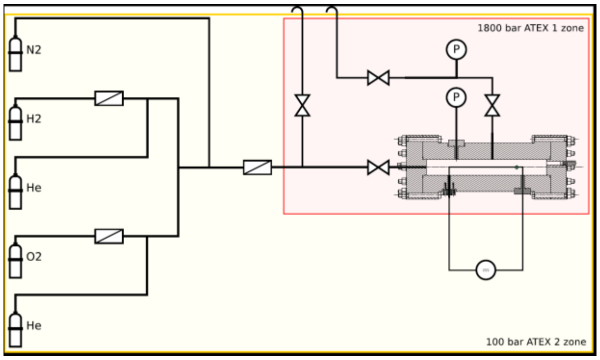

Fig. 2 Reduced diagram of the Gas Filling System, Test Bombe, Ignition wire and respective power supply.

IV. GAS CONTROL FILLING SYSTEM

The general block diagram for the gas filing control installed on the ESTHER control room is depicted on Fig. 3.

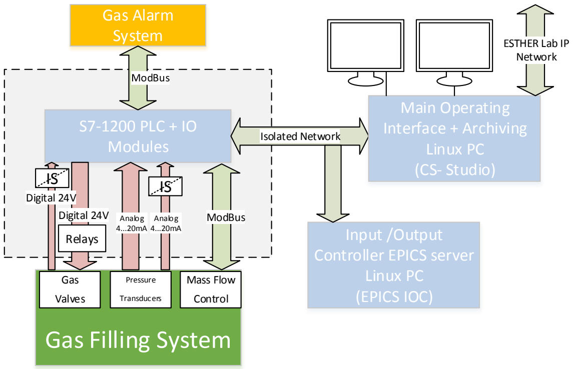

Fig. 3. Gas Filling Control System Block Diagram.

The low level control system is based on an industrial standard Siemens PLC (S7-1200 CPU Module 1215C) equipped with a series of I/O side modules. The PLC is connected to all valves and pressure transducer though relays or isolation barriers for those equipment installed on the ATEX bunker zone. The list of all physical connection is depicted in Table 1.

TABLE I. GAS FILLING I/O CONNECTION AND TYPE

Type	Description	Quantity
Analog Inputs (4…20mV)	Pressure transducers	9
Analog Inputs w/ “Ex” Isolation Barrier	Pressure transducers of combustible gases	4
Digital Outputs (24V)	Gas Valves control	23
Digital Inputs (24V)	Doors closed switch sensor	3
	Emergency stop button	1
Digital Inputs w/ “Ex” Isolation Barrier	Bunker Gas Valves limit Switches	8
ModBus RS485 I/O	MFC Valves	1
	Security gas alarm system	1

The PLC program includes a series of “Function Blocks” written in Ladder Logic that comprise:

- Main block with the top logic (start/stop, etc) and main stage sequence.
- Start-up block for system and variable initialization (e.g. ALARM setup Limits)
- Periodic block (100 ms) to acquire the analogue pressure sensors signal from the transducers and conversion to engineering units.
- 9 blocks for logical gas filling “stages”
- ABORT filling process block
- Gas circuits leak check procedures
- MODBUS communication blocks

The PLC is connected through a 100Mb Ethernet connection to an EPICS IOC Server Linux computer. This is compact embedded computer with no moving parts (fans, hard disk, etc.) multicore Arm-based computer (Raspberry Pi Model 2) running a standard Debian 8 32bit Operating system. This computer does not run any specific control logic but serves as an interface to the EPICS environment, connecting all important PLC variables (Tags) to EPICS Process variables (PV)

On the same Ethernet network a second desktop PC is connected. It is a full-fledged INTEL i7 CPU Linux workstation (Debian 8 64 bit) serving as the operating console, the SCADA control supervisor and the data archiving system. The software was based in Control System Studio control tool for the operator interface and the archiving engine. The process data is continually stored in MySQL database. This PC also hosts the Siemens TIA Portal V13 PLC developing environment for the logical PLC programing and debugging, running in a VirtualBox virtual Windows environment.

V. GUI OPERATING PANELS

A number of CSS/BOY panels were created both for the gas system final operation and also to assist along the PLC programming phase or to help investigating possible future system failures. The first panel on Fig 4 top includes controlling buttons to start/stop the controller, initiate the filling process and leak test procedure and start/stop the abort stage the monitoring of all pressure transducers, mass flows and alarms and list of buttons to open secondary BOY panels. The panel on Fig. 4 bottom is a mimic of the gas pumping diagram.

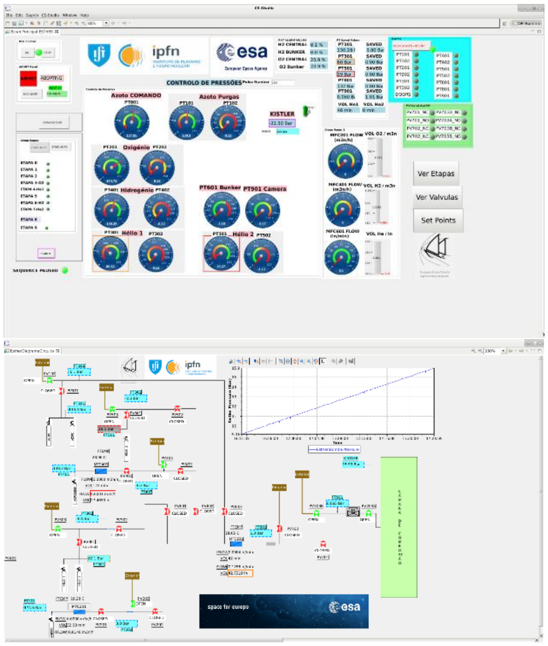

Fig. 4. CS-S GUI main operating panel (top) and gas filling system mimic (bottom).

VI. FAST DIAGNOSTIC ACQUISITION

The fast diagnostics comprise a Kistler ballistic pressure gauge with a heatshield and its conditioning amplifier system and a LEM inductive sensor for current intensity on the ignition wire. Both signals are acquired synchronously with a Red Pitaya board at 14-bit resolution and up to 16 MSPS data rate, using a modified firmware/ecosystem capable of streaming the real-time data through a UDP dual port connection server [5]. Fast signals are stored first in local raw binary files and subsequently transferred to an MDSplus data acquisition and storage system [6].

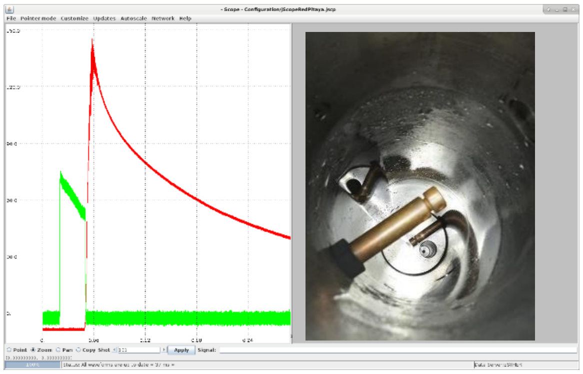

Fig. 5. MDSplus jScope panel showing pressure and ignition wire current during one experiment plus a photo of the bombe after camera opening.

REFERENCES

[1] A. N. Laboratory, “Experimental Physics and Industrial Control System Engineering Software.” [Online]. Available: http://www.aps.anl.gov/Epics

[2] CS-Studio, “Control System Studio Engineering Software.” [Online]. Available: http://controlsystemstudio.org

[3] F. D. Maio, L. Abadie, C. Kim, K. Mahajan, P. Makijarvi, D. Stepanov, N. Utzel, A. Wallander, I. Organization, R. D. Vinon, “The CODAC Software Distribution for the ITER Plant” in Proceedings of ICALEPCS 2011

[4] D. E. Aguiam, B. B Carvalho and M L Silva “Feasibility Study of a Control System based on PLC and EPICS for the ESTHER Combustion Gas Injection”, proceedings of the “3rd Experiment@International” Conference, Ponta Delgada, Azores, Portual, June 2015

[5] Nils Roos,“Red Pitaya Forum: New feature: high speed continuous recording” http://forum.redpitaya.com/viewtopic.php?f=7&t=317

[6] G. Manduchi, T. Fredian, J. Stillerman Future directions of MDSplus, Fusion Eng. Des., 89 (2014), pp. 775–779