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Real Time Flow Control System for Precise Gas Feed in COIL

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ABSTRACT

This paper reports development of a real time flow control system for precise, controlled and uniform gas feed to a flowing medium Chemical Oxygen Iodine Laser (COIL). The optimal operation of this prominent laser depends upon the desired supply of gas constituents such as nitrogen (N_2), chlorine (Cl_2) and iodine (I_2) to achieve adequately mixed laser gas. The laser also demands real time variation of flow rates during gas constituent transitions in order to maintain stabilised pressures in critical subsystems. Diluent nitrogen utilised for singlet oxygen transport is termed as primary buffer gas and that for iodine transport is termed as secondary buffer gas (with main and bypass components). Also, nitrogen in precise flows is used for mirror blowing, nozzle curtain, cavity bleed and diffuser startup. A compact hybrid data acquisition system (Hybrid DAS) for precise flow control using LabVIEW 2014 platform has been developed. The supported flow ranges may vary from few mmole.s^{-1} to few hundred mmole.s^{-1}. The estimated relative uncertainty in the largest gas component i.e. primary buffer gas feed is nearly 0.7%. The implementation of in-operation variation using flow ramp enables swift stabilisation of singlet oxygen generator pressures critical for successful COIL operation. The performance of Hybrid DAS is at par with fully wired DAS providing the crucial benefit of remote field operation at distances of nearly 80m in line of sight and 35m with obstacles.

Keywords: Flow control; Hybrid DAS; Gas feed; Flowing medium; COIL

1. INTRODUCTION

COIL is a scalable and highly potential laser source amongst various other high power laser sources[1-2]. In COIL, chlorine gas reacts with liquid reagent i.e. Basic Hydrogen Peroxide (BHP)solution to generate singlet oxygen (Pumping medium). Singlet oxygen both dissociates and pumps iodine (lasing medium) for subsequent lasing action. Laser is extracted through the resonator assembly attached to the optical laser cavity.

In COIL, pressure and flow uniformity of involved gas constituents viz., nitrogen (N_2), chlorine (Cl_2) and iodine (I_2) is very crucial. N_2 gas supply system plays a pivotal role by feeding primary buffer gas, secondary buffer gas and fulfilling other auxiliary gas requirements of mirror blowing, nozzle curtain and diffuser start up at various pressure ranges. Primary buffer gas is meant to mix with the singlet oxygen flow for reducing its self-quenching.

COIL system requires fast stabilisation of singlet oxygen generator pressures for efficient pumping medium generation and negates any possibility of catastrophic liquid reagent carry over[3] and ensuing liquid quenching losses.

Secondary buffer gas is meant as carrier for the lasing species i.e. iodine to laser cavity on account of it being the heavier gas. The flow of both the secondary main and secondary bypass needs to be adjusted in situ during operation to provide uniform and regulated I_2 flow. The optimal laser power is essentially a strong function of iodine flow rates.

Keeping in view, both the short operation duration (few seconds) and safety concerns (due to the use of hazardous Cl_2, I_2 and BHP solution) in flowing medium COIL, real time flow control system with hybrid (wired and wireless) features has been developed to provide controlled flow of gases to different subsystems of COIL from remote distances. This flow control system performs the function of providing preset flow rates, in operation flow rate variation and online pressure monitoring.

Previously reported flow control systems[3-6] provide controlled flow of nitrogen and stabilised singlet oxygen by the application of wired DAS using Advantech-GeniDAQ software. But the developed flow control systems apparently had limitations in terms of user interface flexibility, system compactness and lack of remote operation (safety concern). In order to address these aspects a compact hybrid real time flow control system has been developed and utilised for buffer gas supply including in operation flow variation in (using Ramp VI pattern of) LabVIEW 2014 platform with software flexibility. The developed compact Hybrid DAS is compact and can be operated from the remote distance of around 35 m with obstacle sand at 80 m line of sight[7]. The novelty of the work primarily lies in it being a Hybrid system using Master -Slave concept, in which the master module controls the slave

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module using wireless communication. The slave module is subsequently connected in a wired manner to the actual COIL system. This provides immense flexibility in terms of on-field operation of a technologically complex laser system such as COIL without any loss of functional control when compared to a fully wired system. The developed system supplies nitrogen in ramp fashion using LabVIEW 2014 with Wi-Fi operation for the first time for such high end complex laser system with parametric uncertainties to the best of our knowledge from open literature.

2. FLOW CONTROL HYBRID DAS ARCHITECTURE AND IMPLEMENTATION

Developed compact flow control system utilises a unique hybrid architecture[7-12] implemented apparently for the first time for operating high power flowing medium COIL laser. A basic building block diagram of hybrid data acquisition and flow control system is shown in Fig. 1. Developed hybrid DAS is a combination of wired and wireless architecture and consists of three main parts:

1. Actual controller (Master)
2. Virtual controller (Slave)
3. Signal acquisition, monitoring and output control

Actual controller (master) commands the virtual controller through Wi-Fi and performs various COIL operations such as predefined control of valves, monitoring of various sensors, gas feed flow control and current status of COIL subsystems from a distance of around 35 m.

Virtual controller (slave) consists of a Transceiver EKI-1361, Processor ARK-1122C, and Router (D-Link AC750). EKI-1361 and ARK-1122C receives the signal from the Master controller through a wireless (Wi-Fi) connection. All the Hybrid DAS signals are decoded by the router. Again, the router sends this information to wireless serial server card EKI-1361 and ARK-1122C through Wi-Fi connection. ARK controller controls the whole processes of the operations and transfers the data back to the master controller which is a display and control device with application software. All the measurement and actuation, which is performed at the slave unit is recorded with the master unit for further optimisation of the flowing medium laser.

Signal acquisition, monitoring and output control comprises various sensors (temperature, pressure and level) and signal conditioners. The temperature sensors are employed for measurement of liquid reagent and iodine temperature. Pressure sensors are used for measurement of the flowing medium (chlorine, iodine, nitrogen) pressure. Level sensors are used for measuring tank liquid reagent level.

Signal conditioner modifies the input signals to make them compatible to various HDAS cards. ADAM 4117, ADAM 4118, and ADAM 4015 have been used for slow process sampling and USB 4716 has been used for fast sampling of data, utilised in emergency interlocks. ADAM 4024 and USB 4716 have been selected to provide supply of controlled gas constituents including displaying real time valve/ pressure reducer status and also cater emergency situations if required.

Output control system is utilised for switching (on/off) of the different actuation valves.24 V supply to Hybrid DAS cards, sensors, pressure reducers, signal conditioners, actuators is provided by the power supply module. COIL laser operation is viable only due to the control/actuation of the different valves, which occurs in accordance with a pre-set time sequence.

2.1 Hybrid DAS Interfacing for Gas Flow Control

Optimum performance of flowing COIL system is governed by the controlled and uniform flow[13-15] of buffer gas N_2, Cl_2 and I_2. A gas feed system based on hybrid scheme has been developed using ramp pattern VI in Lab View-14 platform. The output flow is a function of input pressure which is controlled by varying the analog voltage generated by data acquisition card. Analog output (AO) from hybrid data acquisition system varies the input voltage over a range

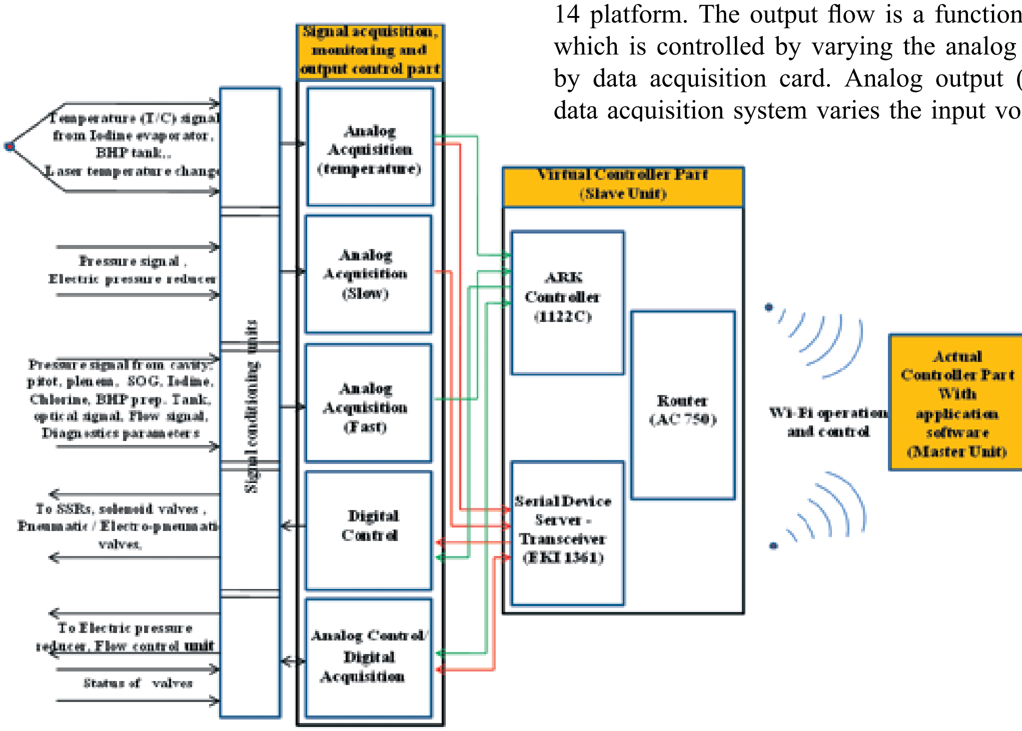

Figure 1. Block diagram of developed hybrid data acquisition flow control system.

of 0–10 V for Electrical pressure reducer (EPR-ITV 3000 series) to achieve line pressure control. EPR also provides 0-10 V output to the Hybrid DAS (Analog Input, AI) for status/analysis of system performance. EPR are used in conjunction with a filter to protect from foreign particle ingress.

The actuator solenoid valves (SV, M/s SMC Pneumatics Make, VXZ 2000 series) are responsible for controlled supply of gas. The solenoid valves are operated in a certain pre-defined sequence with a digital output (DO) from Hybrid DAS through USB 4716 (16-bit multifunction module) and ADAM 4069. A feedback signal (Digital Input, DI) showing SV status (on/off) is obtained in form of digital input (DI) from solenoid valveusing ADAM 4051.

ADAM 4069 is a power relay digital output module (with Modbus protocol) having current driving capability upto 5A per relay capable of directly driving 24 V, 500 mA solenoid valves without using an extra circuitry. All the data communication from the Hybrid DAS cards occurs via master controller. Similar hybrid data acquisition flow control scheme has also been utilised for chlorine supply system keeping in mind the required safety demands.

In the present system the overall COIL laser gas flow rate is 70 gs^{-1}, which requires precise and uniform flow of primary and secondary nitrogen, chlorine ensured by appropriate application of upstream pressure. The scheme and developed hardware of gas feed control are shown in Figs. 2 and 3, respectively. Overall errors in pressure, temperature, EPR, flow sensors are ±0.32%, ±0.59%, ±0.37% and ±0.59% respectively based upon root sum squares of errors of sensors, signal conditioner ADAM 3014, USB 4716/ADAM 4118, processing error and reliability (for 95%).

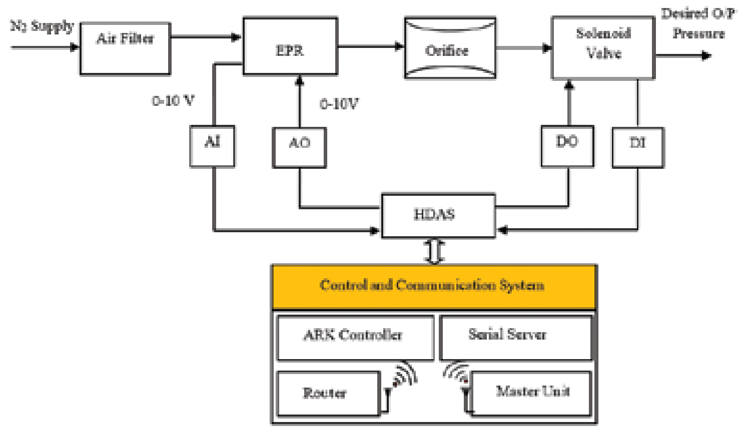

Figure 2. Gas feed flow control HDAS scheme.

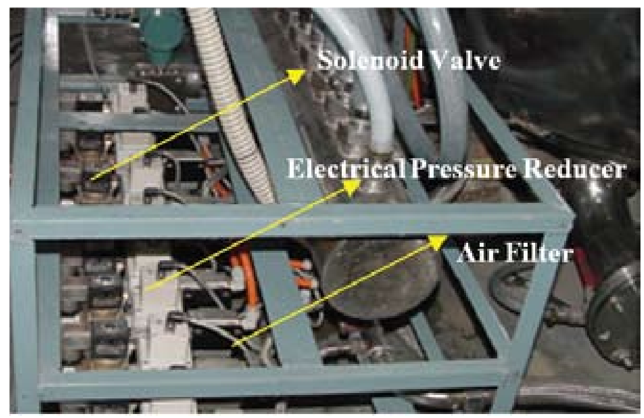

Figure 3. Gas feed flow control hardware.

3. APPLICATION SOFTWARE PROGRAM

An application software program has been written using LabVIEW 2014 platform which makes the software more flexible and can incorporate additional channels on requirement. Ramp VI pattern is used for generating ramping pressure signal for gradual application in order to achieve uniform flowing gases flow control. Analog output channel of USB-4716 is used for ramp O/P. In this, a special provision for providing either ramp o/p signal or fixed signal is incorporated. All ramp data array is also available in graphical form. Figure 4 shows developed application software for providing ramping pressure signal.

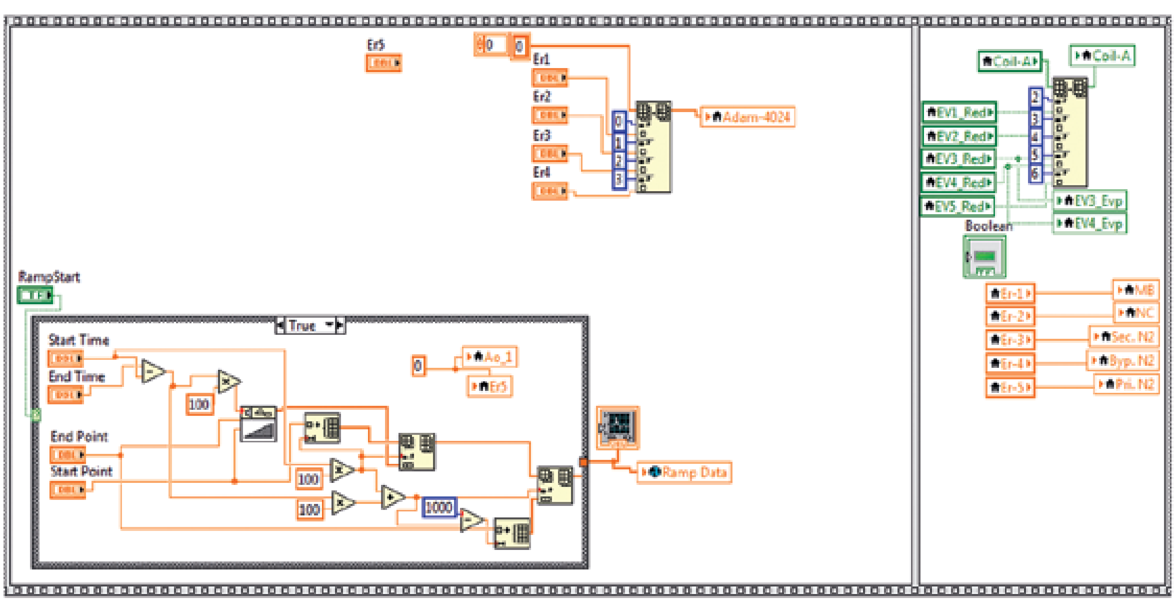

Figure 4. Developed application program for ramp pressure.

3.1 Graphical User Interface Windows

Eight graphical user interface (GUI) windows have been developed for monitoring and recording of online temporal parametric variations. GUI 'RED' has been programmed for setting different N_2 feed pressures (either in fixed or ramp manner) and is shown in Fig. 5. During COIL operation, primary nitrogen pressure is supplied from 7 bar to 4.4 bar in ramp pattern over a time period of 2.4 s to 6 s. This signal is calibrated online using another GUI 'CALIBRATION' for online display in pressure format (Fig. 6).

4. RESULTS AND DISCUSSION

The developed real time flow low control HDAS scheme has been validated by employing it to provide gas feed based on ramp pattern VI to operate COIL source. Several experiments have been carried out to evaluate that uniform gas flow and stabilised pressure conditions are obtained in the laser system.

Equation (1) represents the relation governing the gas flow rate variation under choked flow operation of the orifice applicable for all gas constituents (primary N_2, secondary N_2, Cl_2)[16-17],

$$\dot{m} = \sqrt{\gamma/R}\left\{P_0 A/T_0\right\} C_d \left[2/\gamma+1\right]^{\gamma+1/2(\gamma-1)} \tag{1}$$

wherein, $\dot{m}$ is the mass flow rate of gases, γ is the gas specific heat ratio, P_0 and T_0 are stagnation pressure and stagnation temperature respectively, C_d is the discharge coefficient (0.93), A is the orifice area and R is characteristic gas constant.

Relative uncertainty in primary N_2 flow gas feed is obtained as Eqn (2) by taking partial differentiation of Eqn (1), and evaluated as 0.7%.

$$\frac{u_{\dot{m}}}{\dot{m}} = \sqrt{\left(\frac{u_{P0}}{P_0}\right)^2 + \left(\frac{u_A}{A}\right)^2 + \frac{1}{4}\left(\frac{u_{T0}}{T_0}\right)^2} \tag{2}$$

All the signal communication to operate various solenoid valves/EPRs are performed wirelessly via the master controller (display and control device). Although, ramp pattern VI based gas feed supply system has been utilised for chemical oxygen iodine laser, it may also be used for operating other flowing medium lasers including diode pumped alkali laser (DPAL), CO_2 reagent based gas dynamic laser (GDL), Hydrogen/ Deuterium Fluoride (HF/DF) during laser generation process.

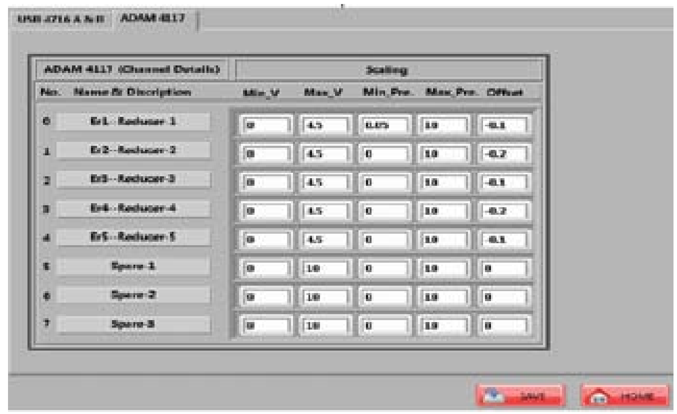

Figure 6.Calibration GUI.

4.1 Online Pressure Variations in Nitrogen Flow Without and with Ramping Pattern

Gas flow with uniform and stable pressure is supplied with the use of ramp based flow control system and measured at various subsystems locations like SOG, cavity, Pitot and plenum. The supply pressures of diluents nitrogen and chlorine are extremely crucial for optimal performance of laser source. All the parametric variations in N_2 are recorded online during laser operation using Hybrid DAS system with/ without ramping pattern in the GUI 'GRAPH'. Figures 7 and 8 shows the various pressure variations in nitrogen gas acquired online at different locations in the laser source flow tunnel without and with ramping pattern respectively.

4.2 Effects on Singlet Oxygen Stabilisation Time

One of the most noticeable aspects observable in Fig. 7 is that stabilisation time of singlet oxygen generator (SOG) pressure is quite large (around 9 seconds). This is a substantially a long time in the context of short duration operation of high-power COIL laser system.

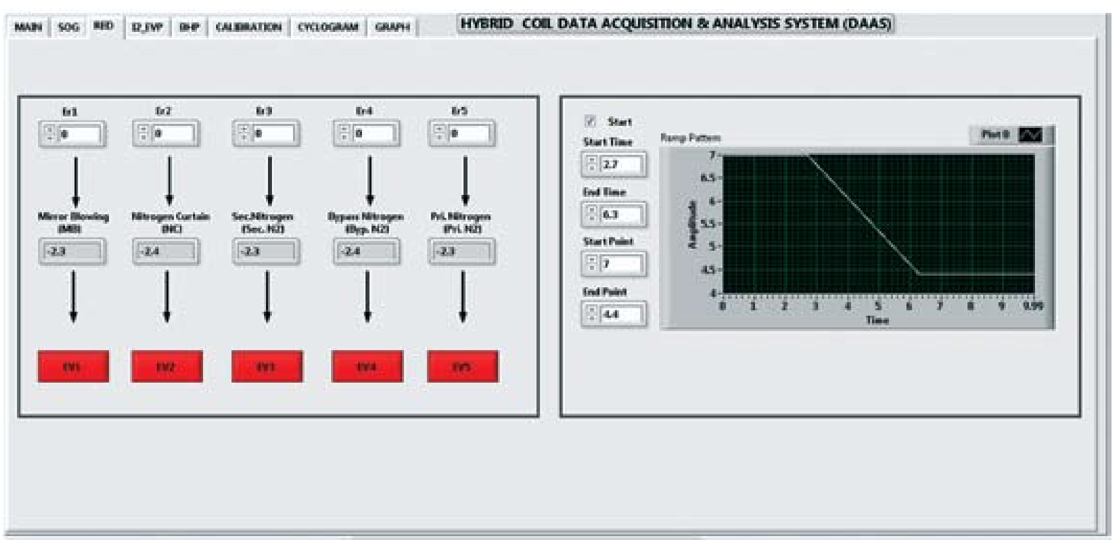

Figure 5. Gas feed GUI.

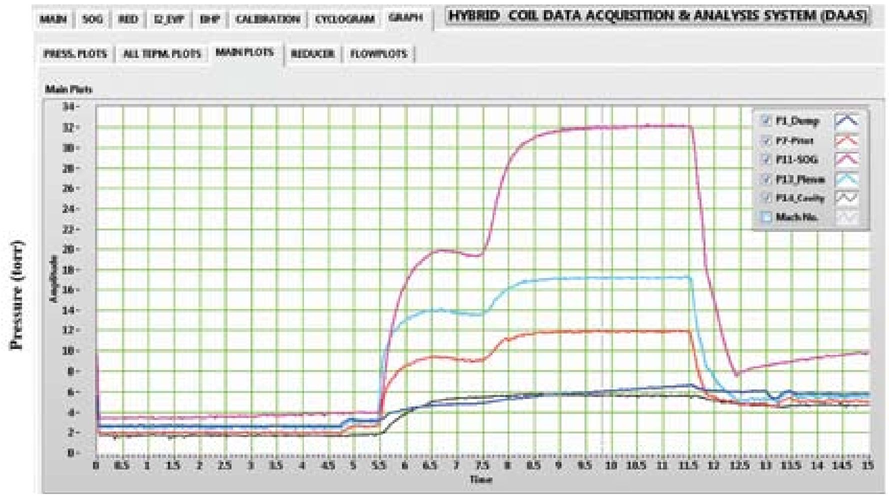

Figure 7. Temporal pressure variations in diluent N_2 without ramping pattern using HDAS.

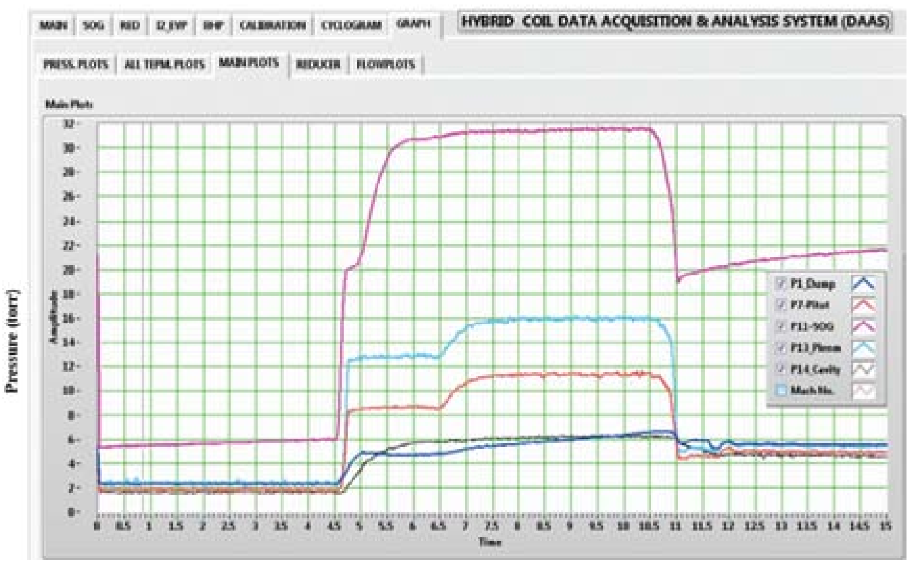

Figure 8. Temporal pressure variations in diluent N_2 with ramping pattern using HDAS.

On the other hand, pressure variation plot shown in Fig. 8 depicts SOG pressure with reduced stabilisation time (around 6 seconds) achieved by using developed flow control Hybrid DAS with supply of diluent N_2 in a ramp pattern.

It is apparent from the two plots that the swift SOG pressure stabilisation is on account of using ramp pattern VI of LabVIEW 2014 platform. The same is corroborated by the corresponding molar flow plots of diluent (under 'GRAPH' GUI), refer Figs. 9 and 10 for diluent N_2 stabilisation without and with ramp respectively. Figure 10 shows real time acquisition and monitoring of diluents nitrogen ramp by gradual application from 2.7 s to 6.3 s using Hybrid DAS system as compared to the flow in Fig. 9.

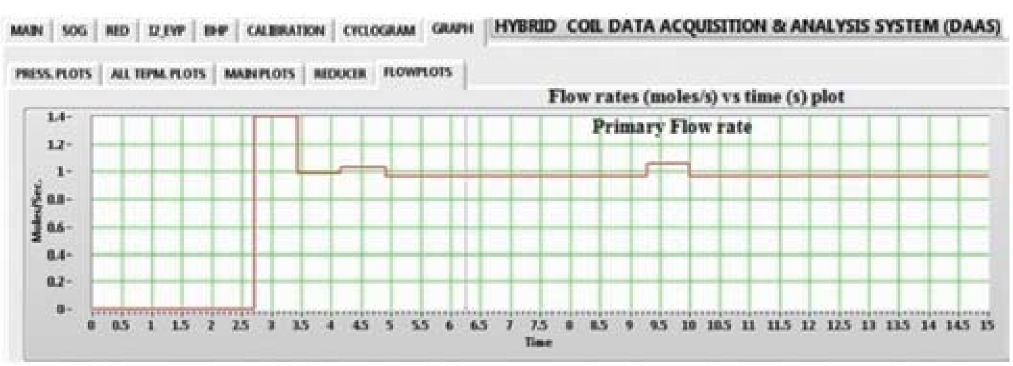

Figure 9. Temporal flow rate variations in diluent N_2 without Ramp using HDAS under "GRAPH"GUI.

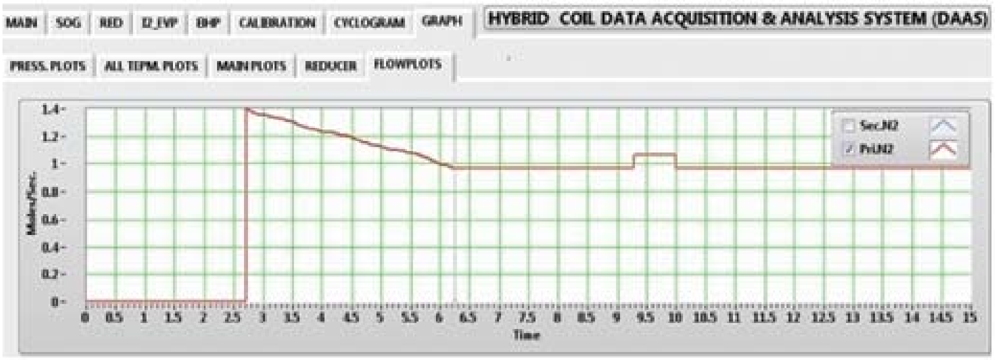

Figure 10. Temporal flow rate variations in diluent N_2 with Ramp using HDAS under "GRAPH"GUI.

5. CONCLUSIONS

A compact real time flow control Hybrid DAS system based upon Wi-Fi interface with controlled supply of input pressures using Ramp Pattern VI of LabVIEW 2014 platform has been developed and successfully tested for its efficacy with flexible software program. Both reduced singlet oxygen stabilisation time and stable COIL operation have been achieved by using developed hybrid data acquisition system (HDAS). A precise, controlled and uniform flow of gas constituents is achieved in the range of mmole.s^{-1} to few hundred mmole.s^{-1} with relative uncertainty of 0.7% in primary flow. Master controller performs all the sequence actuations of different solenoid/electro-pneumatic valves and monitoring and acquisition of various parameters by commanding the virtual controller from a remote distance of around 35 m with obstacles and at 80 m line of sight. Remote operation is an additional advantage of compact Hybrid DAS system over wired data acquisition systems for the safe operation of high power flowing medium COIL laser. This provides benefits in form of compactness and remote operation in an on-field scenario. The concept is easily extendable to other flowing medium lasers such as diode pumped alkali laser (DPAL), CO_2 reagent based gas dynamic laser (GDL), Hydrogen/ Deuterium Fluoride (HF/DF) and liquid laser.

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In the current study, he has carried out LabVIEW based software and Graphical User Interface windows (GUI) development suitable for laser experiments and written/prepared the manuscript.

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In the current study, he has carried out for complete design and development scheme.

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In the current study, he has carried out the entire sensor selection for acquisition of parameters during laser operation and optimisation through various experiments.