Gas Fuelling System for SST-1 Tokamak

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Abstract. SST-1 Tokamak, the first Indian Steady-state Superconducting experimental device is at present under operation in the Institute for Plasma Research. For plasma break down & initiation, piezoelectric valve based gas feed system is implemented as a primary requirement due to its precise control, easy handling, low construction and maintenance cost and its flexibility in the selection of the working gas. Hydrogen gas feeding with piezoelectric valve is used in the SST-1 plasma experiments. The piezoelectric valves used in SST-1 are remotely driven by a PXI based platform and are calibrated before each SST-1 plasma operation with precise control. This paper will present the technical development and the results of the gas fuelling system of SST-1.

1. Introduction

Magnetic fusion devices require fast-responding, versatile and accurate gas injection system in order to initiate the plasma breakdown and subsequently to maintain and control the plasma density. A number of techniques like external gas feed, neutral beam injection, pellet injection and their combinations are employed in fusion devices to maintain the plasma density at desired levels for long periods. Main functions of the gas fuelling system are (a) pre-filling of the vessel to the required pressure, (b) feeding of required amount of gas during plasma current and density build up phase, (c) feeding of required amount of gas to maintain plasma density at the desired value, (d) feeding of gases into the vessel during wall conditioning and (e) feeding of required amount of gases in the divertor region to remove the heat and exhausted particles. For all these operations, a very efficient gas fuelling system is essential and therefore developments of effective fuelling methods has been one of the key issues in the plasma study. Hydrogen gas feed, Supersonic molecular beam injection and pellet injection are the techniques implemented for the SST-1 tokamak.

The steady-state superconducting tokamak (SST-1) has a minor radius of 0.2 m and a major radius of 1.1 m and was designed for a steady state plasma operation of 1000 s with both single null and double null configuration[1,2]. Commissioning of SST-1 was completed in 2013 and the machine was under operation for initial plasma break down up to 100 kA limiter-assisted circular plasma for more than 100 ms using hydrogen gas. Graphite plasma facing components were installed inside the vessel in mid 2015 and a maximum plasma current of 110 kA forms has been achieved with a toroidal field of 1.5 T using ohmic transformer (OT) and ECRH system of 250 kW & 42.6 GHz. A pair of vertical field coils provides equilibrium during this phase. The vacuum system of SST-1 comprises of an ultra-high vacuum vessel (VV) and a high vacuum cryostat. SST-1 VV is fabricated from SS 304L material in torus D-shaped form. It has 16 rectangular radial ports (RPs), 16 triangular top vertical ports, 16 triangular bottom vertical ports, 16 interconnecting rings and 16 vessel sector rings. It has two radial pumping lines connected to turbo-molecular (TMP) pumping stations with a total effective pumping peed of 4675 l/s (N₂ gas) [4]. The total pressure is monitored in the vessel radial port as well as in the...
pumping lines using a hot cathode ionization gauge. The vacuum vessel and plasma facing components are baked at 150 °C and 250 °C respectively using hot nitrogen gas heating & supply system [4]. DC and RF assisted glow discharge cleaning using H₂/He gas and their mixture was carried out both before and in between plasma shots. For this purpose, two rectangular SS electrodes mounted at diagonally opposite ports and two power supplies each having a rating of 0-1000 V, 0-15 A and an RF supply of 300 W at 13.56 MHz were used. Few of the SST-1 machine as well as operating parameters are given in Table 1.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Major radius               | 1.1 m                  |
| Minor radius               | 0.2 m                  |
| Toroidal field             | 3.0 T                  |
| Plasma current             | 220 kA                 |
| Plasma species             | Hydrogen               |
| Pulse length               | 1000 s                 |
| Configuration              | Double null            |
| Vessel base pressure       | <5.0 × 10⁸ mbar        |
| Effective pumping speed (Hydrogen) | 6500 l/s |

2. SST-1 Gas Fuelling System

Three types of fuelling systems have been installed on SST-1 vacuum vessel such as (a) Supersonic molecular beam injection system (SMBI) (b) Pellet injection system (PI) and (c) Fast gas injection system (FGI). A schematic of the SST-1 tokamak with the pumping lines and the injection points of these three fuelling systems are shown in figure 1.

2.1. Supersonic Molecular Beam Injection system (SMBI)

The SMBI was designed for feedback based density control. Main advantage is that the neutrals are fed at supersonic velocity and therefore have higher probability of penetrating into the core as compared to ordinary gas puffing. Two (02) numbers of M/s Parker make solenoid valves have been installed on the high field side at radial port nos. R-7 & R-10. An inlet pressure of 10 bar(g) was maintained at the valve inlet and a rectangular voltage pulse of 20 VDC with varying time duration was applied to feed the desired number of neutrals into the plasma chamber. Each of these two valves has a molecular injection rate of 2.8 × 10²² H-atoms/s.

2.2. Pellet Injection System (PI)

A single barrel hydrogen pellet injection system has been recently integrated with SST-1 vessel which is capable of producing pellets of 1.6 mm length having 1.8 mm diameter with a velocity in the range of 700 to 900 m/s. This injector is an in-situ gun type injector, in which, a solid hydrogen pellet is formed and accelerated to high speed using high pressure propellant gas.

2.3. Fast Gas Injection Fuelling system (FGI)

Out of the three fuelling systems installed on SST-1 vessel, only the fast gas injection method has been used extensively in SST-1 plasma campaigns. The objective of fast gas injection system is to feed the desired amount of hydrogen gas during pre-filling and density build-up phase during the plasma operation as well as to feed fuel gas during the wall conditioning, Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Resonance Heating (ICRH) assisted plasma shots. The key element of this
system is piezoelectric valve which was chosen due to its fast response time of ~ 2.0 ms, capability to work in the presence of magnetic field, low cost and reliable performance.

![Figure 1. Schematic of the SST-1 tokamak showing the pumping and fuel injection locations.](image)

This valve has a maximum throughput of 625 sccm at 100 V, 25 °C and 1.0 bar(g) inlet pressure. The throughput of this piezo valve is linear with respect to its inlet pressure and has a capacity to withstand a maximum inlet pressure of 3 bar(g). FGI system consists of reliable hardware and software necessary to control and monitor the flow of gases required for the plasma experiments remotely from the control room. Four (04) numbers of M/s. Maxtek make MV-112 piezo valves (02 nos. on the high field and 02 nos. on the low field side) are used to feed gas into SST-1 vessel during pre-filling. Another two (02) numbers of valves were used during the density build-up phase. These valves were mounted in radial ports diagonally opposite to each other to maintain the overall balance of gas distribution inside the vessel. In addition, two (02) more numbers of valves were mounted on either side of LHCD antenna and one (01) number of valves near ICRH antenna to feed the desired amount of neutrals during LHCD and ICRH assisted plasma shots. For Glow discharge cleaning (GDC) and boronization experiments, two (02) numbers of valves were mounted at diagonally opposite radial ports R-3 and R-11.

Research grade ultra-high pure hydrogen, helium and their mixtures were used in SST-1 plasma experiments. A palladium based hydrogen purifier was connected in hydrogen inlet line which provides 99.99995% pure hydrogen gas at its outlet. Since the variation in inlet pressure to the valve
changes its flow rate, this ultra-high pure gas was stored in buffer chamber and then fed into the vessel. The buffer chamber was maintained at 2.0 bar(g) with closed loop feedback system. A schematic of closed loop feedback control for auto refilling of the reservoir is shown in figure 2.

![Schematic diagram of closed loop feedback control for auto refilling the gas reservoir.](image)

**Figure 2.** Schematic of closed loop feedback control for auto refilling the gas reservoir.

The entire gas feed line was fabricated using Swagelok connectors and electro-polished SS pipes. The entire piping and the connectors were leak tested in sniffer mode at 3.5 bar(g) helium pressure for the leak tightness at a background of $1.0 \times 10^{-6}$ mbar l/s. A square voltage pulse of 100 VDC with different time duration was applied to the piezo-valves for gas puffing. All these piezoelectric valves were electrically isolated both from high-pressure side and low-pressure side using isolators to avoid the grounding interference which may changes the applied signal. The Piezoelectric valves were operated according to the requirement of the different gas puffing modes such as: (1) Pulsed flow through software, (2) Continuous flow at constant pressure and (3) Pulsed flow using density feedback.

3. Results and analysis

3.1. Calibration of the fuelling system

Four numbers of piezo valves were used for prefilling the vessel from $7.0 \times 10^{-6}$ mbar to $3.0 \times 10^{-5}$ mbar for plasma discharge operation. During operation, the total amount of gas puffed into the vessel was varied from phase to phase by varying the amplitude and time duration of applied DC voltage to the piezo valve. The injection rate of $1.92 \times 10^{21}$ H-atoms/sec was estimated when four numbers of the piezo valves were used. With an inlet pressure of 2.0 bar(g) when a pulse of 100 VDC and a width of 7 ms was applied to the piezovalve, an estimated $1.3 \times 10^{19}$ H-atoms were injected inside the chamber. This was experimentally verified by the pressure-rise method. The pressure vs. time plot acquired is shown in figure 3. From the plot the number of hydrogen atoms injected into the vessel is found to be $1.0 \times 10^{20}$. This difference may be due to the inaccuracy in the total pressure measurement and also due to the difference in the inlet pressures.

3.2. Effect of reservoir pressure

The effect of reservoir pressure on piezo valve characteristics was studied for the reservoir pressure range varying from 0.5 bar(g) to 2.5 bar(g). The maximum vessel pressure achieved for a 7 ms pulse width is shown in table 2. It is observed that a change of 25 % in the reservoir pressure results in 10-20 % change in the injected gas molecules.
Figure 3. Pressure-time plot for 7 ms and 20 ms pulse width.

Table 2. Effect of reservoir pressure on piezo valve characteristics.

|Tank Pressure (bar-g) | Peak Vessel Pressure (mbar) |
|----------------------|-----------------------------|
| 0.5                  | $6.5 \times 10^6$           |
| 1.0                  | $7.5 \times 10^6$           |
| 1.5                  | $9.2 \times 10^6$           |
| 2.0                  | $1.0 \times 10^5$           |
| 2.5                  | $1.1 \times 10^5$           |

3.3. Gas puff with and without plasma shot
A screenshot of the vessel pressure is shown for a pulse width of 7 ms in the presence and absence of plasma shot in figure 4.

Figure 4. Pressure-time plot for 7 ms (a) During plasma shot (b) Without plasma shot.
4. Conclusion
From SST-1 campaigns, it is observed that the amount of gas injected through piezo valve plays an important role in achieving a repetitive plasma shots. Also experimental measurements show that a change of 25% in the reservoir pressure results in 10-20% change in injected gas molecules. In order to reduce such effect, auto refilling of reservoir with closed loop feedback controlled is very important. Experimental measurements validate that the theoretical estimate of the injection rate is more than $\sim 10^{21}$ H-atoms/s.

References
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