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Technical Note

Rapid and massive throughput analysis of a constant volume high-pressure gas injection system

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ABSTRACT

Fusion power shutdown system (FPSS) is a safety system to stop plasma in case of accidents or incidents. The gas injection system for the FPSS presented in this work is designed to research the flow development in a closed system. As the efficiency of the system is a crucial property, plenty of experiments are executed to get optimum parameters. In this system, the flow is driven by the pressure difference between a gas storage tank and a vacuum vessel with a source pressure. The idea is based on a constant volume system without extra source gases to guarantee rapid response and high throughput. Among them, valves and gas species are studied because their properties could influence the velocity of the fluid field. Then source pressures and volumes are emphasized to investigate the volume flow rate of the injection. The source pressure has a considerable effect on the injected volume. From the data, proper parameters are extracted to achieve the best performance of the FPSS. Finally, experimental results are used as a quantitative benchmark for simulations which can add our understanding of the inner gas flow in the pipeline. In generally, there is a good consistency and the obtained correlations will be applied in further study and design for the FPSS.

1. Introduction

The international thermonuclear experimental reactor (ITER) is a fusion reactor, in which the plasma is contained in a doughnut-shaped vacuum vessel. During plasma discharge, the fuel - a mixture of Deuterium and Tritium, is heated to temperatures in excess of 150 million °C. A hot plasma is formed which needs to be removed by cooling water system. In some accidents, such as the cooling water pipe break, the high temperature water would leak out and the cooling capability will become insufficient. Without the termination system for plasma, the heat load will cause melting of components which could produce hydrogen. So the mixed air could create an explosion which will exceed the design limit of the vacuum vessel (VV).

Fusion power shutdown system (FPSS) is a gas injection system which is required to terminate plasma in accidental events. Two FPSS facilities can be executed in parallel. The simplest structure of this system consists of a reservoir of gas and a dedicated tube for gas injection. As a safety device, quite a few special apparatus require gas injection systems to inject high throughput gas in short times without air supply. For example, Tokamak is injected ~4×10^{22} particles (atoms or molecules) within 2–5 ms to provide adequate gas to mitigate the disruption-caused damage. An injector should provide the plasma with larger amounts of neon to radiate most of the thermal energy, and force the current decay time to within a 50–150 ms interval [1]. Theoretically, components of the system (such as valves, pipes, etc.) and process parameters (such as flow rate, pressure difference, etc.) have great influence on the injection system [2]. Therefore, it is necessary to investigate the performance of the flow field influenced by components and operation processes [3].

In fact, continuous gas supply can achieve fast response and high gas injection. Xiuquan Cao used a mass flow controller (maximum flow rate 25 l/min) to control the working gas supplied to the plasma with an accurate and high gas flow rate [4]. S. C. Bates obtained up to 500 Torr liter/s for hydrogen from a fast valve with 3 ms [5]. Min Jae Kim conducted a high mass flow rate gas inlet of 89.36 kg/s to guarantee high output to the air storage system [6]. In the work of Toufik Boushaki, using a constant flow rate for all

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experiments to ensure high velocity and high quantity introduced gas [7]. This gas supply needs extra source gases and tubes which could increase the response time of the injection system.

Application characteristics of all components used in the injection system had been discussed. Ki-Yong Choi used a quick opening valve which was triggered within 0.5 s to simulate a direct vessel injection line [8]. When the sheath gas was injected through the normal nozzle, the flow rate is higher than that of the other nozzles [9]. The time of injection and the time between successive injections could be controlled by a pressure regulation valve because the pressure of injection was manually controlled with it [10]. Eddy current actuated valve could be performed to inject massive gas to plasma in 1–2 ms [11]. From Keith H. Burrell, the sub-millimeter diameter tubing and piezoelectric gas puff valves were used in the system to obtain a fast response time [12–15]. Nevertheless, all these factors can decide the property of the system and they affect mutually. Thus studying a factor solely cannot reflect the total phenomenon of the FPSS, such as velocity, density, response time, etc.

In this work, we present a gas injection system to satisfy the FPSS requirements. All the factors are considered according to the actual application for ITER, including constant volume system, rapid response time, high pressure difference, high throughput and big flow resistance. Then simulation models are analyzed to verify the reliability of the experiment and numerical data can assist to account for the internal flow filed in this system. All the data of this work are to experimentally observe the specific phenomena of the system without gas supply. And these results can be used for further studies and designs of the FPSS.

2. Experiments

Based on the massive gas injection concept and the plasma shutdown time, the FPSS could inject gas over a minimal volume of 3000 Pa.m^3 with a limited time of 3 s. A tradeoff exists between time response, source pressure, source volume and injected volume. Details of the experimental apparatus and procedure have been published detailedly here.

2.1. Experimental apparatus and procedure

Fig. 1 depicts the schematic of experimental apparatus. The system has some major components: gas storage tank, flow pipe, vacuum vessel, valve, pressure transducer and vacuum pump. Through the closed pipe circuit, the upstream has being controlled by valves and monitored by manometers. During the process, after the valve is open, the gas flows from the tank to the vessel through the long pipe. Then the vessel pressure could be obtained to deduce the injected gas while the valve is closed at 3 s.

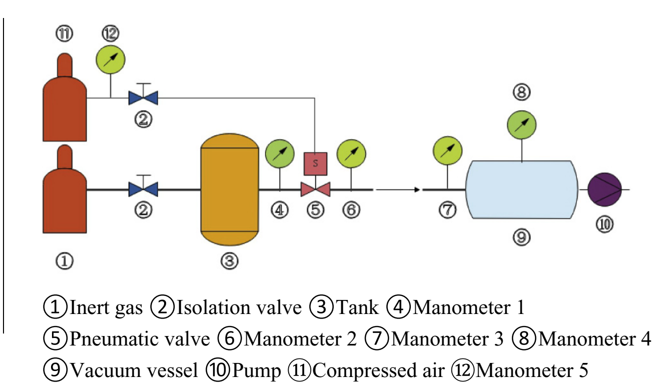

Fig. 1. Diagram of the gas injection system.

The model of the gas pipe shown in this manuscript was designed at a one-to-one scale of ITER. The pipe has length, L, of 23.4 m and inner diameter, D, of 0.01022 m. The valve is installed in the outlet of the tank. Manometers (MKS Inc. USA) are separately located at some positions for the purposes of valve feedback control and injected volume judgment. Among them, one is fitted on the vessel to monitor its pressure, one is fixed at the inlet of the vessel to determine the arrival time of the gas flow, and others are mounted on the inlet and outlet of the valve near the gas supply to gather source pressures. The reading accuracy of all the above manometers is 0.5%. The vacuum vessel has volume, V_V, of 4.5 m^3. A 0.2 m^3/s roots pump is used to evacuate the vacuum vessel pressure, P_V, of 0.01 Pa. In the experiment, the vacuum chamber keeps the vacuum at the initial time and the vacuum pump does not work during the gas injection process. All the components are made of stainless steel and the experimental model can be remotely controlled and calibrated.

2.2. Response times

The flow rate adjusts itself to give a pressure drop equaled to differences between entrance and exit pressures. The response time for flow is a function of average flow velocity, density, viscosity, pressure and pipe length, diameter and other accessories. Nevertheless, the structure of the long pipe is irregular as it is limited by the practical installation condition. The length range of each segment is from 51 mm to 3676 mm, and the angle range of each bend is from 46° to 175°. There are 26 bends, and all the bending radius are 40 mm. Those dramatic changes in structure can yield choked flow due to the friction effects (Fig. 2). So there is a stable response time of the pipe which cannot be modified artificially. Except this qualification, response times varied with valves, gases, volumes and pressures could be developed.

2.2.1. Fast-acting valve response times

In this gas injection system, a controlled explosion creates a brief flow from a gas storage tank with data taken by fast-response valves. The whole period of the transient flow considered in the study is unknown. Generally, response times of valves are somewhat dependent upon the particular manufacturer's design. However, the specific opening and closure times, especially for valves driven by pneumatic actuators, must be pre-confirmed. The pneumatic valve chosen for this application are VAT all-metal angle valve and Swagelok series 1 valve [16,17]. Table 1 lists the specifications of them.

In the test method, the computer sends a command to open the valve, meanwhile, it sends out a trigger pulse to the oscilloscope. Then the pressure graphics can be amplified and read out on the oscilloscope. According to the pressure sensor signal, the response time of the valve in this experiment can be assured. The electronic developed to control the pneumatic actuator applies a maximum voltage of 24 V at the onset of demand. This voltage opens the valve

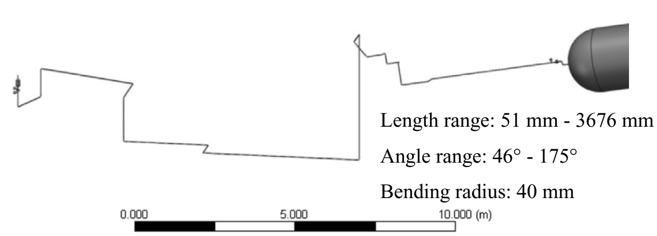

Fig. 2. Layout of the pipeline.

Table 1
Specifications of two valves.

Characteristics		VAT angle valve	Swagelok series 1
Inner Diameter (mm)		10	7.6
Control Pressure (MPa)		0.6–0.8	0.5–0.7
Overpressure (MPa)		0.6–0.9	0.3–1.03
Feedback Voltage (V)	Closure	0	6
	Opening	6	0

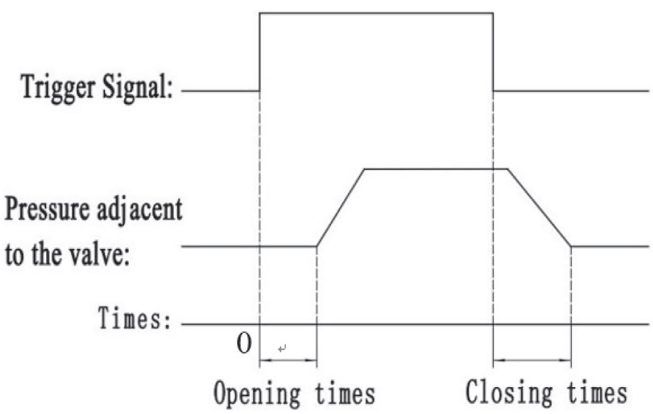

Fig. 3. The trigger signal.

actuator in the shortest time. Under certain conditions, oscillations are observed when the valve is opened and we studied the rise and fall times of the flow.

Three different processes consist the pressure curve (Fig. 3). The first process is the initial stage of constant acceleration, wherein the compressed air propagates from the electromagnetic device. Then the pneumatic valve is opened by the actuator, so the pressure increases under the initial high pressures difference. The second process is the subsequent stage of constant pressure, wherein the gas flows from the tank into the pipe through the pneumatic valve. The pressure maintains stably since the flow field reaches dynamic equilibrium. The final stage is the closing process of constant deceleration, wherein the electromagnetic device outputs low voltage to stop the control pressure until the pneumatic valve is closed. The pressure immediately decreases because of the terminated gas source.

As shown in Fig. 4 (a), the feedback voltage is received from the pneumatic valve. The response of Swagelok valve is faster than that of VAT valve and specific parameters can be obtained from Fig. 4 (b). The minimal response time of the VAT is about 140 ms, but the maximal response time of the Swagelok valve is only 60 ms. So the Swagelok valve is the optimum selection for this work.

The compressed air is used to open the pneumatic valve. The amount of gas consumed when the actuator is working can be confirmed as [18].

$$Q = V \times 10^3 \times [(P + 0.1033)/0.1033] \tag{1.1}$$

Where Q is the consumed gas amount, V is the volume of the actuator, P is the control pressure.

To a pneumatic valve, its volume of the actuator is specified. When the control pressure is larger, the consumed gas can quickly reach the required amount. Additional experiments are desirable to further understand this relationship. The control pressure is monitored at the interface between the compressed air and the actuator. For very small control pressure difference, however, the forward gain is not enough to provide the maximum dynamic. So the valve takes a little longer time to open (about a few milliseconds). From experiments, the fast response occurs on the maximal control pressure of 0.7 MPa and a quick response time of 50 ms has been shown (Fig. 5).

2.2.2. *Test gas response time*

In general gas injection systems, the response time of the gas species has always been ignored. But in this paper, this index has to be investigated because it could affect the whole time of the flow circuit.

In stationary isentropic flows and in the absence of external forces, the Bernoulli's theorem can be written as [19].

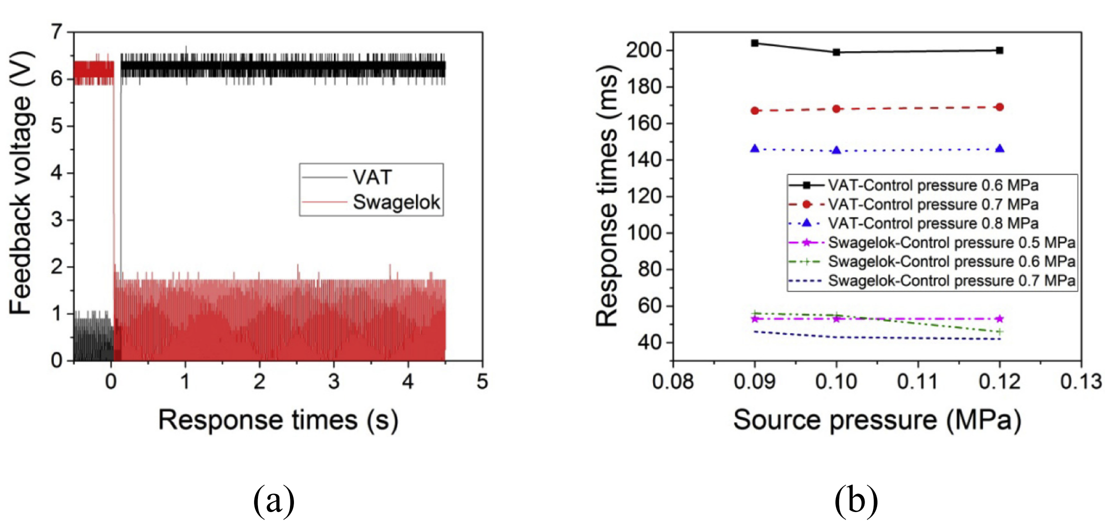

Fig. 4. Valve response times.

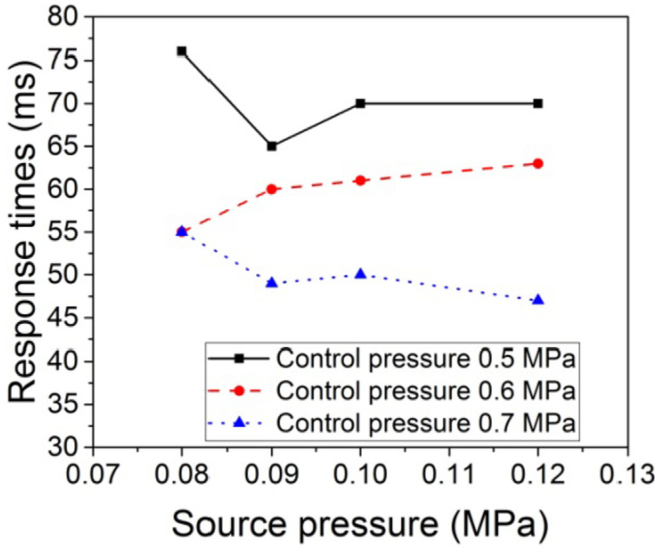

Fig. 5. The response time of the Swagelok valve.

Table 2
Response times of Ne and Ar gases.

Source Pressure (MPa)	Response Times (ms)	
	Ne	Ar
0.2	132	134
0.3	115	120
0.4	111	117
0.5	109	114
0.6	106	112
1	98	110

$$\Delta p = -\frac{\rho \overline{u}^2}{2} + constant \quad (1.2)$$

Where Δp is Pressure drop, ρ is gas density, $\overline{u}$ is mean velocity.

This solution suggests that if the velocity in channel flow with constant pressure gradient increases, the gas density must decrease. Inert gas released from the FPSS is used to prevent fusion reaction and test gases are nitrogen (Ne) and argon (Ar). Among them, the density of the Ne is 0.9002 kg/m^3, and the Ar is 1.7818 kg/m^3. Based on the Bernoulli's theorem, the Ne is appropriate for this system.

Table 2 depicts that the response time of the Ne is always shorter than that of the Ar under different source pressures. This consequence has great agreement with the theory.

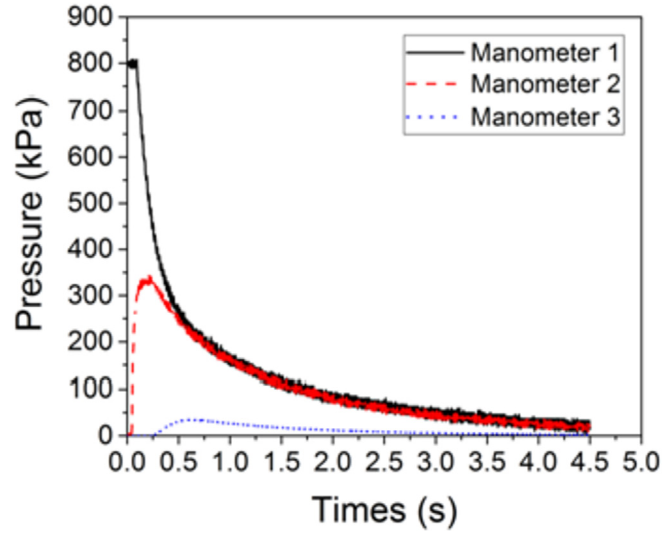

Fig. 7. Experimental data for source pressure.

2.3. Gas injection volumes

2.3.1. Pipe flow equations

Another important index in this study is the injected inert gas of 3000 Pa.m^3 to the vacuum vessel. This volume is deduced by the vessel pressure which is calibrated by a capacitance manometer. Therefore, parameters of the gas source which could decide the throughput must be confirmed, such as the source volume and the pressure.

In the pipe flow, the pressure dropped down the pipe is related to pipe parameters. It can be expressed as

$$\Delta p = \frac{8\eta\overline{u}l}{\alpha^2} \quad (1.3)$$

Where η is coefficient of viscosity, l is tube length and α is tube radius.

The gas expands and accelerates into the vacuum vessel at the end of the pipe. Independent of the fluid state in the tube, the pressure dropped to vacuum is always greater than it in other positions. So the end of the tube acts as a sonic nozzle. The volume flow rate is

$$Q = \frac{\Delta p^* \pi \alpha^4}{8\eta l} \quad (1.4)$$

This equation shows the relation between the volume flow rate and the pressure drop.

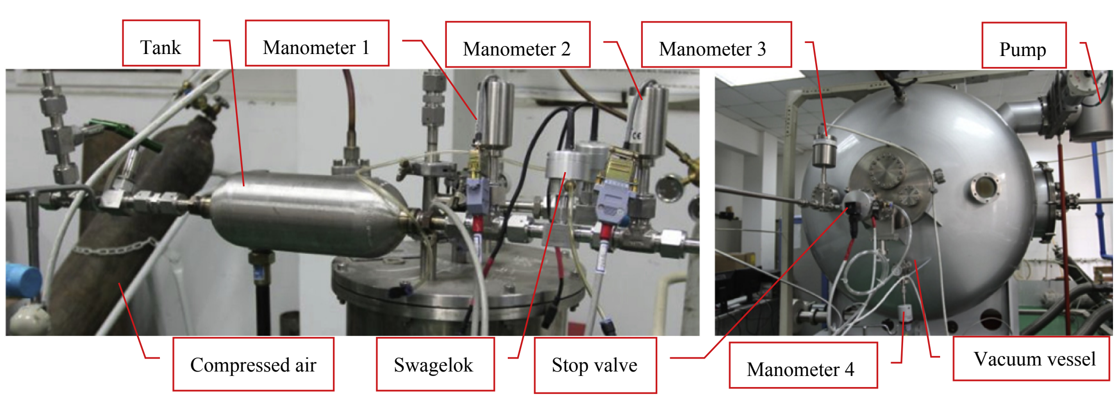

Fig. 6. Experimental layout.

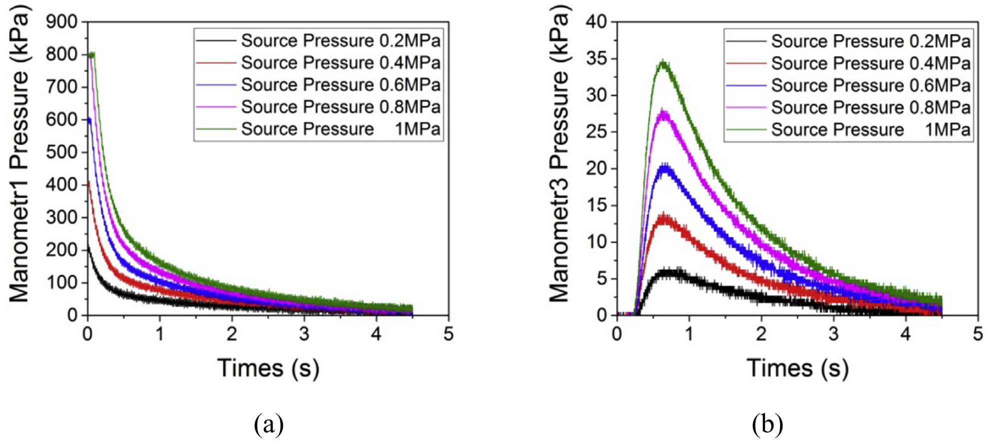

Fig. 8. Experimental data (a) Tank pressures; (b) Pressures at the inlet of the vacuum vessel.

2.3.2. Gas source pressure

To ensure that the gas source is sufficient to produce meaningful injected volumes, the source pressure must be confirmed firstly. In this experiment, the test volume of the gas storage tank is 0.001 m^3, the measured source pressure is increased from 0.1 MPa to 1 MPa, and the Swagelok series 1 valve is chosen (Fig. 6). The stop valve is closed and quickly sealed after the gas is injected into the vacuum vessel in 3s. Two pressure manometers are located on two ends of the valve.

Fig. 7 displays the analog signal showed in the oscilloscope and the pressure change obtained from manometers. After the valve is opened, manometer 1 indicates a decay time of 0.2 s. This time includes the gas flow time and the response time of the valve and the manometer. When the neon gas exits the tank and is excited by the initially high pressure difference, the sudden increase data of the manometer 2 appears.

The data detected from manometer 1 and 3 are shown in Fig. 8 as the flow rate time reaches 3s. The manometer 1 collects tank pressures which decrease rapidly while the valve is opened. Until the pressure reaches about 100 kPa, the descending trend begins to become slow. The reason is that the pressure difference is very small between the tank and the vessel at this time. The manometer 3 gathers the pressure at the end of the pipe (inlet of the vacuum vessel). As the gas flow reaches the vacuum vessel after 0.3 s, the pressure increases largely. After the value reached the peak, the pressure maintains a high level and decelerates slowly. It elucidated that there is still high pressure difference at both ends of the manometer. All the curves above show that the accelerates of the rise velocity and the peak value increases with larger pressure difference.

Following a gas pulse, the total gas efflux is obtained by an independent measurement 4 installed on the vacuum vessel. During 3s, the injection volume of the Ne is significantly larger than that of Ar. The profile represents well the injected volume evolution of the flow in the vacuum vessel (Fig. 9). This figure also reveals that the system can achieve injection volume to 3000 Pa.m^3 with a source pressure of 3.3 MPa. However, this source pressure exceeds the working range of the Swagelok valve, hence a suitable source volume must be insured.

2.3.3. Gas source volume

Five gas source volumes are considered in this work, including 0.001 m^3, 0.002 m^3, 0.004 m^3, 0.006 m^3 and 0.04 m^3. Two Swagelok double-ended cylinders of 0.002 m^3 is connected in series to form a tank of 0.004 m^3, and this is also true for the tank of 0.006 m^3.

Fig. 10 shows results of the injected gas volume in the vacuum vessel. Under the maximal working pressure of the Swagelok

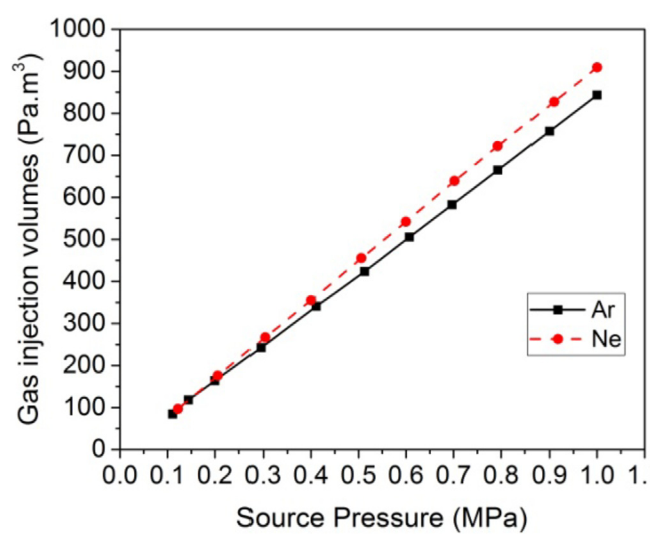

Fig. 9. Injected volume in the vacuum vessel with two gas species.

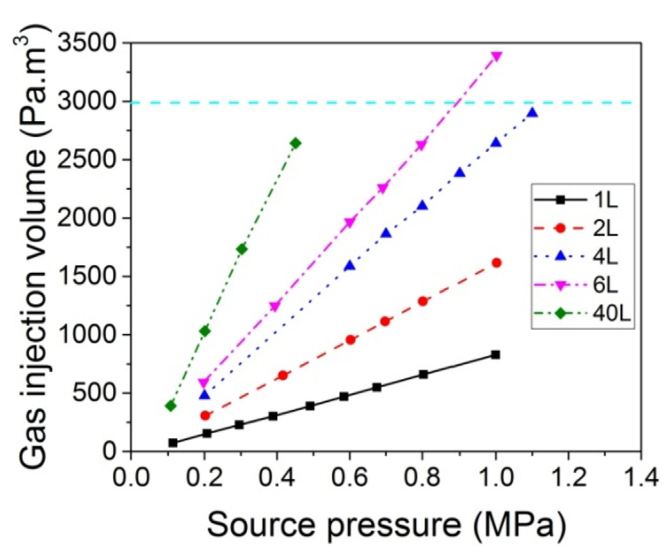

Fig. 10. Injected volume in the vacuum vessel with difference source volume.

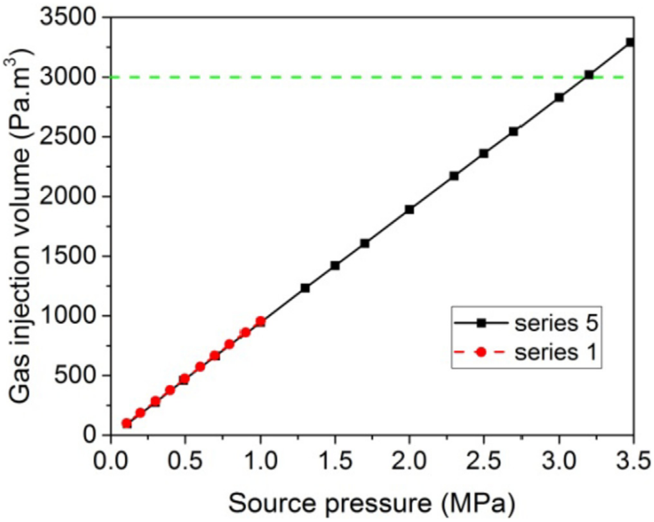

Fig. 11. Injected volume in the vacuum vessel with two Swagelok valves.

Table 3
Optimum parameters for the gas injection system.

Characteristics	Parameters
Pneumatic valve	Swagelok series 5
control pressure	0.7 MPa
Inert gas	Ne
Gas source volume	0.001 m^3
Gas source pressure	3.3 MPa

valve, the source volume must be lager than 0.005 m^3, only then it may inject adquate gas volume. Nevertheless, the inner diameter of the interface between two tanks is much small. This contraction structure could add extra resistance to the flow field, so the system response time may be increased. Meanwhile, the tandem cylinders also ask more installing space, which is not realizable in the FPSS.

Fortunately, another new type of Swagelok valve is provided for the work, which is described as series 5. This kind of the valve has the identical performance with series 1, and its maximal working pressure could reach 6.89 MPa.

Under the source volume of 0.001 m^3, experiments are carried out to ensure the measured data can satisfied the system requirement. Notice that for almost all the data, the injected volume versus pressure relation is basically linear. Fig. 11 presents that under the identical source pressure, two series of valves can inject the same gas volume and the required source pressure is about 3.26 MPa.

Through above experiments, some parameters of best fit in the FPSS are given in Table 3.

3. Simulation verification

We employed CFD (Computational Fluid Dynamics) to demonstrate and understand inner flow phenomenon. The model and boundary conditions are uniform with experimental parameters. In the computational procedure, a segregated implicit solver and second-order upwind scheme are employed. A time-step of $\Delta t = 1 \times 10^{-5}$ s is applied to achieve convergence at each iteration. This convergence of the computed solution is determined based on residuals set at 10^{-3} for the mass conservation and momentum equations [20].

As shown in Fig. 12, all the data have similar tendencies; nevertheless, computational values are less than experiment results. These discrepancies can be due to either inadequate storage or inability to simulate the turbulent flow of irregular geometries.

To generate sufficient injected gas quantity for the vacuum

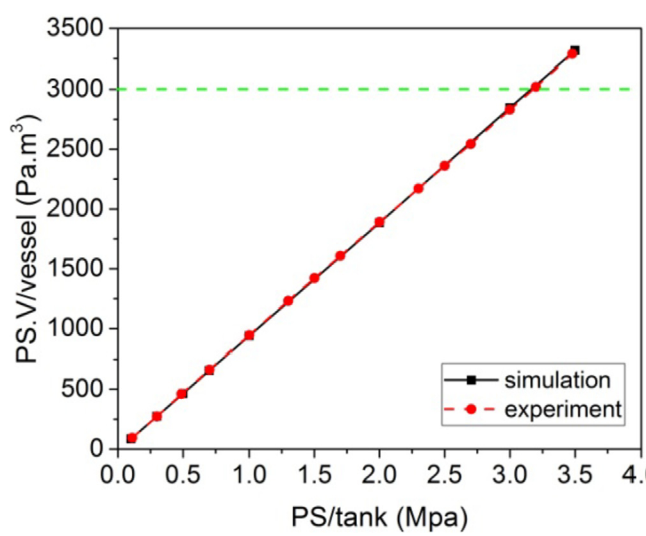

Fig. 13. Relationship between the injected volume and the source pressure.

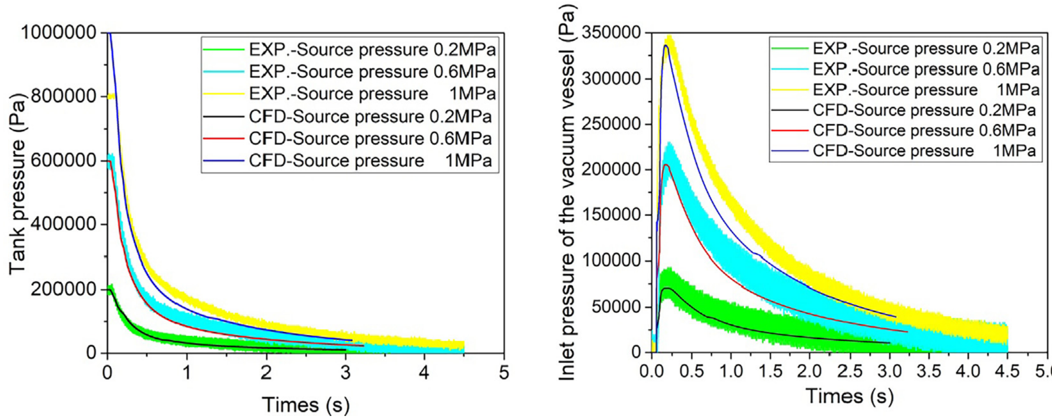

Fig. 12. Comparison on experimental data and simulation results.

vessel, a higher source pressure is needed with 3.12 MPa in Fig. 13. The total gas injection volume obtained through experiments and simulations are compared with each other. A good agreement is found with the both methods.

4. Conclusions

This paper demonstrates a gas injection system for the FPSS which is a constant volume system and has not been supplied extra source gas. Meantime, the pipe length is predetermined and its arrangement is irregular. But this system could satisfy the fast response and high throughput demands. Experimental investigations of the effect of pressure, volume, gas type, tube length, and valve on the requirement have been presented. They are measured in accordance with the design specification for the practical necessary. The resulting data adds our overall understanding of how strong response times, source pressures and volume influence the flow development.

In this study, the neon throughput of up to 3000 Pa.m^3 could be adequate for vacuum vessel to stop the hazard fusion reaction. Through comparisons to simulation investigations, the volume of injected gas is estimated from the pressure difference in the vessel before and after the gas injection. Results show that the source pressure for the gas storage tank must be above 3.3 MPa. Simultaneously, injected gas is linear scale to the source pressure and the simulation also displays a similar tendency. So CFD codes for injection systems are validated and the simulation phenomenon could enhance our understanding of the internal fluid flow in the FPSS.

The device has recently been installed in the practical engineering application of the FPSS and first data has been obtained. Based on this gas injection system, the next step includes studying the components distribution and the structure design of the gas source, the trigger mechanism, the control and monitoring method of the FPSS. Meanwhile, more comprehensive experiments will be performed to verify those researches.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER organization.

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