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New Repetitive Pellet Injectors for Steady State Fuelling

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Abstract

Two new repetitive injectors providing a steady state plasma fuelling by an unlimited number of pellets have been designed for fusion devices. Several thousands of hydrogen pellets of 2 mm diameter each were made and accelerated to 0.8 km/s at the rate of 1 Hz and 2 Hz by an injector equipped with a screw extruder. The extruder had a 5 cm^3 working volume and was used for a continuous extrusion of over 250 cm^3 of solid hydrogen with an average production rate of 65 mm^3/s. Another injector consisted of ten pipe guns with porous units producing solid hydrogen pellets for 5–9 s in every barrel. Over one thousand hydrogen pellets of 2.4 mm diameter were accelerated to 1 km/s in this injector. The injector designs and experimental results are presented.

Keywords:
plasma, fuelling, pellet, injector, extruder, pipe gun

1. Introduction

Future fusion reactors should be equipped with a fuelling system operating in a steady state mode. There are three techniques for plasma fuelling: by gas puffing, by compact toroids and by injection of pellets produced from solidified hydrogen isotopes. A key task of the injection is to develop a reliable pellet injector capable of injecting in a continuous mode an unlimited amount of pellets into a plasma core. Several techniques have been suggested for continuous pellet production. One is an extrusion method using 2–3 extruders operating in a sequence [1] or a 'gas extruder' [2]. Another technique is to freeze the fuel gas onto the periphery of a rotating disk [3]. Recently, two new techniques have been proposed: the use of a screw extruder for a continuous extrusion of solid hydrogen [4] and the application of a porous unit in a pipe gun for pellet production from pre-frozen fuel [5]. To improve the first results, new injectors have been designed which are described below.

2. Pellet Injector Designs

Both injectors are pneumatic guns housed in cryogenic chambers and equipped with pellet formation units and fast valves. A fast valve is a pilot-type electromagnetic valve with an open/close cycle time of about 1 ms and a working volume of 6 cm^3. The gun barrel ends are inserted into diagnostic chambers, equipped with lasers, photodetectors and nanopulse flashes, to measure the pellet speed and to photograph a pellet in flight. Pumping systems provide a vacuum in the cryogenic and diagnostic chambers. The fuel and propellant gases are admitted from standard cylinders with reducers and manometers. The pellet formation units are equipped with thermal sensors.

An injector with a porous formation unit called a 'porous' injector, consists of ten pipe guns placed in two rows, five units in a line. The inner barrel diameters vary from 1.5 mm to 3.8 mm for every pair of barrels. Their length is 420 mm. A pellet formation unit is

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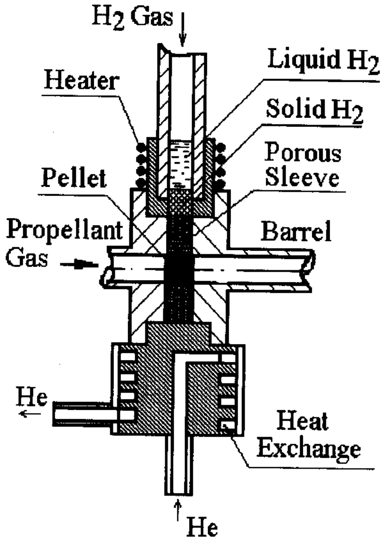

Fig. 1 A schematic diagram of a porous pellet formation unit.

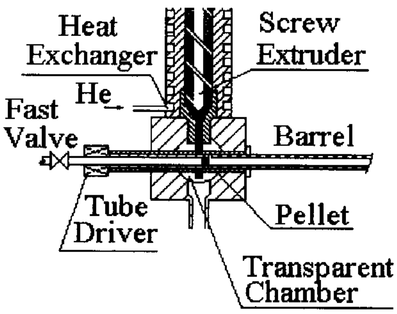

Fig. 2 A schematic diagram of a pellet formation unit with a screw extruder.

made of a copper block with a porous sleeve inside, as shown in Fig. 1. A helium heat exchanger is fixed at the bottom of the block. A heater from a manganine wire is wrapped around the upper part of the block. The porous sleeve (10 mm in diameter and 2–3 mm thick) is made from several copper meshes. The barrel and a tube fitted to the fast valve are brazed to the opposite sides of the copper block. The fuel gas is able to penetrate into the meshes through a hole in the upper part of the unit. The cooling helium vapour is admitted from a dewar vessel through every of ten heat exchangers.

A schematic diagram of the pellet formation unit with a screw extruder is shown in Fig. 2. A transparent chamber is attached to the extruder bottom. A barrel and a tube fitted to the fast valve for propellant gas admission into the barrel are inserted into this chamber from both sides. The tube is equipped with an electromagnetic driver to move it into the barrel. A tube connects the transparent chamber to a vacuum pump. The inner barrel diameter is 2.2 mm and its length is 380 mm. There is a narrow slit (1 mm) between the barrel and an extruder nozzle, whose inner diameter is 2 mm. There are a helium heat exchanger and a 30 W heater mounted along the extruder. The extruder of 150 mm in length is attached by a long (180 mm) tube to the upper flange of the chamber. The screw diameter and pitch are 12 mm.

3. Porous Injector Operation and Test Results

Operating pulses and thermal sensor signals in the porous injector are shown in Fig. 3. The cycle was started up by a pulse from the fast valve. The propellant gas came out of the barrel for 80 ms. The heater was turned on for 0.4 s following the fast valve pulse with a time delay of 10 ms. The porous unit was heated from 9 K to 14 K. The plastic hydrogen in the porous unit was extruded by the hydrogen gas pressure of 2–3 MPa through the pores in the barrel for less than 1 s and was cooled to 9 K there for 3–5 s to form a new pellet. Some of the hydrogen inside the pores was cooled to 12 K for less than 1 s, after which no additional hydrogen could penetrate into the barrel. The porous unit worked as a valve. New portions of continuously admitted hydrogen came into the pores and were frozen there, replenishing the consumption. The propellant and pellet-related gas was pumped, and the injection cycle was repeated. A shot was made by the

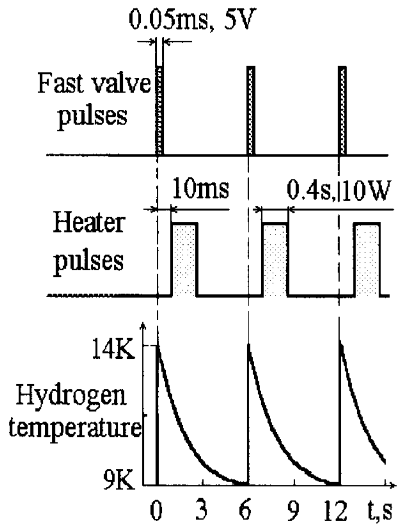

Fig. 3 Operating pulses and temperatures in the porous injector.

Table 1 Series of hydrogen pellets accelerated by injectors with porous and screw extruder formation units.

Parameters	Porous Injector		Injector with a screw extruder
Pellet diameter/length [mm]	2.4 / 4		2 / 2
Propellant gas pressure [MPa] / average speed [m/s]	0.5 / 600 0.6 / 900 0.7 / 1100		0.3 / 600 0.4 / 650 0.5 / 780
Hydrogen pressure [MPa]	2-3	0.1	0.1
Cycle time, [s]	5 6 7	9 11 19	1 1 3
Pellet number	12 25 13	55 26 47	>1000 120 30
Reliability, [%]	92 88 92	60 73 77	- 100 100

fast valve every 6 s. Every barrel is able to inject pellets independent of the others. The minimum duration of a cycle was found to be 5 s. The pellet velocities above 1 km/s were achieved with the initial propellant helium pressure of 7 MPa. Over 100 pellets were formed and accelerated in several series in this mode. Some of the experimental data obtained are presented in Table 1. The injection reliability has been calculated as the ratio of unbroken pellets to all pellets in a series.

If the heater was turned on for 0.8 s, the frozen hydrogen in the pores was melted and liquid hydrogen penetrated into the barrel. This operation mode was stable at hydrogen pressure of 0.1 MPa. The duration of an injection cycle increased to 9 s due to the additional time to cool liquid hydrogen to the melting point and due to the liquid-solid phase transition. Over 1000 pellets were formed and accelerated to 0.8–1.1 km/s in several series in this mode. Some of the data obtained in these series are shown in Table 1.

4. Tests of the Injector with a Screw Extruder

During the testing, the screw rotated continuously in the extruder at 10–20 rpm, pushing out compressed solid hydrogen. An electromagnetic driver moved the tube into the barrel, thereby cutting off a section of the solid hydrogen rod to form a pellet. The fast valve was opened 50 ms after that, and the pellet was accelerated by the propellant gas. The electromagnetic driver was returned to the initial position, and the cycle was repeated.

The most stable extrusion mode was registered at 10–11 K at the rotation rate of 15 rpm and the extrusion speed of 20–25 mm/s. Over 250 cm^3 of transparent hydrogen rod of 2 mm diameter were being extruded continuously for one hour in this mode.

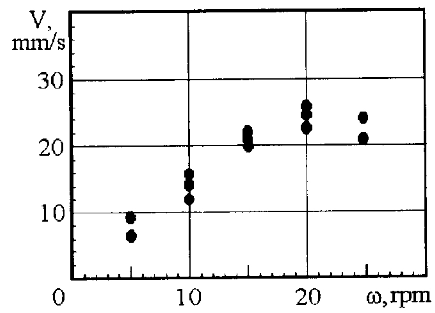

Fig. 4 An extrusion speed V of a solid hydrogen rod versus a screw rotation rate ω at the temperature of 11 K.

Considering the withdrawals, over 25,000 pellets could be produced from this volume. At the same time, less than 5 cm^3 (or 800 pellets) of solid hydrogen was housed in the extruder during the operation time. The extrusion speed was varied by varying the screw rotation rate, as shown in Fig. 4. However, the extrusion became gradually decelerated and finally stopped because of the solid hydrogen heating, when the rotation rate exceeded 30 rpm.

Several pellet production and acceleration series were performed in the repetitive mode. Every series was carried out continuously at the rate of 1 Hz for over 1000 s. One series included an additional 2 Hz operation of 30 s duration. As a result, over one thousand pellets were produced and accelerated to 0.6–0.8 km/s in every series. Some of the results are presented in Table 1. All accelerated pellets fixed by photos were intact. Neither temperature deviations of the extruder nor other harmful effects of the propellant gas were registered.

5. Conclusion

An injector with a screw extruder and a porous injector providing a continuous injection of an unlimited number of pellets in a steady state mode have been designed. The injector designs are compatible with and attractive for the tritium operation. The injector with a screw extruder contains 5 cm^3 of fuel and is capable of producing 65 mm^3/s of extruded billets for pellet production. The injection of 2 mm hydrogen pellets was demonstrated at the rate of 1 Hz and 2 Hz during 1 hour continuous operation. The screw extruder can also be attached to a centrifuge injector. The pellet formation unit has no movable parts in the porous injector. This injector contains only 2–3 pellets as a reserve fuel for a steady state operation. The injection cycle could be reduced to 5 s per shot from one barrel. A new porous unit is being developed now to reduce the pellet production time to 1–2 s.

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