PELLET FUELING DEVELOPMENT AT ORNL*

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ABSTRACT

Advanced plasma fueling systems for magnetic confinement devices are being developed at the Oak Ridge National Laboratory (ORNL). The general approach is that of producing and accelerating frozen hydrogenic pellets at speeds in the range of 1-2 km/s and higher. Two specific concepts are under development: (1) high-speed pneumatic acceleration and (2) mechanical (centrifugal) acceleration. Both approaches are being pursued to meet the projected pellet size and delivery rates for major near-term plasma confinement devices, such as the Tokamak Fusion Test Reactor (TFTR), Tore Supra, the Joint European Torus (JET), JT-60, and Doublet III-D (DIII-D), as well as future applications. In addition to these confinement physics related activities, ORNL is pursuing advanced technologies to achieve pellet velocities significantly in excess of the 2-km/s range already attained with pneumatic injectors and has embarked on a development program designed to explore the feasibility of fabricating and accelerating tritium pellets. This paper describes these ongoing activities.

1. INTRODUCTION

In the last two years, the state of the art of pneumatic pellet injectors has been advanced through the development at ORNL of the repeating pneumatic injector [1]. This versatile machine gun-like device attains maximum pellet speeds of 1.9 km/s with 4-mm hydrogen pellets and operates at a repetition rate of 6 Hz. In 1985 this injector was installed on TFTR [2] and has since produced the highest values for plasma density (approaching $4 \times 10^{14} \text{ cm}^{-3}$ on axis) and Lawson product ($1.4 \times 10^{14} \text{ cm}^{-3} \cdot \text{s}$) recorded on TFTR [3,4]. The repeating injector has been replaced by a new ORNL eight-shot pneumatic device that features variable pellet size capability at a design speed of 1.5 km/s (with deuterium pellets). The eight-shot injector will be used in a collaboration between ORNL and the Princeton Plasma Physics Laboratory (PPPL) to create and sustain high-density target plasmas for the high-power (22-MW) neutral beam heating phase on TFTR in the 1986-87 time frame. As a result of the successful outcome of the initial pellet fueling experiments on TFTR, ORNL was directed by the U.S. Department of Energy to develop a more versatile injector based on the repeating pneumatic injector design to be used on JET in 1987 as a part of a major collaboration between the United States and the European community on plasma fueling and transport physics in the high plasma density regime. These experiments will coincide with, and are expected to contribute to, the JET program to achieve energy breakeven conditions at reactor-relevant

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plasma parameters. The pneumatic pellet injectors for TFTR and JET are described more thoroughly in another paper [5] presented at this conference.

In the area of centrifuge pellet injector development, ORNL is proceeding with an upgrade of the original device that was used in the first steady-state pellet fueling experiments performed on the GA Technologies, Inc., DIII tokamak in 1984 [6]. The new injector is a prototype of the pellet injector system that is to be featured in a collaboration with the Commissariat à l'Energie Atomique (CEA) on the Tore Supra tokamak under construction. The objective of the ORNL-CEA collaboration in this area is to study long-pulse, reactor-relevant tokamak discharges with simultaneous plasma fueling and exhaust capabilities. The upgraded centrifuge design is discussed below, along with other recent development activities.

2. CENTRIFUGE UPGRADE

The centrifuge pellet injector [7] is a mechanical device that uses centrifugal forces to accelerate pellets constrained to move in a track on a high-speed rotating arbor. Steady-state capability and high pellet feed rates are inherent advantages. The prototype device (fig. 1) that was used on the DIII tokamak [6] operated at 25 Hz and 800-m/s exit velocity with 1.4-mm deuterium pellets. The new injector or centrifuge upgrade is designed to accelerate large (3-mm-diam) deuterium pellets at a rate of 30 pellets per second for extended pulse lengths. This injector is intended to be a flexible fuel source for large, long-pulse tokamaks such as DIII-D and Tore Supra. Variable-mass pellets will be accelerated to speeds of 800–1500 m/s for pulse lengths of 30 s. Development activities are divided into two major parts: (1) construction and testing of the centrifuge accelerator and injection line and (2) development of a new type of pellet fabrication and feed system.

The pellet accelerator shown in fig. 2 is a 50% scale-up of the original centrifuge used for the DIII pellet injection experiments in 1984. The larger (1.5-m) spin diameter of the new accelerator will accommodate

Fig. 1. Centrifuge pellet injector.

Fig. 2. Pellet accelerator for the centrifuge upgrade.

the larger pellets and reduce the stresses on them by extending the acceleration length. The rotor is spun in vacuum by a ball-bearing spindle driven by an induction motor. The rotor has been operated at its full design speed of 9600 rpm, which is equivalent to pellet speeds of 1500 m/s.

The new pellet fabrication system will produce specially shaped pellets to reduce the stresses in the pellets during acceleration. A rim of frozen deuterium is formed on a rotating disk (cooled with liquid helium), from which pellets of variable size are punched. The voids left in the rim after the pellets are produced are refilled as the disk rotates through an injection caliper. The device, which has been named the Zamboni machine, is shown in fig. 3. To date, a rim of solid deuterium has been formed on the cold disk, and individual pellets have been successfully punched from it. An automated punch mechanism is being developed to allow production of 30 pellets per second and changes in the pellet size from one pellet to the next. This feature will allow, for example, increasing the pellet mass during the auxiliary heating phase of a tokamak shot or, conversely, decreasing the mass during current ramp-up.

Fig. 3. Schematic of the Zamboni machine.

3. HIGH-VELOCITY PELLET INJECTORS

Two approaches are being pursued at ORNL to produce a pellet fueling system capable of speeds significantly greater than 2 km/s: (1) electric arc discharge and (2) an electron beam-heated rocket.

3.1 Electric arc discharge

A prototype high-velocity pneumatic pellet injector now under development uses arc discharge heating [8] for increased propellant pressure and sound speed. A cylindrical arc chamber (fig. 4) has been interposed between the propellant inlet valve and the gun breech and fitted with a ceramic insert to generate swirl in the incoming gas stream. The arc is initiated after the propellant valve opens and the breech pressure starts to rise; a typical discharge lasts 300 μ s with peak currents up to 2 kA at arc voltages ranging from 100 to 400 V. The system is instrumented with piezoelectric pressure transducers at the propellant valve outlet, the gun breech, and the gun muzzle.

The gun was initially operated with 4-mm-diam polyurethane foam pellets (density of 0.16 g/cm³), an 80-cm-long gun barrel, and various gas propellants at pressures exceeding 70 bar. At $\langle I_{\text{arc}} \rangle = 1.2$ kA and $\langle V_{\text{arc}} \rangle = 300$ V, with hydrogen as the propellant gas ($P = 55$ bar), the arc produces a twofold increase in P_{breech} (Fig. 5). For a 12-mg foam pellet, the projectile speed increased from 975 m/s without the arc to 1550 m/s with the arc; this represents a 9-J increment in the pellet kinetic energy for 90 J of electrical

Fig. 4. Prototype gun arc chamber.

Fig. 5. Gun pressure and arc characteristics. (a) Arc voltage, (b) arc current, (c) pressure in valve region, (d) pressure in breech region. At the arrow, $V_{arc} = -314$ V, $I_{arc} = 1.68$ kA.

dissipation in the arc. At present the arc discharge is driven by a single-stage capacitor bank power supply, which is not well suited to driving the $0.2\text{-}\Omega$ load. A pulse-forming network arc power supply for increased arc power has been designed.

Recently, the apparatus has been combined with a new single-shot pneumatic injector (discussed in the next section), and tests are proceeding with the acceleration of cryogenic deuterium and hydrogen pellets. Pellet velocity increases from 1.2 km/s to 1.6 km/s for deuterium and from 1.43 km/s to 1.85 km/s for hydrogen have been obtained for pellets with a nominal size of 4 mm diam $\times$ 8 mm long.

3.2 Electron beam-heated rocket

The second method under development at ORNL for increasing velocity is based on an electron beam-driven rocket [9]. The beam required to accelerate 6-mm-diam pellets to a speed of 10–20 km/s is estimated to be 70 kV and 70 A magnetically compressed to a spot size of 3 mm radius. The required electron beam is very similar in power levels to those used in gyrotrons for high-power ECRH experiments. The device will have an acceleration path of 20 m, which will allow pellets to be accelerated at pressures near those presently used for lower velocity, thus minimizing the probability of shattering the pellets during acceleration. A cryogenic apparatus that fabricates the long (16-mm) pellets required for the rocket gun has already been tested. A high-power gyrotron-type E-gun will be used to demonstrate the feasibility of the method.

4. TRITIUM INJECTOR

A new single-shot pneumatic pellet injector [10] was built in 1985 as a prototype tritium peller injector, in support of future applications on TFTR. The device (fig. 6), which is similar to the tritium proof-of-principle (TPOP) injector shown in fig. 7, is patterned after a concept proposed by Claudet [11]. In the simple "pipe gun" design, the pellet is frozen *in situ* directly from the gaseous hydrogen isotope and then accelerated in the gun barrel. The potential advantages of this design for tritium service include: (1) the absence of moving parts in the cryostat, (2) minimal tritium inventory and waste, (3) a simple operating cycle, and (4) tritium-compatible materials. The ORNL single-shot injector has operated at up to 1680 m/s with 4-mm-diam, 8-mm-long hydrogen pellets (1380 m/s with deuterium pellets of the same size). The design and construction of the apparatus shown in fig. 4 are proceeding in order to test tritium pellet acceleration limits.

The development activities discussed in this paper will help to bring pellet fueling technology closer to reactor-relevant parameters.

Fig. 6. Single-shot pneumatic pellet injector (simple pipe gun).

Fig. 7. Schematic of the TPOP pellet injector.

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