Helium-3 Fueling Concepts for Magnetically Confined Fusion

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Abstract

A summary of fueling techniques indicated that the injection of fuel pellets is the most fully-developed technique for near-term applications. A conceptualized process flow scheme is presented for the fabrication of fuel pellets, 3 to 4 mm radius, composed of thin-wall polymeric shells filled with liquid He-3 and overcoated with D_2 ice. The carbon introduced by the polymer constitutes less than one percent of the fuel. These fuel pellets are designed to survive cryogenic storage and delivery by the pellet injector. Advanced fabrication techniques include the use of lithium foil shells and the incorporation of polarized He-3 fuel.

Introduction

The conceptual design of a fueling system for a large, high temperature plasma operating on the d-^{3}He fuel cycle at an electron temperature, Te, of ~80 keV represents a formidable challenge at this time. This task is difficult because this Te is approximately 3 times higher than for a d-T reactor-relevant plasma, which will not be tested for many years, and is ~20 times higher than in presently operated deuterium fueled devices. Also, no experience is available on actual dT plasmas in which the fusion products, α-particles, remain in the plasma. In the d-^{3}He plasma the fusion products will include a 15 MeV proton plus this α-particle.

The experimental techniques presently demonstrated for plasma fueling are gas puffing and pellet injection of frozen particles [1] of H_2 and D_2. For large reactor relevant plasma devices, advanced fueling techniques may need to be developed such as plasma guns [2], accelerated plasmas from compact toroids [3] or laser ablation of pellets [4]. In the meantime, several plasma experiments have demonstrated that pellet injection is a successful fueling technique and superior to gas puffing because it delivers clean fuel into the center of the plasma much faster than the time required for gaseous fuel to diffuse into the plasma. Such fueling results in increased density and energy confinement in the plasma. Multiple fuel pellet injections into TFTR demonstrated [5] (nτ) values of 1.4 x 10^{20} s · m^{-3} at central ion temperatures of 1.4 keV. Because of the success of pellet fueling, the concept of d-^{3}He fuel pellets is considered in this study for use in the next generation of tokamak devices, such as NET, in which energy breakeven experiments, Q=1, may be demonstrated at Te as low as 30 keV [6]. Also, d-^{3}He fuel pellets may be useful in the present experimental plasma programs which aim to simulate the effect of α-particle confinement by use of the protons released from d-^{3}He fusion.

Concept for He-3 Fuel Pellets

The fabrication of a He-3 fuel pellet is extremely difficult because the critical temperature

(3.2 K) is the lowest of any substance. In addition, as the temperature is decreased further the liquid does not solidify (Fig. 1) but transforms to super-fluid type A and B phases. Solidification requires a pressure of ~3 MPa. Because a fuel pellet could not be delivered into a plasma at such a high pressure, the fuel pellet must therefore contain liquid He-3.
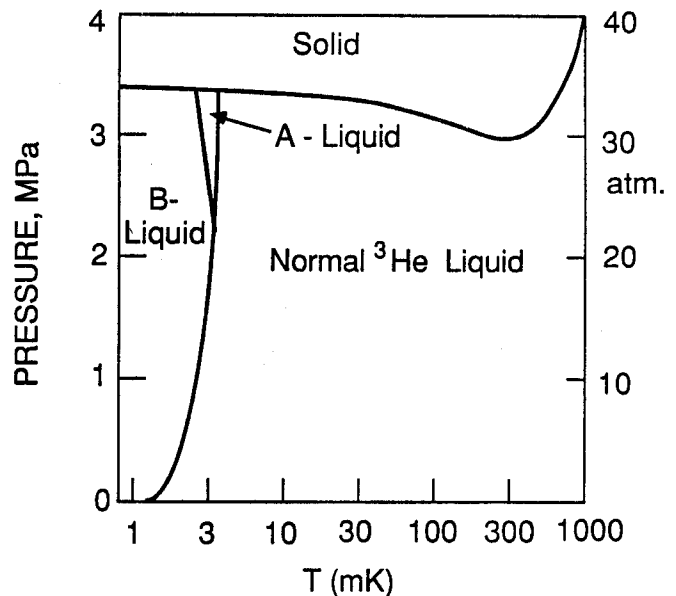

Fig. 1. Solid-Fluid Phase Diagram for He-3 below 1 K.

Several concepts were evaluated for the fabrication of liquid fuel pellets as follows:

1) Acceleration of liquid droplets. The possibility of accelerating liquid droplets of He-3 for fueling was quickly discarded because of experimental observations that liquid hydrogen droplets begin to fragment at velocities of ~2 km/s [7]. Because the cohesiveness of a droplet is somewhat related to its latent heat of vaporization, which is ~3 J/mole of He-3 and ~220 J/mole of H_2, then it is reasonable to assume that the liquid He-3 droplet would disintegrate at a much lower velocity than the H_2 droplet.

2) Frozen pellets of D_2 with entrapped He-3. This concept envisions the solidification of D_2/He solutions because liquid deuterium is known to dissolve helium, although high pressures are required. Souers [8] has calculated that at a pressure of 2 MPa and a temperature of 30 K the solubility of He-3 in liquid D_2 would be only 0.024 mole fraction. In addition, the He-3 solubility decreases as the temperature decreases so that it is only 4 x 10^{-3} mole fraction at 20 K and 2 MPa. As a result, the He-3 solubility in a frozen pellet of D_2 would be negligible.

The possibility of entrapping "hot" atoms of He-3 from the gas phase during the condensation of D_2 might be also considered. Such an experiment has apparently not been performed; however, a related experiment has demonstrated that He-4 can be pumped by cryocondensation pumps at 3.4 K from a vacuum chamber during the continuous deposition of D_2 ice [9]. This experiment showed that the D_2/He ratio had to be $>10^5$ before a significant fraction of the He was deposited. Both of these concepts were discarded, therefore, because the amounts of He-3 in D_2 ice would be too dilute.

3) Liquid He-3 enclosed in a inert shell. Liquid He-3 could be encased in thin-wall, spherical shells of silicate glass, polymers or metals. The inert shells would need to have sufficient tensile strength to contain the He pressure, ~0.1 MPa at 3 K, and not severely contaminate the plasma. Because of high Z materials in silicate glasses, this material was not considered; however, polymeric materials composed of only carbon and deuterium might be useful if the C/He-3 ratio were kept at <1%, which would be a "clean" plasma for present-day experiments.

Fabrication of He-3 Fuel Pellets

The fabrication of a fuel pellet consisting of a droplet of He-3 liquid encased in a polymeric membrane shell involves only the adaptations of known techniques and could, therefore, be developed for near-term use. The conceptualized fabrication process for such a pellet is presented in Fig. 2, using polystyrene as an example of the polymeric shell. This study was directed toward fueling a NET-type experiment at low Q values in which the plasma contains ~35 mg He-3 and ~24 mg D at $T_e \approx 30$ keV [6]. If the fuel pellet contained 10% of the fuel in the plasma, the pellet would contain 3.5 mg He-3 in a sphere of ~3 mm radius or 14 mg He-3 in a sphere of 4 mm radius at 40% of the fuel as in the plasma. In such cases, the thickness of the polymeric shell would need to be <3 μm in order to maintain the C/He-3 mole ratio at ~1%.

A filled fuel pellet containing liquid 3.5 mg of He-3 in a polymer shell only 3 μm thick must then be transported to the pellet injector. If the pellet injector were cooled to 4 K, all of the liquid He-3 would vaporize in approximately 20 ms because of the low thermal resistance of the thin shell and the low heat of vaporization of the He-3, 8.5 J/g. For this reason, an insulating coating of D_2 ice approximately 1 mm thick must be deposited on the fuel pellet. The use of D_2 ice avoids the introduction of impurities into the plasma. During the time the pellet is accelerating through the injector, ~20 ms, the thermal resistance of the D_2 ice is sufficient to permit the vaporization of only 1 to 2% of the He-3; consequently, the pressure in the pellet remains at 0.1 MPa (1 atm) so that the pellet can survive up to the edge of the plasma.
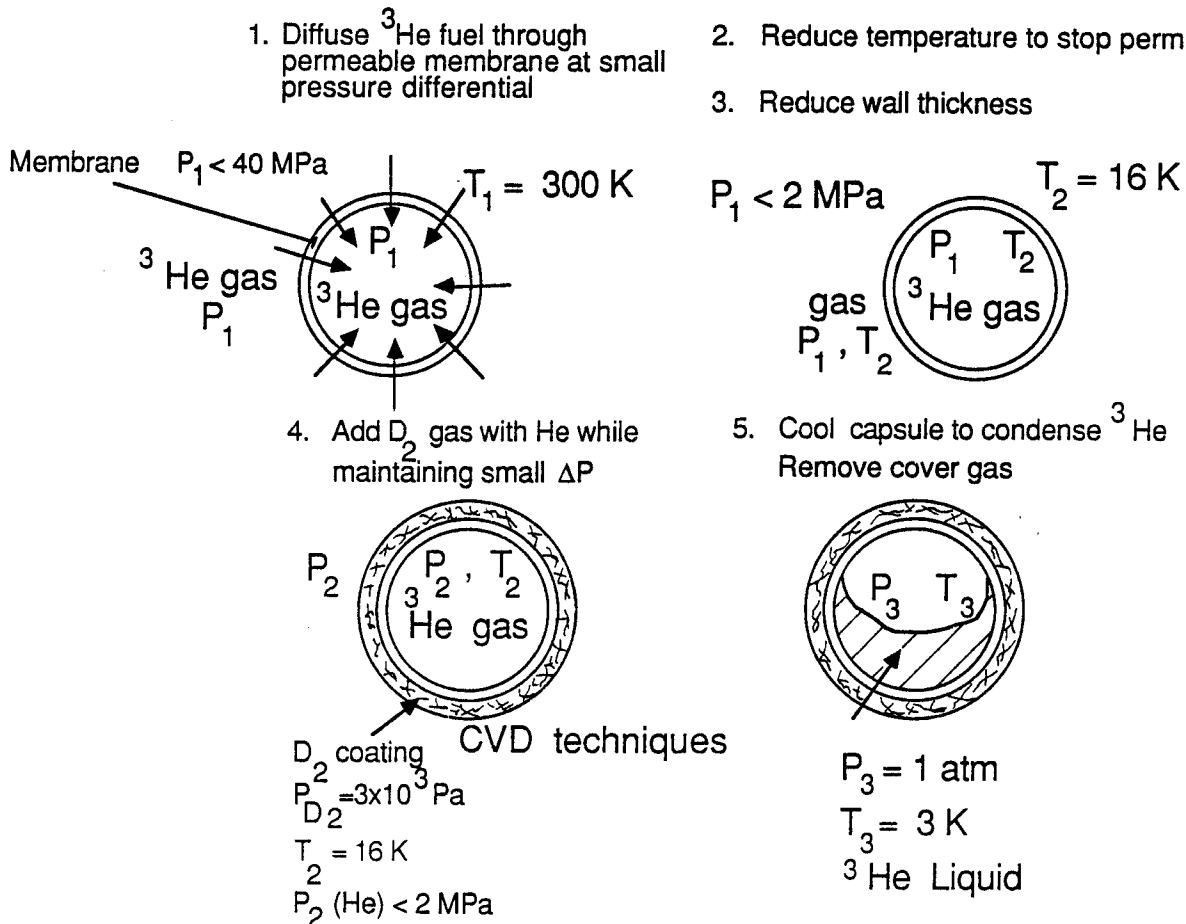

Fig. 2. Schematic Flow-Diagram for Fabrication of He-3 Fuel Pellets.

The fabrication of the pellet, Fig. 2, proceeds in the following manner.

Step 1. The process utilizes hollow polymeric shells, which have been mass produced for the ICF program [10] but with smaller diameter and higher tolerances. Such high-quality shells would not be necessary for MCF fueling. These spheres are placed in a pressure vessel containing He-3 so that the He permeates the polymeric membrane and fills the hollow sphere. The pressure of He-3 is gradually increased to ~40 MPa so that they will be nearly filled with liquid He-3 when cooled to 3 K. As Campbell et al. [11] point out, the ΔP (pressure difference between inside and outside of the shell), must be kept small or the shell will fail by buckling. Based upon their graphical relationships, for the present case, where tw (wall thickness) = 2.1 μm, diameter = 6 mm, and E (Young's modulus) = 7 GPa, the maximum ΔP is < 10 kPa and would require 4 days to fill the shell. For this reason, the shell is initially fabricated with a thicker tw = 18 μm, so that ΔP is < 350 kPa and the filling can be completed in 24 hrs.

Step 2. The entire contents of the pressure vessel is cooled to ~16 K so that the permeation rate for He through the polymeric membrane becomes essentially zero. The He-3 gas pressure is maintained in the vessel so that ΔP is small across the shell.

Step 3. At the low temperature the particles are abraded by agitation against a roughened surface such as is done conventionally by use of a ball-mill. The final thickness, tw, should be <3 μm.

Step 4. Deuterium gas is admitted to the chamber together with the He-3 gas. The temperature of the spheres is below the solidification temperature of D_2; consequently, a coating of D_2 ice forms on the spheres. The spheres need to be levitated to insure uniform coating as is routinely performed in chemical-vapor deposition processes.

Step 5. The entire pressure vessel is cooled to ~3 K where the vapor pressure of liquid He-3 is ~0.1 MPa. The external He surrounding the spheres is removed either as a liquid or by evaporation. At this temperature the vapor pressure of D_2 ice is negligible and the coating will remain intact. If the tensile strength of the polymer shells were similar to their room temperature values, the shells are calculated to contain the pressure of the He. The loaded fuel pellets must be kept at 3 K during their transport to the pellet injector.

The parameters used at each stage of the fabrication process are summarized in Table 1. Note that the C/He-3 ratio for both sizes of spheres is ~1%. The thickness of the D_2 can be adjusted after some experimental information is available regarding the amount of D_2 that is vaporized in the pellet injector.

Some interesting variations on this fabrication process are:

1) Metallic spheres - metallic shells of low Z metals, Li and Be, could be tolerated by the plasma. Also, at the high temperature of an operational d-He-3 reactor, the fusion reaction ^6Li (d,α) ^3He would provide additional power. Currently, commercial production of lithium foils has been achieved to a minimal thickness of 75 μm [12]. Thinner foils for the

Table 1

Parameters for Fabrication of He-3 Fuel Pellets

| | Polymer Shell Radius, mm | |
	3	4
He-3 mg	3.5	14
Shell thickness, μm		
Initial	18	48
Final	2.1	3
Pressure, He-3, MPa		
ΔP, during fill	0.35	1.4
P @ 300° K	23	39
@ 16° K	1.2	2
@ 3° K	0.1	0.1
Time to fill, hr	24	35
C/He-3 atomic ratio	0.011	0.01
D_2, overcoat, mg	20	40
D_2/He-3 atomic ratio	9	4

fabrication of shells could probably be developed if the need arose. Thin-wall hemispheres formed of Li foil would be introduced into the pressure vessel in Step 1. Two hemispheres when brought together to form a sphere would contain the required amount of He-3. These spheres might be sealed by swaging, friction-welding techniques or by the application of a cold, vapor-deposition technique in which the deposited coating would not adversely affect the plasma.

2) Polarized fuel - If liquid He-3 in a fuel pellet were pressurized to >3.3 MPa in the presence of a magnetic field and the required radiofrequency wave, the He-3 solid would become polarized. It has been observed that as the pressure is released, the liquid also remains polarized while in contact with the solid [13]. The polarization of the solid should take place below a temperature of 30 mK, Fig. 1. Then, as the pellet warms up during transport in the pellet injector the ratio of solid to liquid He-3 actually increases because of the minimum in the solid-liquid phase boundary near 300 mK. If the pellet could be delivered into the plasma while the polarized liquid remains, the plasma would be fueled with polarized He-3 fuel. With polarized D_2 in the plasma also, the neutron production has been calculated [14] to be only one per 10^4 fusion events.

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