Issues in Formation of Cryogenic Pellets for Fusion Applications

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Abstract - Cryogenic pellets are used for injection into fusion plasmas to add fuel to build up density and replace the ions lost from fusion reactions and imperfect confinement in the plasma. These pellets are formed at cryogenic temperatures with pure hydrogenic isotopes or mixtures of the isotopes. Technology to make these pellets and inject them into plasmas has been under development for many years and various methods using freezing or desublimation have been shown to produce high quality solid pellets suitable for injection. The throughput needed and possible impurity content from the necessary recirculation of fusion exhaust gases are two of the key issues to overcome for fusion pellet fueling systems in long pulse burning plasmas. Here we describe the technical challenges associated with these issues and the capability of pellet formation extruders to overcome them.

Cryogenic pellets of deuterium, neon, and argon are also used in fusion tokamak devices for disruption mitigation in the form of large pellets that can be injected on demand to quickly dissipate the plasma thermal energy through radiation and add significant density in order to prevent runaway electron formation. Here the issue is not throughput as with the fueling pellets but rather is the time it takes to form pellets of the size needed and the ability to dislodge them immediately on demand when needed to mitigate a disruption. The method used to make these pellets by desublimation is described and examples related to how pellet size and input gas parameters affect the formation time are provided.

Index Terms—Cryogenic Pellets, Disruption Mitigation, Pellet Injection

I. Introduction

Injection of pellets of solid hydrogenic isotopes is the preferred method to add fuel to fusion plasmas because of the ability to penetrate the plasma boundary before the pellet atoms become ionized and thus add fuel directly to the confined plasmas. Gas fueling, as predominantly used in today's fusion experiments, will have limited ability in a reactor environment to penetrate beyond the plasma peripheral scrape off layer where it will become ionized and flow to the divertor before entering and fueling the confined plasma[1] .

The fueling throughput for future burning plasma devices will be significantly higher than in current and previous smaller scale plasma experiments and the required duration of the fueling will also be much longer, eventually reaching steady state. Figure 1 shows an estimate of the throughputs needed in past and present-day fusion experiments, for the ITER-DT scenario, a fusion pilot plant (FPP), and for a demonstration reactor (DEMO). This log-log plot makes it clear that these future devices will need continuous fueling at high throughputs to achieve their missions. Once tritium becomes a constituent of the fuel, the fueling system will be more difficult to design to safely handle the tritium and be able to efficiently recirculate any solid fuel material not injected as a pellet into the plasma.

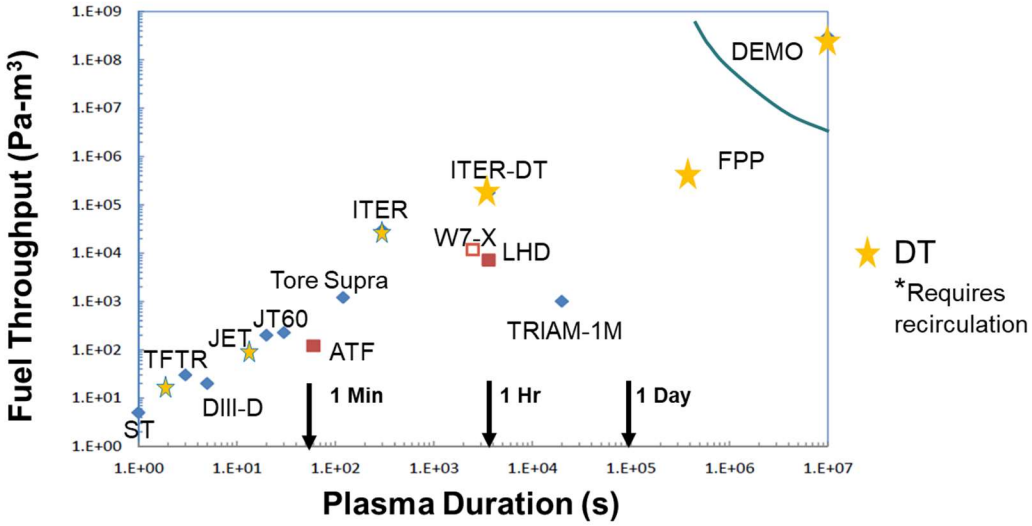

Fig. 1. Fuel throughput from present day fusion experiments and projections for future DT burning plasma devices as a function of plasma duration in a log-log representation. Red points are stellarators and blue are tokamak devices. Yellow points are devices that have or will use tritium.

There are two common methods used to form hydrogenic pellets for injection into fusion plasmas. These are illustrated in the

hydrogen isotope phase diagram in Fig. 2 (made from data in Ref. 2) where pellets can be formed by desublimation (gas directly solidified at low pressure) or by first forming liquid that is then frozen at pressures above the triple point. The desublimation technique is used in a pipe gun device where the pellet is formed in situ in a cold gun barrel and then fired when needed. The extrusion method is enabled by a cryogenic extruder device that is designed to take input gas at pressures above 500 mbar (0.05 MPa) that is cooled in a heat exchanger to form liquid and subsequently cooled further to be frozen into a solid billet that is then extruded by a piston or screws.

In the subsequent sections of this paper we describe the desublimation process in detail and discuss experiments performed to determine the rate of desublimation for commonly used fusion materials. We also describe how extruders produce force to move the solid material through nozzles to form appropriately sized ribbons of hydrogenic solid from which the pellets are cut just before accelerating them into the plasma. Experiments to determine these forces for different isotopes and nozzles are described and compared with two models for flowing solid hydrogen. Mixtures of neon in the fuel gas can impact extruder performance by increasing the extrusion force required and we describe results estimating what the tolerable levels of neon are for high throughput extrusions.

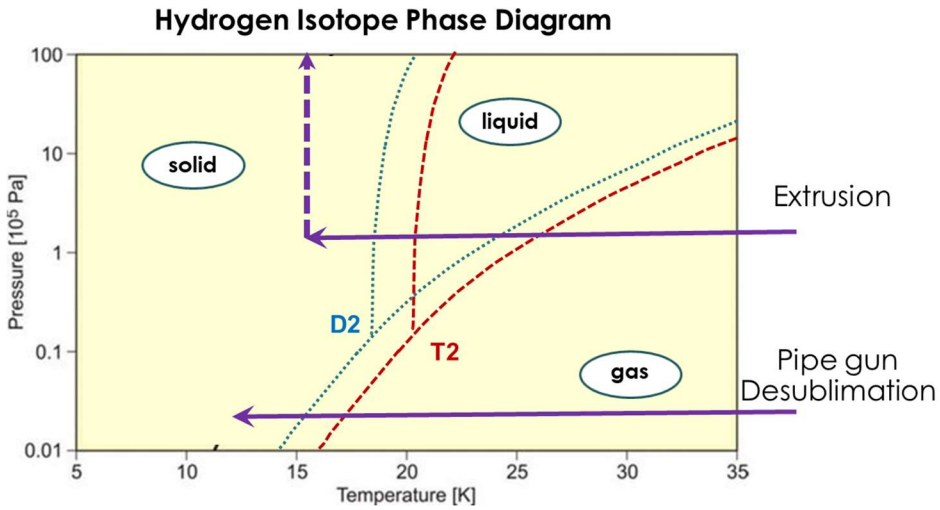

Fig. 2. Phase diagram of deuterium and tritium isotopes showing the methods to form pellets through extrusion and desublimation. Arrows indicate the incoming gas used to form the solid. The vertical dashed arrow represents the pressure increase to compact and produce flowing solid in an extruder.

II. Desublimation Technique and Experimental Measurements

The simplest technique to make a cryogenic pellet is known as a pipe gun where a pellet is formed as a solid plug in a gun barrel that has contact with a cold cryostat over the length of the desired pellet. Gas is fed into the barrel from one or both sides of the

cold zone where it will form a solid pellet through desublimation when the gas contacts the cold section of the barrel. A pipe gun uses either a cold helium heat exchanger or a cryocooler to produce the cold zone that forms the pellet. Such a configuration has been used for many years to produce pellets for fueling experiments[3] and more recently for disruption mitigation research.

The feed gas pressure in the pipe gun must be kept low (< 50 mbar) to limit conduction heating from the gas to the cold zone. If excessive heating occurs the pellet will sublimate during the formation process leading to a positive feedback scenario that completely sublimates the pellet and thus requires the pellet formation process to be started over. Figure 3 schematically shows the formation process where the gas forms a ring of solid in contact with the stainless steel barrel and then fills in the center of the pellet and transfers the heat of fusion through the solid material and barrel wall into the cooled copper. The thermal conductivity of the stainless-steel barrel at typical formation temperatures is < 1 W/m-K, which is approximately three orders of magnitude lower than that of copper. The commonly used pellet materials of hydrogen isotopes or neon have even lower thermal conductivity[3] than that of stainless steel, thus limiting the pellet formation rate, especially for large diameter pellets where significant heat must flow through the thick pellet material during the desublimation process. The low thermal conductivity of the pellet material therefore has a significant influence on the ability to form large pellets and the time to do so.

A 12.5 mm diameter pipe gun with a 12.5 mm long cold zone was used to measure the rate at which deuterium pellets can be formed at different cold zone temperatures as a function of gas pressure in the barrel. Data from these measurements is shown in Fig. 4 for 10 K and 15 K cold zone temperatures. In these experiments the gas entered the barrel at room temperature while slowly varying the barrel pressure. The measured gas flow rate is translated into the solid volume growth rate. The 10 K data shows approximately a 2.5x higher solid formation rate than at 15 K. Taking into account the starting surface area of the cold zone, a solidification rate of 0.025 mm^3/mm^2-s is estimated at 10 K.

An effective sticking coefficient of 0.05 is calculated from the estimated solidification rate and incidence rate from kinetic gas theory, which is significantly lower than what has been observed for low temperatures (< 4 K) and low pressures (10^{-7} mbar) with low incidence rates of < $2x10^{13}$ molecules/cm^2-s[4]. Under these conditions the sticking coefficient onto a metal surface was measured to be 0.9[4]. During these pellet formation experiments it exceeded 100 monolayers of surface coverage by the gas species molecules, thus it is in a cryocondensation regime and the coefficient is more representative of a condensation coefficient. There is also a geometry dependent capture probability that is not explicitly factored into our coefficient determination. The incidence rate in our configuration at a pressure of 10 mbar is estimated to be $7.5x10^{21}$ molecules/cm^2-s or more than 9 orders of magnitude higher than from the sticking coefficient measurements in the literature[4].

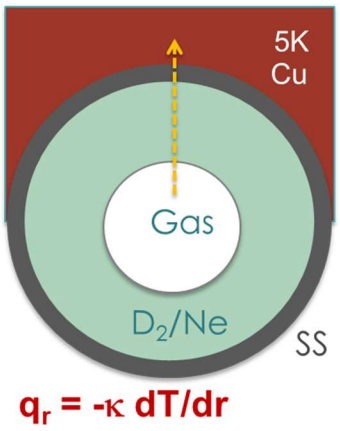

Fig. 3. Schematic showing the formation of a pipe-gun deuterium/neon mixture pellet from desublimation and the flow of heat of fusion through pellet material, barrel, and into the cold copper cryostat. The radial heat flux is the product of the material thermal conductivity and temperature gradient.

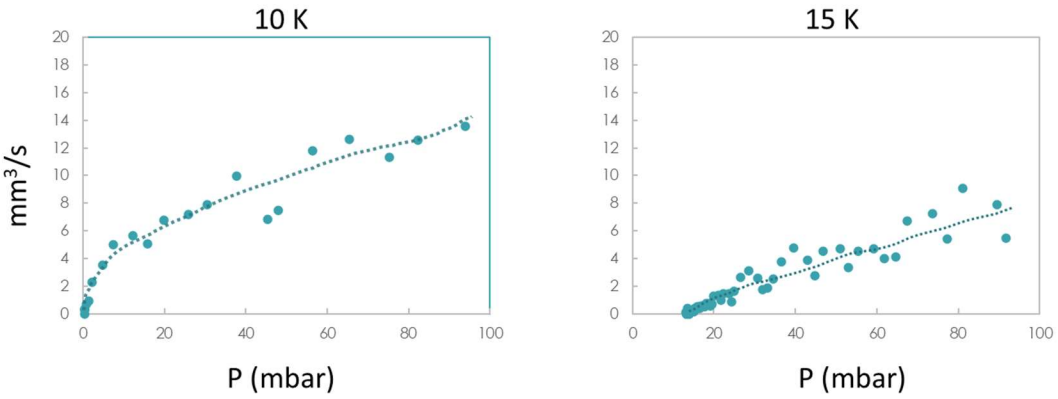

Fig. 4. Solidification rates for 300 K input deuterium gas as a function of pressure in the cold zone in a 12.5 mm diameter pipe gun configuration. The dashed curves are fits to the data.

Experiments to measure the desublimation rate of deuterium onto a cold copper surface for gas that was precooled before entering the cold zone were also performed. The experimental setup is shown schematically in Fig. 5 where a cryocooler was used to cool the copper cold block to temperatures as low as 10 K A temperature sensor and resistive heater were mounted on the copper cold zone with the heater controlled by a temperature controller using a PID loop control algorithm to maintain a desired setpoint temperature. The primary purpose of this setup was to document the desublimation rate to support the design of

an extruder that could form solid D_2 from gas without the use a liquefier. These data were then used to determine the amount of cold surface area required within the extruder for a given flow rate and operating conditions.

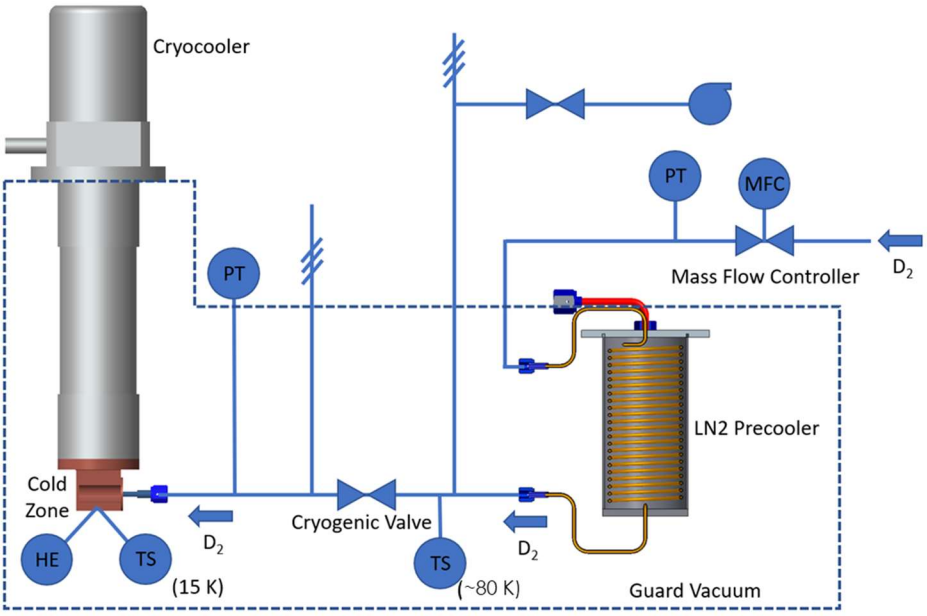

Fig. 5. Experimental setup to measure the desublimatio nrate of deuterium at different temperatures with precooled incoming gas. The dashed line indicates the vacuum boundary.

Figure 6 shows the results of a test to determine the maximum flow rate that could be desublimated in this setup geometry at 15 K with the gas precooled to 80 K. At a D_2 gas flow rate of 1600 SCCM the pressure in the cold zone continuously increases indicating that the cold zone cannot desublimate at that rate. The pressure equilibrates at a flow rate of 1400 SCCM, which corresponds to a maximum stable solidification rate of 21 mm^3/s. The resulting desublimation rate as a function of the area then is 0.043 mm^3/mm^2-s. This rate is approximately 3 times higher than for 300 K (not precooled) incoming gas. This is as expected since the enthalpy of the inlet gas is reduced by approximately a factor of 3 by precooling it to 80 K.

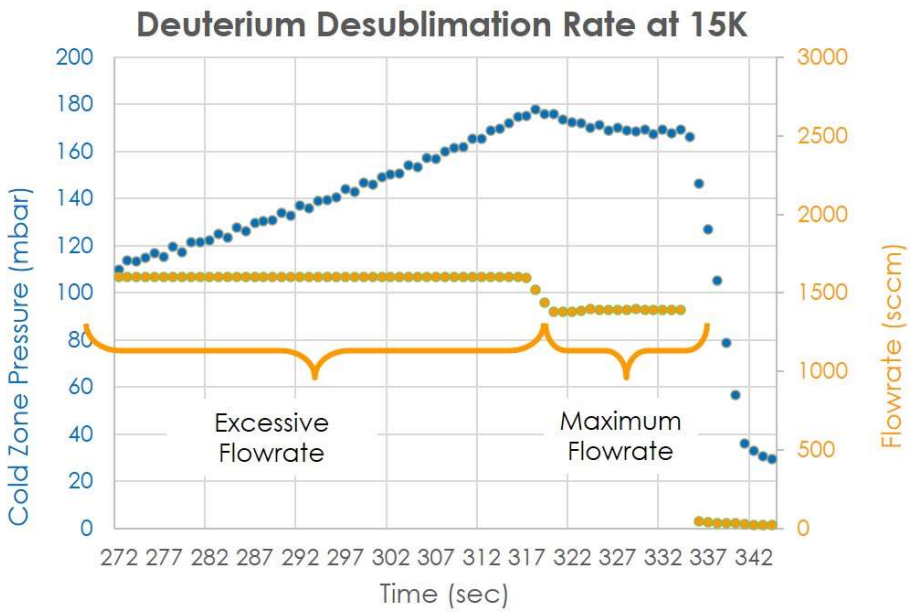

Fig 6. Pressure response within the cold zone for different flow rates of D_2 gas input at 80 K.

III. Extrusion Formation of Solid DT for Fueling Pellet Formation

Extruders have been developed to produce ribbons of solid hydrogen and force the flow through a nozzle to produce a shape where pellets can be cut out to be injected into fusion plasmas by means of a gas gun or a centrifuge[3]. Piston and screw-based extruders shown schematically in Fig. 7 now exist with the latter able to produce a continuous flowing ribbon and achieve steady-state fueling with pellets[3]. Two primary challenges for producing high throughput hydrogenic extrusions are (1) the heat transfer required at cryogenic temperatures and (2) the force needed to extrude the material as a function of temperature and the nozzle geometry. In this paper we do not discuss the heat transfer aspects as this has been discussed in other publications[5].

Extruders have been designed to operate using cryocoolers as the cooling mechanism. These do not have a liquefier section as shown in Fig. 7, but rather rely on desublimation to make the initial plug in the extruder since the inlet pressure must be kept low to not overwhelm the cooling available. This approach follows the path in the Fig. 2 phase diagram noted as a pipe gun method. Once the extruder is full, the inlet pressure can be increased and it essentially operates in the extrusion path of Fig. 2, except there is only a very small region at the top of the extruder barrel that operates in the liquid phase.

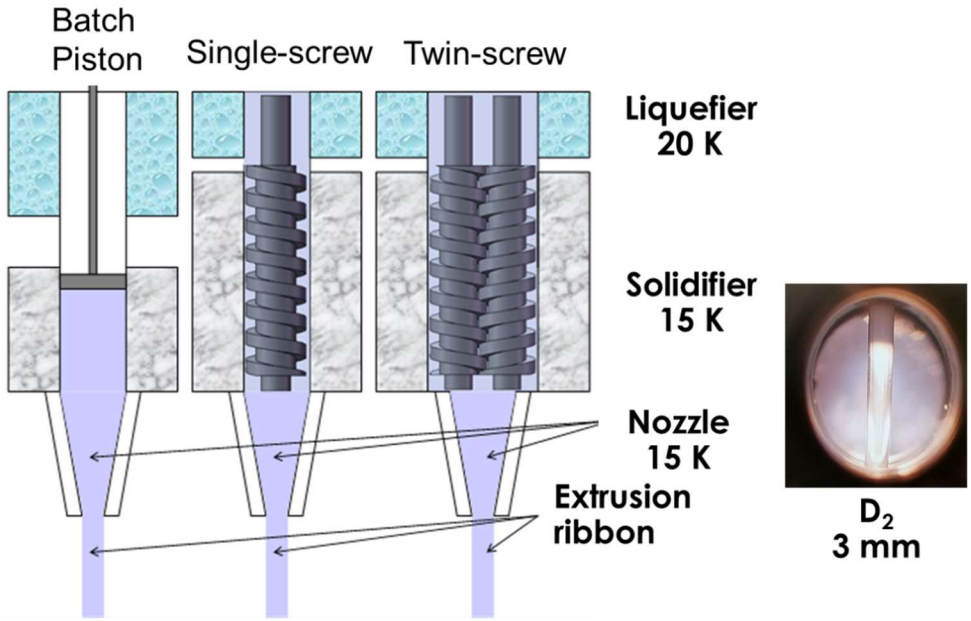

Fig. 7. Schematic of different types of extruders that have been used to produce hydrogenic extrusions. Temperatures noted are for D_2 operation. An example 3 mm diameter extrusion ribbon of D_2 from a twin-screw extruder is shown on the right.

IV. Extrusion Forces

Solid hydrogen isotopes are known to be a Bingham plastic, meaning that they behave as a rigid body at low stresses but flow as a viscous fluid at high stress[3]. (Other examples of such materials are toothpaste and chocolate.) The Buckingham-Reiner model for fully developed laminar pipe flow in a Bingham plastic[6,7] relates the volumetric flow Q and differential pressure ΔP to drive it to the viscosity μ and shear strength τ of the material:

$$Q = \frac{\pi \Delta P R^4}{8 L \mu}\left[1 - \frac{8}{3}\frac{L\tau}{\Delta P R} + \frac{16}{3}\left(\frac{L\tau}{\Delta P R}\right)^4\right] \qquad (1)$$

where R and L are radius and length of the flow path. Using this formula, an iterative numerical technique is used to determine the necessary ΔP to achieve a given flow rate. We then integrate along the path of the extrusion to take into account any changes in the geometry along the path.

A different model developed for a piston-based extruder is based on dynamic shear stress, σ, along the surface area of the extruder such that the force required is:

$$F = \sigma_D A_S \qquad (2)$$

The pressure required to overcome an area reduction in the nozzle is taken from the well-developed metal extrusion research[8] and is given by:

$$P = \sigma_D \, ln \, (A_1 / A_2) \qquad (3)$$

where A_1 and A_2 are the nozzle inlet and outlet areas. Thus the total force in the piston extruder is given by $F_{tot} = F + P \times A_1$. We call this model the Fisher model as it was first used in DT extrusion experiments[9] to determine dynamic shear stress data for the different isotopes.

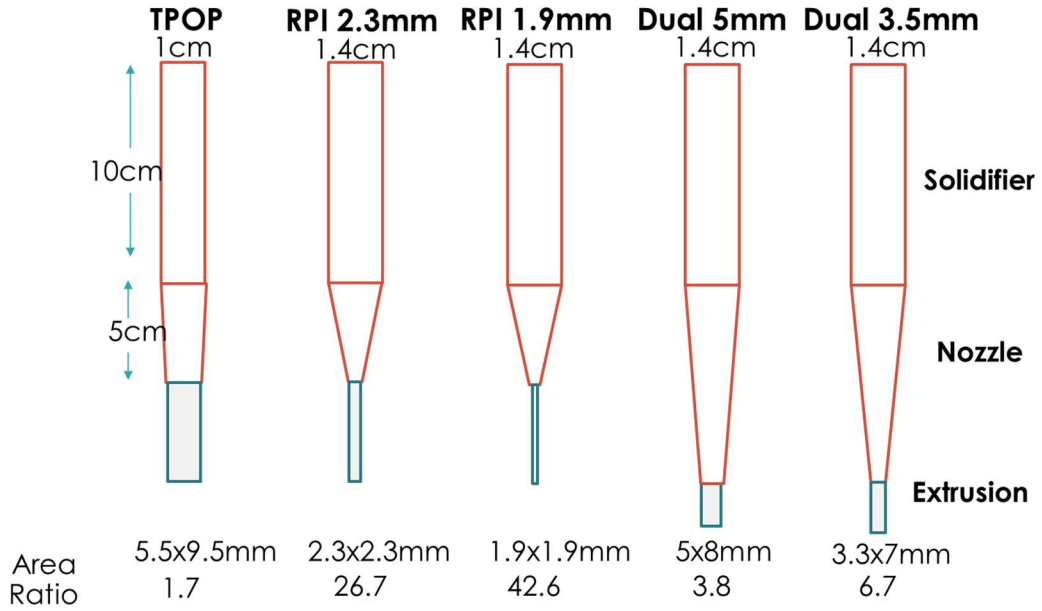

Fig 8. Batch extruder and nozzle geometries tested for extrusion force shown approximately to scale. The diameter of the piston extruder and its solidifier length are noted. The exit cross section and area ratios of the nozzles used are indicated at the bottom. The Dual nozzle labels refere to a dual nozzle with a 5mm and a 3mm branch that are independent.

Multiple extrusions were performed with batch piston extruders[9,10] using the various nozzle geometries shown in Fig. 8. The nozzles employed had vastly different area ratio changes as shown in the figure that range from 1.7 up to 42.6. These extruders can have a maximum solid volume of 14 cm^3 (except TPOP at 10 cm^3), but in practice only about 8 cm^3 of material can be extruded due to incomplete filling of the solidifier and material remaining in the nozzle. When the piston is pulled out of the solidifier new solid is made from liquid that flows in by gravity from the liquefier using flutes around the piston.

Data from a typical extrusion made with the batch piston extruder connected to the Dual 5 mm nozzle in Fig. 8 is shown in Fig. 9. The piston speed is determined from the time derivative of a position measurement made with a linear potentiometer attached to the extruder piston shaft. The force is measured by a Futek strain gauge type FTH300 load cell on the piston drive and the flow is calculated by the volume rate of change in the solidifier determined from the piston speed and cross sectional area assuming no flow goes around the piston. Measurements of the flow made by analyzing video images of the output solid ribbon generally correlate well with the ideal flow derived from the volume change in the solidifier except at higher

temperatures close to the extrusion triple point when backflow around the piston is observed[11]. The initial part of the force curve is monotonically increasing due to the piston moving in the top part of the solidifier and compacting the material to fill the nozzle. The peak force is reached when the material begins to move though the nozzle, after which the force reduces as the amount of material in the extruder decreases. The flow rate in this example was such that over 30 seconds of extrusion duration through the nozzle was achieved with nearly 8 cm^3 of material extruded. The peak force implies a pressure on the extrusion of nearly 160 bar, which is well within the estimated 225 bar capability of the piston extruder.

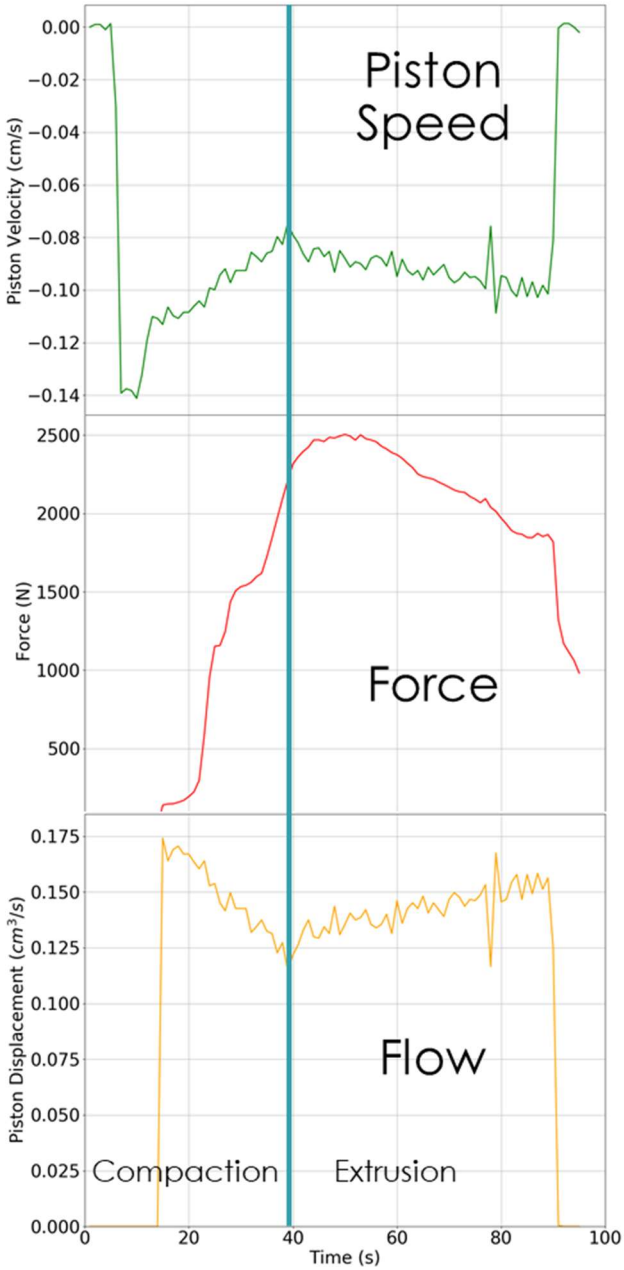

Fig. 9. The piston speed, force, and volumetric flow rate from a typical batch extruder D_2 extrusion obtained in the Dual 3.5mm nozzle configuration from Fig. 7 operated at 12 K. The vertical line indicates when compaction ends and extrusion flow begins.

To compare with the extrusion force models we use the force data as in Fig. 9 and the piston position just after the peak force to estimate the expected force for the temperature of the extrusion and isotope used in the particular nozzle geometry. The extruded material is assumed to be the same temperature as the extruder solidifier. Figure 10 shows the results of this comparison for a set of cases with the different nozzles from Fig 8 where it is indicated which isotopes are used. The results generally show that the measured forces are higher than either model would predict. The outliers to this trend are for H_2 extrusions that were much colder than the triple point temperature using the Buckingham-Reiner model. This may be due to the uncertainty in shear stress properties at these lower temperatures that are extrapolated from warmer temperature data. Additional data at different H_2 temperatures is needed. Both models generally follow the trends of the data for all the isotopes such that using the models for future predictions with a 50% correction factor can reasonably predict the forces necessary to extrude H, D, or T.

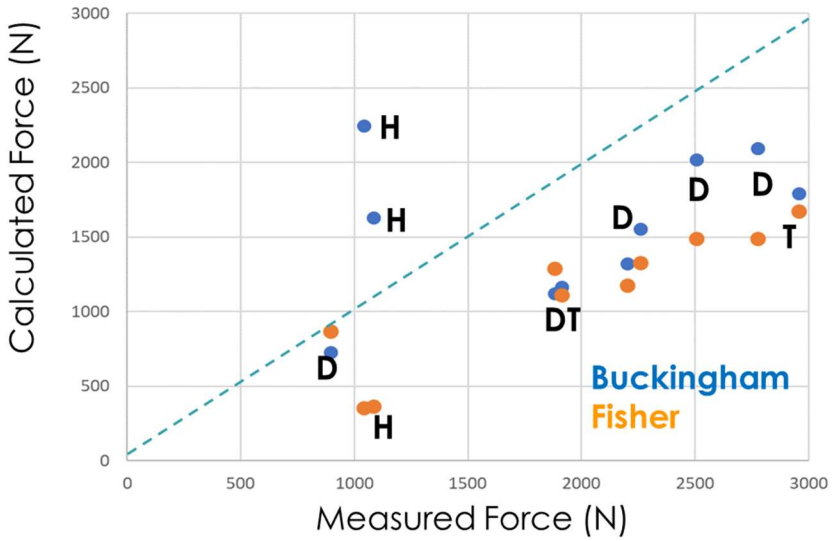

Fig. 10 Plot of the calculated extrusion force vs the measured force for different isotopes (H,D, DT, T) and nozzle geometries using the Buckingham and Fisher force models.

The data are plotted again in Fig. 11 by showing the measured over calculated force ratio as a function of nozzle area ratio to determine if there is any needed correction associated with that parameter. In almost all cases the measured forces are approximately 50% higher than the calculated force, except again in the cold H case where both models are far off; -the Buckingham model being too low and Fisher model too high. Again, additional data for H is needed over a range of

temperatures to better understand these outliers. Despite the dramatic difference in nozzle area ratios, both models seem to capture this parameter properly and do not predict a large change in force strictly due to the large area change in a nozzle. In absolute terms, the force necessary to extrude the heavier isotopes is larger because of their higher dynamic shear stress[12].

These results show that the change in cross sectional area of the nozzle does not play a significant role in the force (and therefore pressure) required to extrude hydrogenic isotopes in extruders. Previous empirical experience indicated that this was the case, but these experiments quantify that the nozzle cross sectional area decrease is not the dominant factor in the extrusion pressures required as was assumed by Fisher in his model using the metal extrusion pressure formula from nearly a century ago.

The Buckingham-Riener model was formulated for pipe flow with constant cross section and so our use of this model in a dramatically changing cross sectional area system may be responsible for some of the differences between the measurements and the model predictions. This does not appear to be a significant factor because the difference was shown to be independent of the nozzle area reduction ratio. Future experiments are planned to dynamically change the cross-sectional area while extruding to better quantify the area reduction dependence on the force.

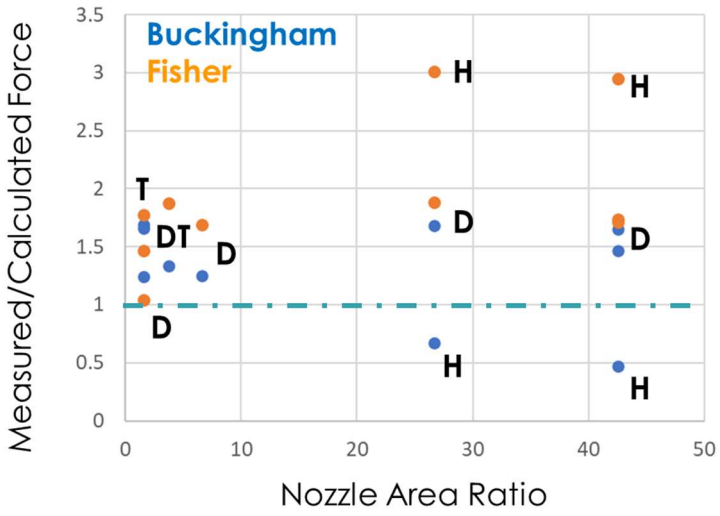

Fig. 11 The ratio of measured to calculated force for the different nozzles as a function of the nozzle area ratio using both force models.

In some of the extrusion tests using the 2.3 mm extrusion output nozzle, a mixture of neon was added to the deuterium gas in making the extrusions. This was done to simulate the expected amount of neon in a fusion reactor exhaust gas if neon were to be used as a divertor radiating material to reduce heat flux on the divertor and improve plasma performance[13]. Removing neon from the fusion exhaust gas is difficult to do cryogenically because its triple point temperature is 24.6 K, which is close to that of T (20.6 K shown in Fig. 2) and thus separating out the neon in a predominant DT mixture with a cold trap is challenging.

Molar concentrations of up to 2% neon gas feed were tested in the extruder. The resulting extrusion forces normalized to the volumetric flow rate of the extrusion are shown in Fig. 12. As can been seen in these results, adding neon to a D_2 extrusion greatly increases the required extrusion force to extrude such that at more than 1% neon the force necessary for high extrusion flow rates becomes problematic. Small flow rates are still possible with the available extruder technology, but higher flows will require much more force than the current systems can realistically achieve.

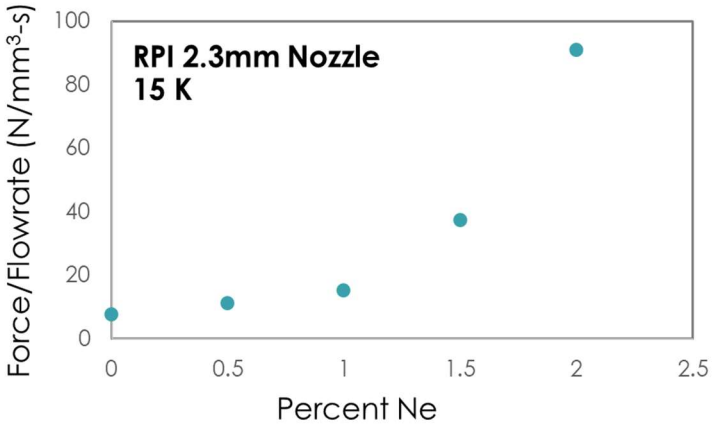

Fig. 12 Extrusion force measured normalized to the flow rate as a function of the molar percemt Ne in the extrusion input gas.

These force measurements were made with the batch piston extruder, but we expect that screw extruders will also need to reach the same nozzle pressures to achieve similar flow rates. The measurement of the extrusion force in a screw extruder is more difficult to make, but it can be achieved with a load cell that measures the reactive force on the screw shaft. Such measurements with a twin-screw extruder are underway and will be compared to these results when the data becomes available

V. Conclusions

The required cold surface area and time needed to desublimate D_2 gas for forming extrusions directly from gas were measured and is not difficult to achieve in practice if the flow rate does not exceed the extruder thermal capacity. The time required for pellet formation in a pipe gun is limited by the poor heat transfer through the solid pellet material. Therefore, it is not a practical pellet formation method to use for rapid production of fueling pellets. It nonetheless is quite useful for disruption mitigation pellet formation where limited numbers of large pellets are needed on demand to rapidly radiatively dissipate the energy in a

disrupting plasma. Pellet diameter, inlet gas pressure, and coldzone temperature are key parameters that dictate the required formation time.

Pellet formation by cutting from continuous solid extrusions is the only practical means for the high pellet throughputs needed for fueling future fusion burning plasmas. The force needed to extrude different isotopic mixtures through different nozzle geometries at different temperatures was examined and compared with two models. The measured forces required to extrude through the different nozzles are consistently about 50% higher than predicted. The forces are not excessive for practical high throughput extruders except at temperatures well below (< 3 K) the triple point temperature. Future force measurements in screw extruders with dynamically changing nozzle openings are planned.

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