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Abstract

A large collection of particles can behave collectively like a fluid. In this work, we examine the fluid behavior of a large collection of particles in the absence of a background gas phase. The use of granular fluids, as opposed to liquids, has several advantages for free-surface plasma-facing coolants: low vapor pressure, absence of electromagnetic interactions, and chemical inertness, to name a few. Overall, granular fluids are expected to benefit from substantially reduced plasma interaction as compared with liquids. However, one of the primary concerns is the lack of fluid cohesion which, in an unconfined geometry, creates a difficult problem with flow control. Some of the concerns include maintenance of adequate packing fraction, particle ejection into the plasma and flow around obstructions. Numerical particle dynamic simulations have been performed in order to improve our understanding of flow control issues and to suggest design solutions which would allow this class of coolant and plasma-facing material to be used in a commercial fusion power plant.

Simulations were performed using the “distinct element” method, which directly simulates the momentum equation and force-displacement relations for a large collection of interacting circular particles. The method allows for static and sliding friction between the particles (and with the walls), finite normal and shear stiffness, and bonding forces.

Initial results highlight the difficulty in maintaining dense uniform packing in a fully free-falling region. Internal contact forces must be avoided in the inlet zone to prevent the bed from dissociating and creating excessive porosity. Alternatively, the geometry of the substrate can be tailored with baffles or curvature. The basic flow behavior for these geometric elements are presented and design strategies proposed.

1. Introduction

Plasma-facing components, including the first wall and divertor, are subjected to very severe environmental conditions and must exhibit relatively high reliability and lifetime in a fusion power plant. Concerns include thermomechanical responses to high heat flux, plasma particle erosion, neutron damage and electromagnetic forces. The idea of using liquid plasma-facing surfaces was recognized from the earliest days of fusion power plant studies as a potential solution to many of these concerns [1]. A rather extensive R&D program in the former Soviet Union helped to develop several free surface liquid metal design concepts [2], and more recently the U.S. has embarked on an intensive program to explore a wider range of advanced in-vessel design concepts that includes free-surface liquids [3,4].

A potentially fatal flaw with liquid plasma-facing surfaces is the plethora of plasma interactions that are almost completely unknown. Evaporation of neutral atoms into the plasma edge will limit the operating temperature and power handling capability of liquids, and may lead to degraded and/or unpredictable plasma performance. MHD and transient electromagnetic interactions with the plasma are highly uncertain and complex. Previous attempts to introduce a liquid plasma-facing surface into tokamaks have found substantial impurity ingress and severe degradation of plasma performance [5,6].

Granular concepts have been considered for many years as an alternative coolant in confined channel flows [7] as well as a candidate for direct plasma exposure [8]. In addition to impurity control advantages, the surface heat flux handling capability of a fast-flowing stream of pebbles has been shown to exceed 100 MW/m^2 [9]. The main features of granular fluids that distinguish them from liquids include low vapor pressure, high temperature limits, absence of magnetohydro-dynamic and electromagnetic interactions, and also the ability to engineer the pebbles with multiple layers to satisfy plasma-interactive, tritium transport and heat removal requirements individually.

One of the most fundamental concerns with granular fluids is flow control – whether or not a granular medium can be injected and guided without a plasma-facing wall in such a way as to remove heat while maintaining acceptable performance without interfering with the plasma. Most of the difficulty with flow control stems from the lack of fluid cohesion. Some of the concerns include maintenance of adequate packing fraction, particle ejection into the plasma and flow around penetrations.

Figure 1 shows the cross section of a low aspect ratio (ST) power core with a granular first wall and divertor that served as the reference geometry for flow analysis. The flow is introduced from the top where it is guided by SiC baffles and allowed to free-fall into a collection zone at the bottom. Initial studies of granular flows have been performed on this geometry using particle dynamic simulations in several basic flow geometries: a straight vertical chute, a vertical chute fed by a hopper, and a vertical chute with curved back wall. These studies have shown a characteristic feature of these flows – compaction and its resulting internal contact forces invariably lead to decompaction and a tendancy for the bed to separate. Fortunately, the requirement on bed packing fraction is very modest, such that even a few percent is adequate to intercept 99% of the plasma radiation heat flux.

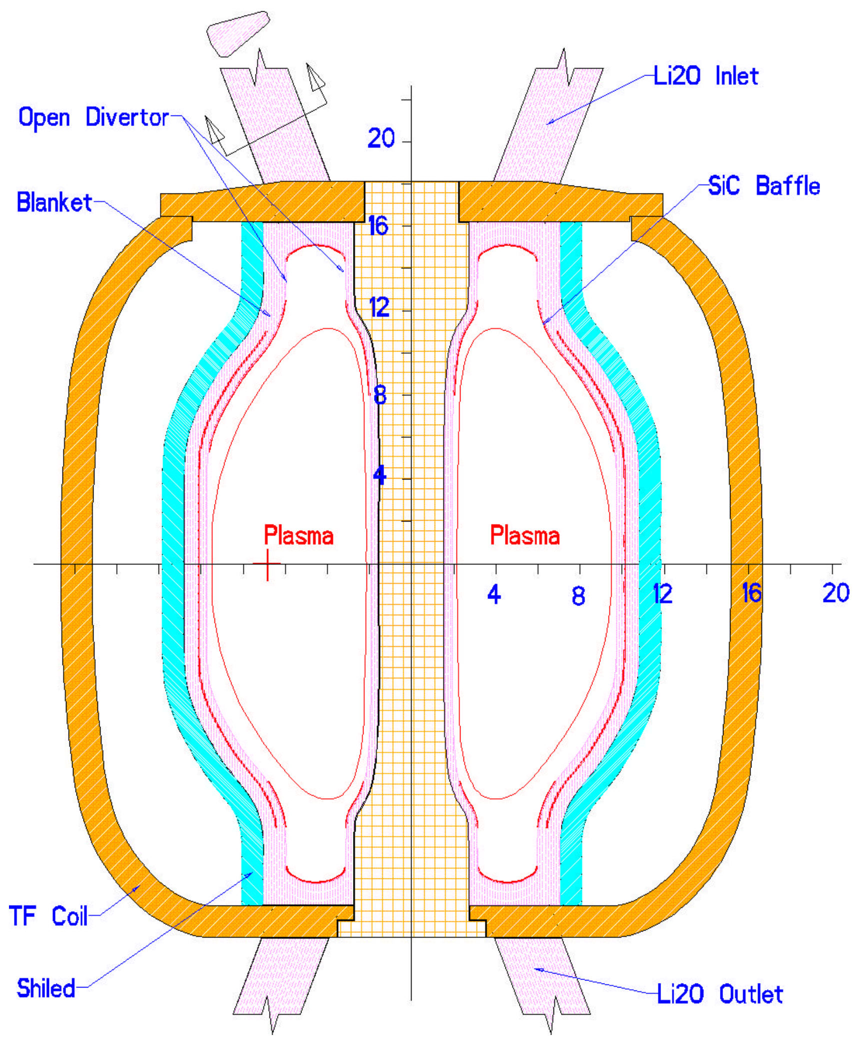

Figure 1. Cross section of the APPLE concept

2. Analysis Method

2.1 Particle flow model

Particle dynamic simulation has seen a renaissance during the past several years due to computer advances that allow solutions of the equations of motion for large assemblages of particles. At present, commercially available codes are available for both 2D and 3D dynamic simulations. Using the PFC2D modeling tool [10], particle trajectories, contact forces and rotational motions have been studied for various inlet and downstream configurations.

PFC2D models the movement and interaction of stressed assemblies of circular particles using the distinct element method (DEM). The DEM was introduced originally by Cundall [11,12] for rock and soil mechanics problems, and has been applied extensively to the analysis of plug flows [13,14]. The interaction of particles is treated dynamically with states of equilibrium developing as the internal forces balance. The solution alternates between the application of Newton's second law to individual particles (to determine the motion of each particle arising from the contact and body forces acting upon it) and a force-displacement law at the contacts (to update the contact forces arising from the relative positions at each contact). The particles interact with each other and with walls only at contact points, using a soft-contact approach wherein the rigid particles are allowed to overlap one another. The small amount of overlap between the rigid bodies (see Figure 2) is related to the force by either a linear or Hertz-Mindlin relation. Both normal and shear forces are determined using the corresponding normal and shear stiffnesses:

$$F_i^n = K^n \, U^n \, n_i \tag{1}$$

$$\Delta F_i^s = -K^s \, \Delta U_i^s \tag{2}$$

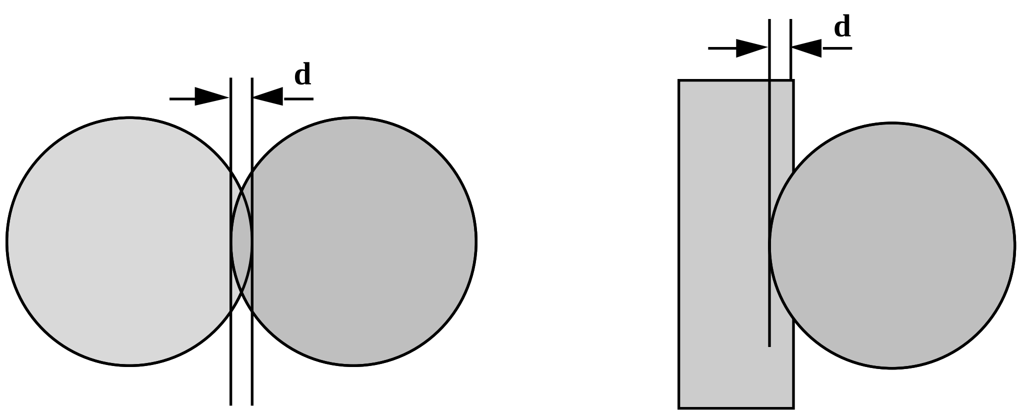

Figure 2. Contact between two spheres and between a sphere and a wall

where K^n and K^s are the normal and shear stiffness, respectively, and U^n and U^s are the normal and tangential overlap. The translational and rotational motions of a single rigid particle are determined by the resultant force and moment vectors acting upon it using the translational and rotational equations of motion.

2.2 Radiation opacity

One of the principal requirements on a free-surface granular flow is to intercept the majority of the plasma thermal radiation before it arrives at the first solid structural wall. A first-order estimate can be obtained using Bouger's Law applied to a uniform bed of depth d:

$$I = I_o \exp(-a_\lambda d) \tag{3}$$

where a_λ is the spectral absorption coefficient. For spherical particles with radius r, number density n and spectral absorption efficiency e_λ, the absorption coefficient can be expressed as [15]:

$$a_\lambda = \pi r^2 n e_\lambda \tag{4}$$

The bed porosity (ε) can be related to the number density of particles as follows:

$$\varepsilon = 1 - 4/3\, \pi r^3 n \tag{5}$$

Combining Eqns. 3–5 for a grey medium with e_λ=1, we find:

$$I/I_o = \exp\left(-3/4\, (1-\varepsilon)\, d/r\right) \tag{6}$$

For example, using pebbles with 0.5-mm radius, the product of packing fraction and bed depth must be at least 3 mm in order to reduce the time-averaged radiation heat flux by two orders of magnitude. This can be achieved with a 5-cm bed having 94% porosity or a 15-cm bed having 98% porosity.

3. Simulation Results and Discussion

3.1 Vertical chute

In order to illustrate the basic flow characteristics of a free-falling bed, a simple vertical chute was examined first. For all cases examined, 2D cylinders with 1-mm diameter were simulated. The number of particles varied between 10,000 and 20,000, and a particle friction coefficient of 0.5 and various wall friction coefficients from 0.1–0.5 were used.

Conservation of mass dictates that the bed will decrease in effective thickness as its downstream velocity increases. Unlike liquids, the actual thickness tends to remain constant and the porosity increases proportionally with velocity. In free fall:

$$v^2(x) = v_o^2 + 2gx \tag{9}$$

The initial velocity should be larger than $(2gx)^{1/2}$ in order to avoid substantial reduction in downstream porosity. Friction with the walls can help decelerate the bed downstream, however excessive wall interactions can lead to particle scattering and/or over-compaction.

An initially uniform bed with uniform velocity has been shown to flow essentially as a slug (see Figure 3), which is a desirable outcome. The downstream porosity evolves consistent with Equation 9. However, establishing the initial uniform condition is not easy in practice. Figure 4 shows the opposite extreme of a vertical chute which is initially plugged near the channel exit. A compaction wave emanates from the obstruction and causes a buildup of internal contact forces (identified by dark black areas in the figure). As particles on the downstream side of the compaction zone escape, they accelerate away from the bulk of the bed, leading to large increases in downstream porosity and erratic, nonuniform flow patterns. Clearly, the method of injection is one of the most important factors in determining the downstream conditions.

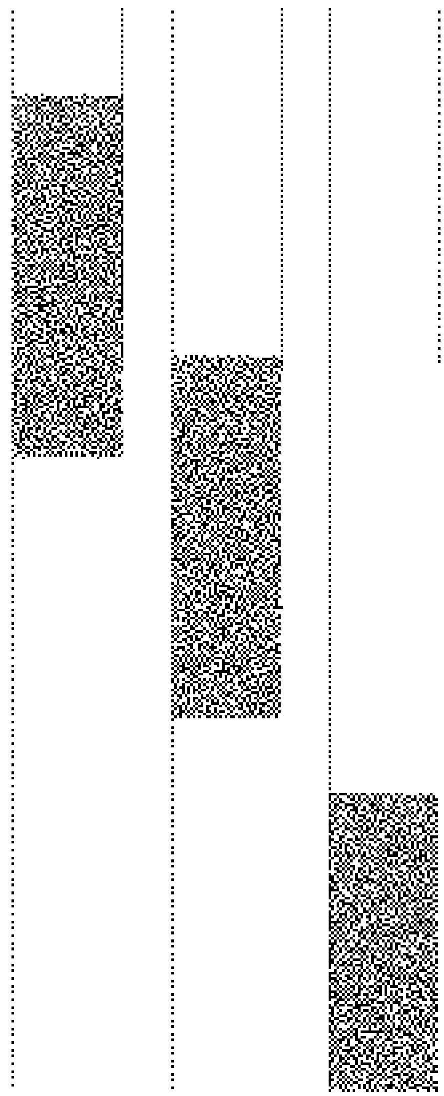

Figure 3. Flow geometry in a vertical chute with uniform initial condition

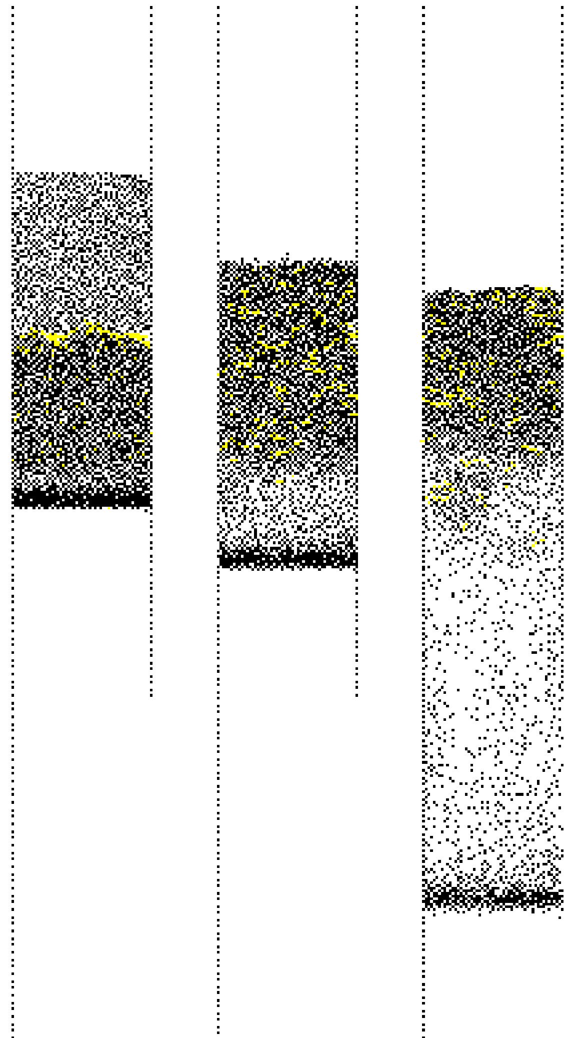

Figure 4. Flow geometry in a vertical chute with plugged initial condition

3.2 Flow from a hopper

In order to examine more realistic inlet conditions, a simple hopper was modeled. Particles are fed into the top of the hopper and undergo some amount of densification as they accumulate. Particles then escape from an exit slot at the bottom. The exit slot width is chosen to be large enough to avoid complete bridging across the exit; however, internal contact forces always arise due to the angle of the walls with respect to gravity. As shown in Figure 5, a boundary layer appears on the walls near the throat and grows until it fills the throat region. The accumulation of contact forces in this region leads to substantial densification, followed by downstream porosity increase similar to the case of an initially plugged opening. The downstream porosity in this case is ~98%. As with the straight vertical chute cases, particle scattering is not seen to be a problem.

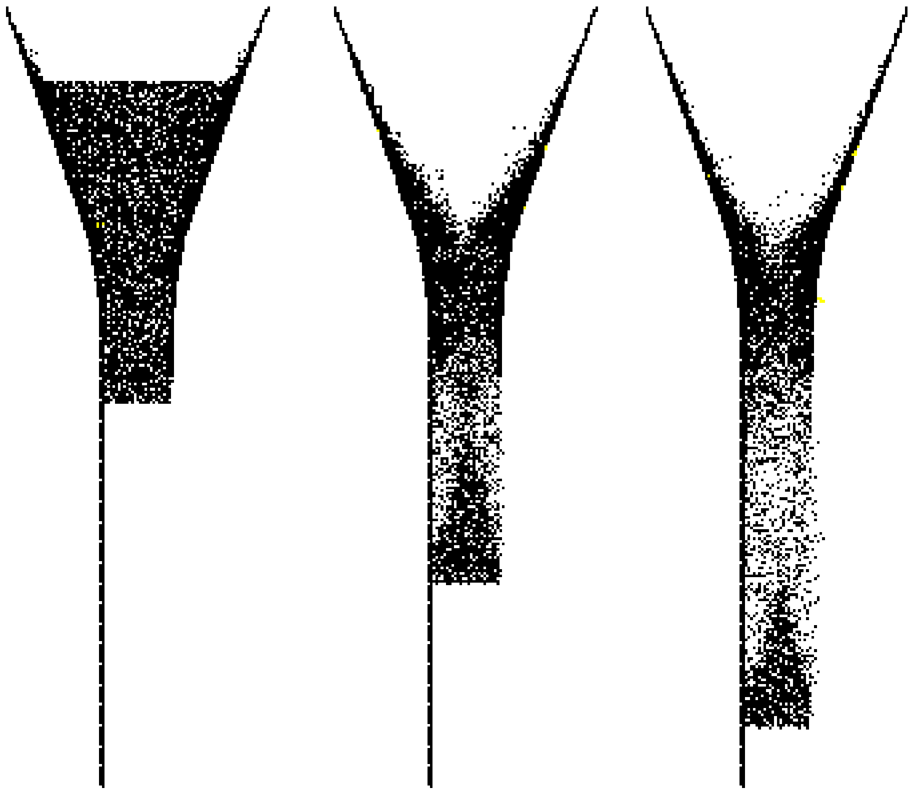

Figure 5. Flow from a hopper

3.3 Flow along a curved back wall

Figure 6 shows an example of the effect of a curved back wall used to guide the flow. The fluid is given an initial velocity of 10 m/s at the inlet and subsequently piles up against the wall at the location where the curvature changes. A boundary layer clearly can be seen to grow from this location. Gravity acts on the flow so as to create an additional boundary layer on the tip of the front wall. Thus, one can observe interaction between the particles leaving the tip and the stagnated boundary flow on the back wall, resulting in substantial particle scattering. Such multiple compaction points are clearly something to be avoided.

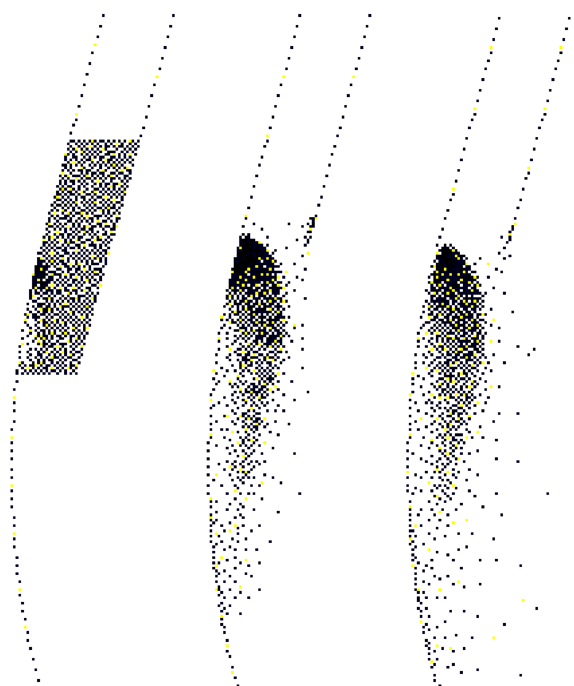

Figure 6. Flow along a curved back wall

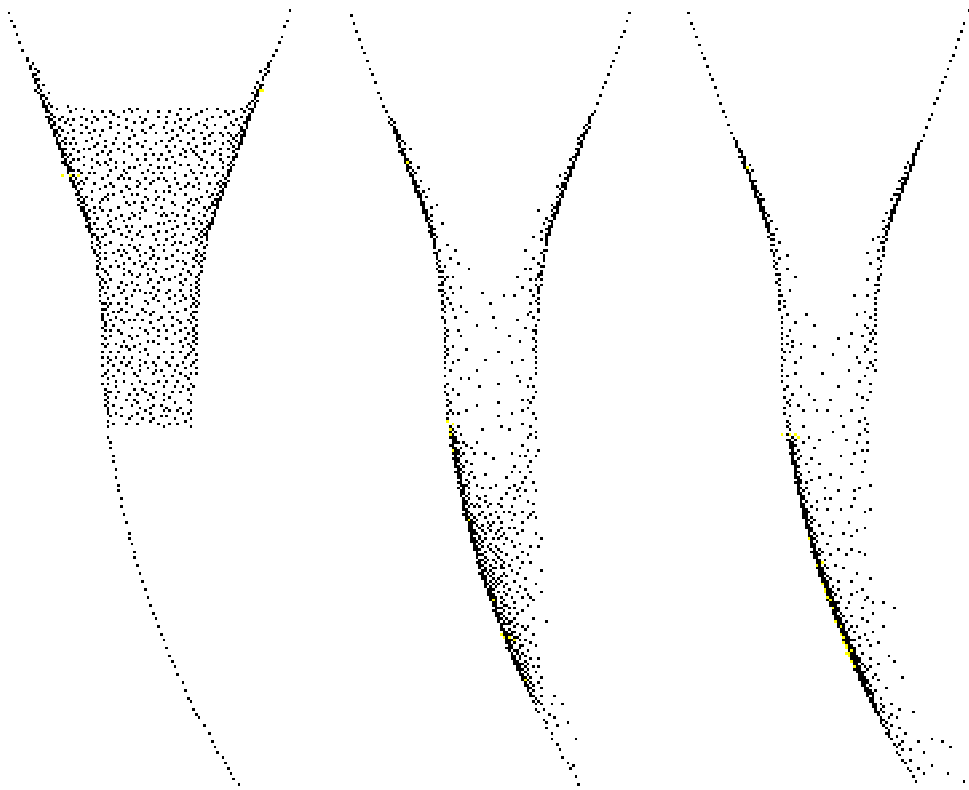

Figure 7. Flow from a high-porosity inlet condition

3.4 High porosity inlet condition

The recognition that compaction and decompaction phenomena are likely to dominate the down stream flow behavior of free-surface granular flows suggests that the inlet porosity might be a dominant parameter. Higher initial porosity might lead to lower downstream porosity if internal contact forces can be avoided. In Figure 7, a hopper is underfilled with a higher porosity (ε=0.965) as compared with the case shown in Figure 5 (ε=0.915). The downstream boundary layer is evident, but does not grow to fill the entire flow path. Rather, the wall retains good coverage and a somewhat more uniform flow distribution results.

4. Conclusions

A variety of compaction, decompaction and scattering phenomena have been observed in the simulation of free-surface granular flows. In the absence of cohesive forces, contact forces are the dominant mechanism that determines the downstream porosity and trajectories. The existence of wall curvature or obstructions invariably leads to some amount of bed compaction, followed by decompaction. However, the modest requirement on bed porosity to adequately screen the first solid wall from plasma radiation appears to be achievable.

The presence of multiple compaction sites can lead to interactions that scatter particles away from the bed. Situations in which a realtively controlled flow is achievable have been observed; these generally require large radius of curvature and low friction coefficient. Careful control of the inlet conditions, including both the velocity and porosity, is a critical factor in achieving well-behaved downstream flows.

These initial studies ha ve not definitively confirmed nor denied the existence of acceptable flow regimes in a real three-dimensional plasma chamber. Further numerical and experimental studies are needed, in combination with more detailed configurational designs.

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