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Gas jets and their interaction with magnetically confined plasmas

Ghassan Y. Antar* and Thomas C. Jernigan**

* *Fusion Energy Research Program, University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0417, USA*
** *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

Abstract

Recently, high pressure jets were used for disruption mitigation. This article reports on studies for understanding the gas jet dynamics in vacuum and as it comes in contact with the plasma. Results of simulations indicate that the neutral jet penetrates very little into the plasma with properties similar to the DIII-D tokamak.

Introduction

Neutral gas injection is routinely used in magnetic fusion devices for a variety of purposes. The most common is gas puffing to maintain and control the plasma density. Recently, massive gas jets have been used successfully to mitigate disruptions [1]. It is generally accepted that disruption control is critical for the viability of ITER-type devices. Being able to mitigate disruptions in this type of devices is of prime importance and is the driving motivation of this work.

The purpose of this brief communication is the dynamics of gas jet interaction with the plasma *via* numerical simulation. The first part deals with the gas jet propagation in ducts and into vacuum. The second part is dedicated to simulating the gas jet-plasma interaction. The specifications of the DIII-D gas jet are used.

Gas jet behavior in vacuum and inside ducts

The first stage of the process is free expansion from the nozzle (here it denotes the valve) until the jet encounters the duct tube. The sound speed of a gas at rest is denoted by c_s [2]. The Mach number is defined as $M = V/c_s$ where V is the jet average axial velocity. To solve the problem of gas jet expansion into vacuum, the idea is to put density, temperature, pressure and cross-section area (A) as a function of the specific heat ratio γ and M; For example

$$\frac{n}{n_0} = (1+\frac{\gamma-1}{2}M^2)^{-\frac{1}{\gamma-1}} \ , \ \frac{T}{T_0} = (1+\frac{\gamma-1}{2}M^2)^{-1} \ .$$

The Mach number dependence on the downstream distance from the nozzle is then determined by numerical simulation of the full compressible Navier-Stokes equations. Afterwards, the Mach number dependence on the distance to the nozzle $Z = z/d_{nozzle}$, normalized to the nozzle diameter, is fitted by a polynomial with the following expressions:

$$
\begin{aligned}
M &= (Z)^{\frac{\gamma-1}{\gamma}}(C_1 + \tfrac{C_2}{Z} + \tfrac{C_3}{Z^2} + \tfrac{C_4}{Z^3}) && \text{for } Z > 0.5 \\
M &= 1 + AZ^2 + BZ^3 && \text{for } 0 < Z < 0.5
\end{aligned}
$$

The values of the different constants are given in Ref. [3]. The jet is sonic at the nozzle exit and rapidly becomes supersonic with the Mach number continuously increasing as a consequence of the temperature drop with increasing distance to the nozzle. After a short distance from the nozzle exit, the axial velocity of the jet remains equal to $V_\infty \sim \sqrt{2\gamma/(\gamma-1)T_0}$, and both the temperature and density drop sharply and continue to decrease with increasing Z; T_0 is the gas temperature inside the bottle.

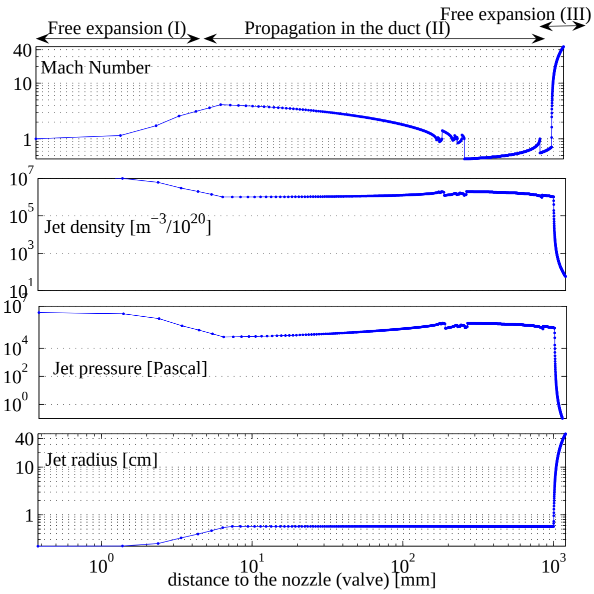

Figure 1: The jet Mach number, (a), density, (b), temperature, (c), pressure and (d) radius. This simulation includes the three stages: free expansion (I), for $z = Zd_{nozzle} < 7$ mm, propagation in a duct with constant area $7 < z < 1000$ mm, free expansion II in the SOL for $1000 < z < 1200$ mm.

For ducts with constant cross-section area, as it is often used for fusion application, the pressure drop because of friction depends on whether the flow is laminar or turbulent which can be assessed using the Reynolds number (Re). In the DIII-D tokamak, the nozzle diameter is 3.8 mm while that of the pipe is 12 mm. When the gas jet hits the tube, the Reynolds number is about 1.6×10^6 indicating that the flow is turbulent. In this case, the effect of friction leads to the so-called friction chokes. The friction force, f, in this case is given by [2]:

$$
\frac{1}{\sqrt{f}} = -4\log_{10}\left(\frac{\epsilon/D_t}{3.7} + \frac{1.25}{Re\sqrt{f}}\right) \;,
$$

where ϵ and D_t are respectively the roughness and the diameter of the pipe. The effect on the Mach number is deduced from the momentum balance equation, leading to

$$\int_0^{L_t} \frac{4f}{D_t} dz = \int_0^{L_t} \frac{2}{\gamma M^2}(1 - M^2)(1 + \frac{\gamma - 1}{2} M^2)^{-1} \frac{dM}{M} \quad ,$$

L_t being the length of the tube. Friction forces in duct tend to decrease the Mach number if the flow is supersonic and to increase it for subsonic flows. The tube in DIII-D is about 1 m long, and the evolution of the Mach number is shown in Fig. 1. The behavior of the temperature is obtained assuming an adiabatic process. The axial jet velocity is then obtained using the definition of the Mach number. The jet density and pressure variations are obtained using the continuity and the perfect gas equations respectively. In most of the applications of gas jet ejection into fusion plasmas, the tube is left relatively far from the separatrix to avoid direct contact with the plasma. In the DIII-D tokamak, the tube ends at approximately 20 cm away from the separatrix. Between the end of the tube and the plasma, the jet expands freely according to the same equations described in the first free expansion. The evolution of the main gas jet quantities is depicted in Fig. 1 as a function of the distance from the nozzle.

Simulating the Gas jet interaction with the plasma

This section describes very briefly the numerical simulation of the gas jet penetration into the plasma. The parameters of the jet and the plasma correspond to that of the DIII-D tokamak. In our approach, we assume neutrality of the plasma (singly ionized) and a toroidal velocity equal to the ion sound speed. The particle balance equation reads $\partial_t n_e = \partial_t n_i = n_e n_0 (S - \alpha)$. It states that the increase of the number of electrons (n_e), and thus the decrease of the number of neutrals (n_0), is determined by the rate of ionization S minus that of recombination α. Solving the continuity equation determines the evolution of the plasma electron density as well as the neutrals of the gas jet. The behavior of the temperature, on the other hand, is deduced from the power balance given by

$$\partial_t (\frac{3}{2} n_e T_e) = P_{ohmic\ heating} - P_{radiation} - P_{ionization} \quad .$$

A sample of the results is shown in Fig. 2 where after 1 ms the gas penetrated the plasma only up to $r/a \sim 0.75$. This is in agreement with recent results obtained by imaging the massive gas jet, where it is clear that the jet did not penetrate to the plasma center. After 1 ms, one can show that MHD activity leads to mixing not accounted for in this model.

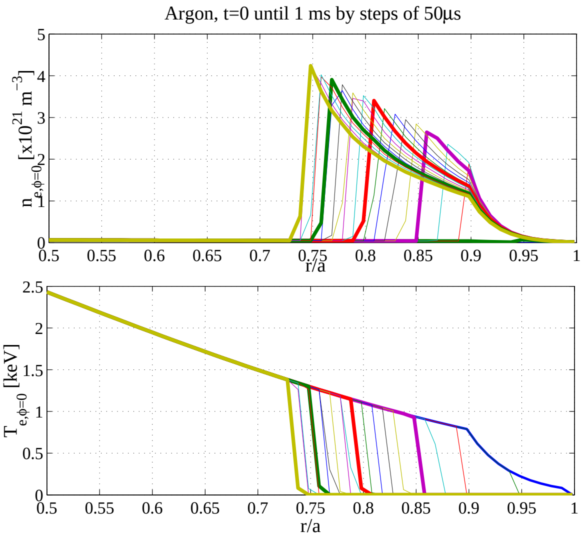

Figure 2: Effect of Argon gas jet on the plasma density (a) and temperature (b). According to this simulation, the jet penetrates to $r/a \simeq 0.75$ after 1 ms.

Conclusion

Analytical expressions of the gas jet propagating either in vacuum or in ducts are presented. The jet expands into vacuum twice; first, as it encounters the duct and second as it emerges from the duct. In the duct, the Reynolds number is very high indicating turbulent flow. Consequently, the friction forces are important leading to a sonic flow at the tube exit. Finally, we showed simulation of the gas jet with the plasma based on the particle and energy balance. We find that after 1 ms the gas jet had penetrated only about 25% of the minor radius. After this value MHD instabilities lead to complex behavior not described in our simulation [4].

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