Throat Curvature For Improved Density Profile Optimization Of Supersonic Gas Jet Targets

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Supersonic gas jet nozzles are a common way of producing under-dense targets for laser-plasma interactions. For many applications, such as wakefield acceleration, the density profile of the target needs to be well understood. A 'flat top' density profile is often preferred and other work optimised the geometry of the nozzle for such profiles.[1] [2]. This type of optimization focuses on the ratios of the main dimensions: The exit/mouth diameter d_e, the throat diameter d^* and the length of the diverging portion of the nozzle l_d.

This approach, while capable of mitigating the effect of shocks generated at the throat, has a limiting effect of restricting the nozzle angles (θ_d) available. Through CFD simulation using Ansys Fluent (see Methods) we will show that new parameter space can be opened up in nozzle design through the use of throat curvature. First, we justify our methodology that establishing smooth profiles for the high pressure case, is sufficient for lower pressures. We then show that the previous approach of smoothing by redirecting shocks, while effective for one gas, may not work for others with a different adiabatic constant. Finally, we show that using throat curvature can provide a smooth density profile for different gases. In this paper we set all nozzles to have $d^* = 1mm$ and $d_e = 20mm$.

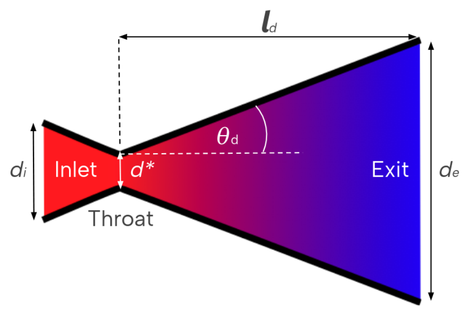

Figure 1: A converging - diverging nozzle with a high pressure inlet and a low pressure outlet.

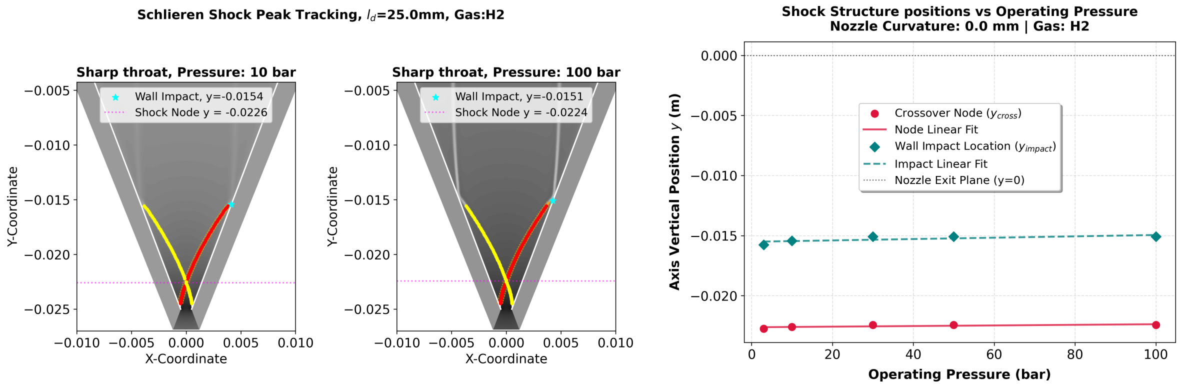

Figure 2: Synthetic schlieren images of the same nozzle at 10 bar (left) and 100 bar (centre) backing pressure. The graph shows the position of the shock crossing and wall impact relative to the mouth, as a function of density.

To study the effect of backing pressure we select a nozzle which clearly shows the effect of throat shocks: $l_d = 25mm$, $d^* = 1mm$ and $d_e = 20mm$.

The images in figure 2 show shocks in the gas flow generated at the throat, reflecting from the inner surface (at the point indicated by the blue star), and disturbing the gas density as it exits the mouth. The graph shows the y-coordinate of the shock crossover and wall impact position relative to the mouth as a function of pressure. We note that over almost two orders of magnitude in pressure, the wall impact position stays almost constant.

Figure 3 shows the density profile (normalised to backing pressure) at 1mm from the exit as a function of backing pressure. The steepest density gradient is marked on each line with a dot. We conclude that, since the flatness of the profile improves with lower gas density, designing a nozzle for high density will likely provide flat profiles for all lower densities.

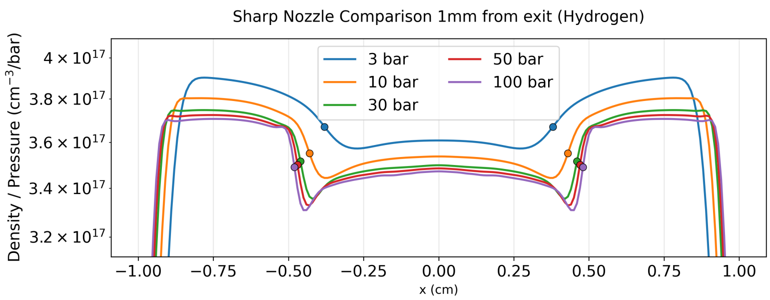

Figure 3: Gas density profile (normalised to backing pressure) at 1mm above the nozzle for a range (3 - 100 bar) of pressures.

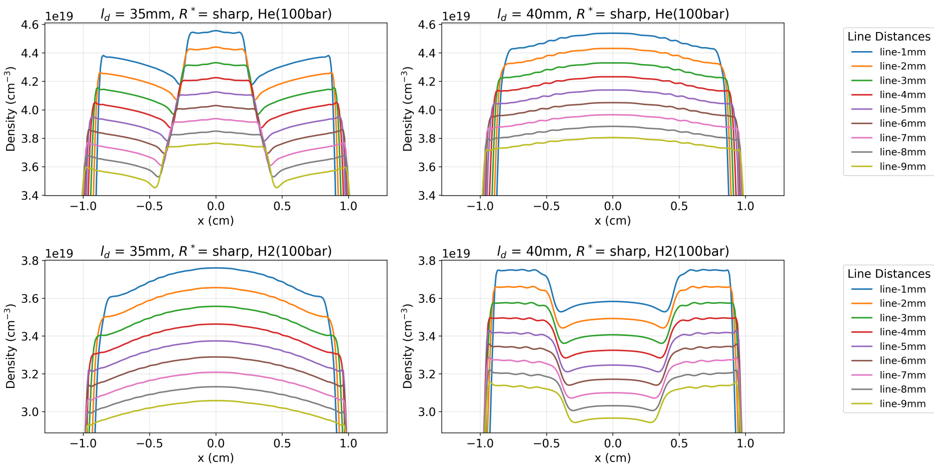

Figure 4: Density profiles for helium (top) and hydrogen (bottom) gas at 100bar (sharp throat). These are produced by nozzle lengths of 35mm (left) and 50mm (right).

Next we consider the effect of adiabatic constant by comparing helium and hydrogen.

Figure 4 shows the density profile of the two gases from two nozzles of differing lengths. Note that, while the choice of nozzle length does allow production of a smooth density profile, a different length must be selected if the adiabatic constant of the gas changes. This is due to different trajectories of the the throat shocks.

We consider the $l_d = 35mm$ nozzle and apply throat curvature, radius R^*, ensuring a smooth transition to the straight nozzle sides to mitigate the shocks. Figure 5 shows the density profiles for this nozzle with R^* of 3mm and 11mm. We find that the steep density gradients are now gone for helium and that with $R^* = 11$ the helium profile has a slight dome while the hydrogen profile has flattened.

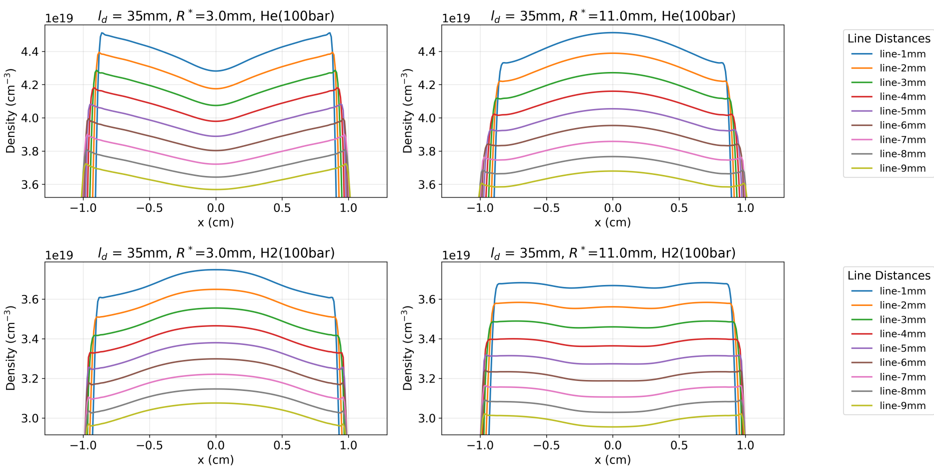

Figure 5: Density profiles for helium (top) and hydrogen (bottom) gas. The throat has been smoothed by a throat curvature, R^*, of 3mm (left) and 11mm (right).

We can also see that the $R^{*} = 3mm$ helium profile is not simply a softened version of the sharp profile shown in fig 4. This is due to a change in the trajectory of the throat shocks. Increasing curvature moves the shock crossing point further into the nozzle. In turn the positions of the outer wall impacts are shifted further towards the nozzle exit. This effect is shown in fig 6 where we can see the shock trajectory from the sharp throat nozzle and one with a large throat curvature. We see that with $R^{*} = 15mm$ the shock entirely miss the lip of the exit. In the case of the $R^{*} = 3mm$ hydrogen profile the shocks were converging near the mouth producing a smooth dip.

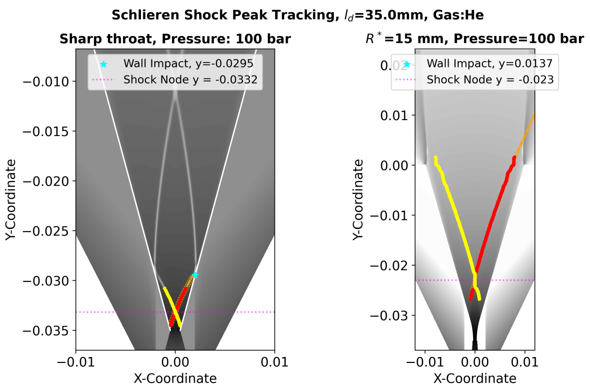

Figure 6: Synthetic schlieren images shows the effect of throat curvature.

Conclusion

A gas jet density profile optimized for high pressure gas will also be suitable for lower backing pressures. Sharp throat nozzles can optimized for either monatomic and diatomic gases but not both. Throat curvature can be used to manipulate the throat shocks both in position and shock strength. This parameter can be tuned to provide flat,domed or dipped density profiles. A gas interchangeable nozzle can be achieved using throat curvature.

CFD Method:

CFD simulations performed using Ansys Fluent. This solves the Navier-stokes equations using a finite volume method. We used a structured mesh of quadrilaterals and double precision steady state density based solver, with energy equations in use and the SST k-omega viscosity model. For all simulations the outlet pressure was set to 1e-4 Pa and the temperature set to 293K. In figures, images used courtesy of ANSYS, Inc.

References

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[2] O. Zhou, H.-E. Tsai, T. M. Ostermayr, L. Fan-Chiang, J. V. Tilborg, C. B. Schroeder, E. Esarey, and C. G. R. Geddes. Effect of nozzle curvature on supersonic gas jets used in laser-plasma acceleration. *Phys. Plasmas*, 28:93107, 2021.