Comparison of mixing processes in a compressible accelerated nozzle flow with subsonic and supersonic injection

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Abstract

In many engineering applications efficient and rapid mixing is necessary. Therefore, extensive research has been done on mixing processes. Most of the investigations deal with mixing in incompressible flows [1] or in supersonic wakes [2] with a constant pressure gradient. In this study the mixing processes in a compressible accelerated nozzle flow with blunt-body wakes were investigated experimentally. The flow structures caused by four different injectors with their trailing edges located in the subsonic part of the flow were discussed in [3, 4]. As a continuation of this work four injectors were investigated that have extended trailing edges, so that the injection takes place in the supersonic region.

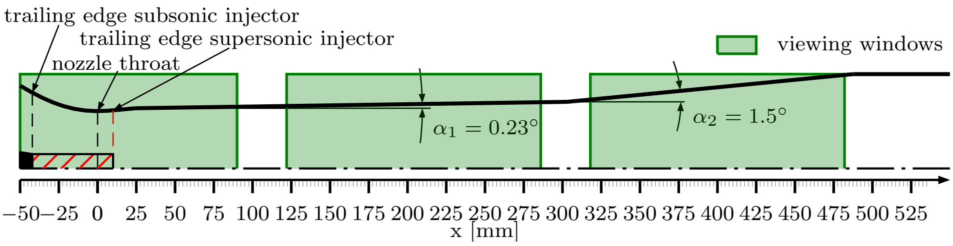
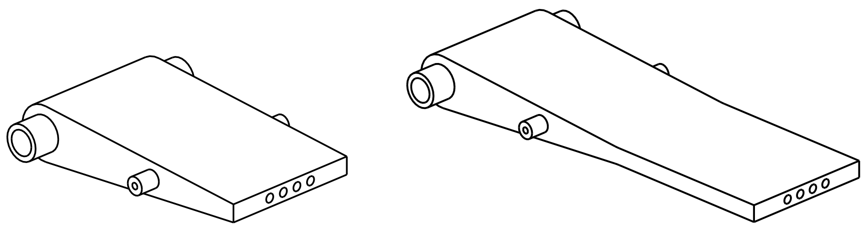


Figure 1: Duct contour including the injector trailing edges, the nozzle throat and the position of all viewing windows

All injectors were installed in a rectangular Laval nozzle which was designed as a model duct for a reactor that has been used for gas-phase synthesis of non-agglomerated nanoparticles by fast gasdynamic heating and cooling [5]. In contrast to many studies that deal with mixing layers in regions with a constant pressure the present study investigates an accelerated flow in a duct (see Figure 1). Injector 1 in Figure 2(a) is shown exemplarily for the injectors with their trailing edge upstream of the nozzle throat. Figure 2(b) shows the extended version of injector 1, where the trailing edge is located downstream of the nozzle throat. This extension resulted in a reduction of the nozzle throat. To keep the mass flow rate through the duct identical to that in the previous experiments with subsonic injection, the total pressure was increased. Thus, the air flow through the duct had a total pressure of 2 bar for subsonic and 2.67 bar for supersonic injection and a total temperature of 308 K in all experiments. The normalized measured wall static pressure can be seen in Figure 3 as a function of distance from the nozzle throat. The trailing edges of the injectors with subsonic (x = -42.1 mm) and supersonic (x = 10 mm) injection and the nozzle throat (x = 0 mm) are labeled in the diagram. Besides injector 5, where parallel injection was observed, two injectors with injection holes at an agle of 45° and 90° to the ambient air flow were tested. Furthermore, one injector was designed with ramps on the upper and lower surface. All these geometries were investigated for the subsonic and the supersonic injection.

A toluene/nitrogen mixture was added into the main air flow through the injectors and the flow structures behind the trailing edges were visualized applying laser-induced fluorescence (LIF) imaging. A 248 nm krypton fluoride excimer laser (Lambda Physik, LPX 120) was used to excite the toluene in the injector flow. Two hundred instantaneous images of the flow were captured using an intensified CCD camera and processed. Figure 4 shows the averaged and



(a) Injector 1: injection at $Ma = 0.79$ (b) Injector 5: injection at $Ma = 1.15$

Figure 2: Two out of eight investigated injector geometries

normalized toluene-LIF intensity profiles perpendicular to the main flow direction 42.1 mm behind the trailing edge for injector 1 and 5 exemplarily. In case of injector 1 the flow was dominated by separated shear layers behind the injector which rolled up to vortices being shed from the blunt trailing edge. Thus, the maximum intensity at the duct centerline decreased fast and the flow had a high spreading rate. In case of injector 5, no vortices could be observed and the growing rate of the wake was smaller compared to injector 1. The injector flow was pushed to the centerline shortly after the trailing edge. This was due to strong oblique shocks located at the injector trailing edge. The smallest cross section of the injector flow was identical with the intersection point of the shocks. Further downstream the flow spread out more and mixed with the ambient air.

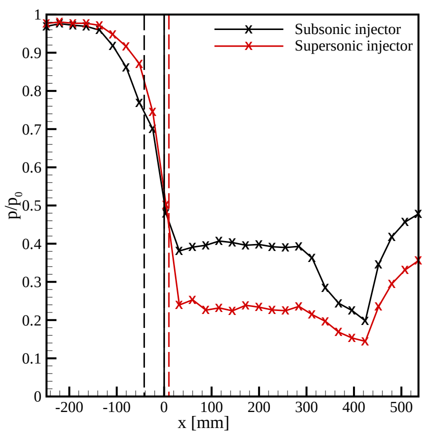


Figure 3: Normalized measured wall static pressure as a function of distance from the nozzle throat

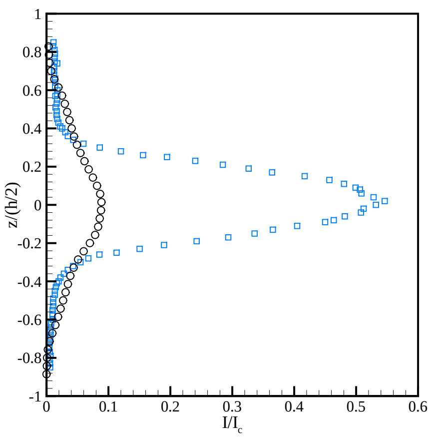


Figure 4: Normalized toluene-LIF intensity profiles behind the trailing edge; ○: injector 1 □: injector 5

References

[1] Wygnanski, I., F. Champagne and B. Marasli. 1986. On the large-scale structures in two-dimensional, small-deficit, turbulent wakes. *Journal of Fluid Mechanics* 168: 31–71.

[2] Gutmark, E. J., K. C. Schadow and K. H. Yu. 1995. Mixing Enhancement in Supersonic Free Shear Flows. *Annual Review of Fluid Mechanics* 27: 375–417.

[3] Wohler, A., K. Mohri, C. Schulz and B. Weigand. Flow structures in subsonic-to-supersonic mixing processes using different injector geometries. *EUCASS, 2011*.

[4] Wohler, A., K. Mohri, C. Schulz and B. Weigand. Mixing processes in a compressible accelerated nozzle flow with blunt-body wakes. *AIAA Journal*. Submitted for publication.

[5] Grzona, A., A. Weiß, H. Olivier, T. Gawehn, A. Gülhan, N. Al-Hasan, G. Schnerr, A. Abdali, M. Luong, H. Wiggers, C. Schulz, J. Chun, B. Weigand, T. Winnemöller, W. Schröder, T. Rakel, K. Schaber, V. Goertz, H. Nirschl, A. Maisels, W. Leibold and M. Dannehl. Gas-phase synthesis of non-agglomerated nanoparticles by fast gasdynamic heating and cooling. *26th International Symposium on Shock Waves, 2009*.