PFE/Master Internship:
Numerical study of the premature unchoking phenomena in transonic nozzles

Place	ISAE-ENSMA, Institut Pprime (CNRS, UPR 3346)
Duration	6 months
Starting Date	by April 2022
Profile of candidate	Engineer/Master 2
Expected skills	compressible fluid mechanics, scientific computing, CFD, turbulence modeling
Allowance	∼670€/month
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Application	Send CV + motivation letter

Framework of the study

The accurate assessment of gas mass flow rate remains a major challenge in aeronautics, space or energy applications. For high-pressure gas transport or storage, reference standards commonly rely on Critical Flow Venturi Nozzles (CFVN) whose discharge coefficient C_d must be carefully calibrated over wide operating ranges. The measurement principle is based on choked flow, where the gas accelerates to sonic conditions at the throat, fixing the mass flow rate independently of downstream conditions as long as the critical back pressure ratio (CBPR) is not exceeded. Industrial calibration consists for example in determining C_d only using the PVT,t (Pressure–Volume–Temperature–time) method, thus by measuring the mass of gas discharged into a reservoir of known volume under controlled upstream conditions. However, no experimental or numerical tool currently allows a fully detailed characterization of the unsteady internal flow features or a full explanation of all factors influencing C_d such as geometric effects, Reynolds-number-dependant transition, non-uniformities, or real-gas effects. Previous studies at Pprime, partly in collaboration with Césame Exadébit company, improved the understanding of the mean flow structure under steady conditions (see Fig. 1 (left)), quantified the influence of surface roughness on C_d [3, 4] and investigated laminar-to-turbulent transition mechanisms[9]. More recent work at PTB (Berlin) also advanced RANS-based numerical approaches to better account for transition or real-gas effects, particularly for hydrogen applications [7, 8]. Further research is still needed to assess the sensitivity to numerical parameters and to establish more robust CFD guidelines for this class of flows.

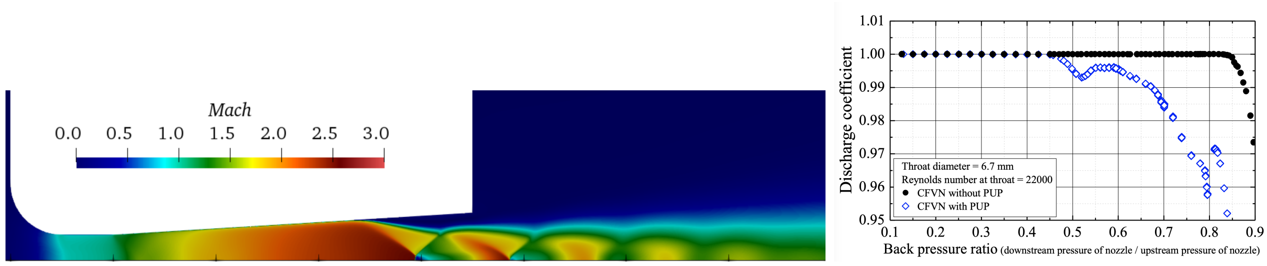

Figure 1: Illustration of nozzle flow structure (left) by means of isocontours of Mach number in a CFVN at BPR=0.2, and example of PUP effect on C_d evolution (adapted from [5]) (right).

A related critical issue concerns the determination and improvement of the CBPR. In PVT,t-based industrial calibrations, operating at high CBPR values is essential to reduce measurement uncertainty (targetting below 0.1–0.2%). Operating at high CBPR is also required in closed-loop applications with high-pressure hydrogen in order to minimize pressure losses and associated economic and environmental costs. In practice, CBPR values up to 0.85–0.9 can be achieved by adding a long, low-angle diffuser downtream of the throat to enhance pressure recovery. However, such geometries may also trigger Premature Unchoking Phenomena (PUP), leading to a sudden intermitted drop in C_d at significantly lower CBPR values values (0.55–0.6), comparable to those of simple convergent nozzles. Only a few numerical studies have reported some numerical observations of PUP associated to downstream pressure oscillations and shock motion in the diffuser [6], whose physical origin yet remains poorly understood. The phenomenon appears to depend on multiple factors, including Reynolds number, surface roughness and diffuser geometry. Existing design recommendations to avoid PUP remains largely empirical, for restricted ranges of Reynolds number and based solely on global measurements of C_d [2, 1]). For example, the use of direct micro-steps at the throat has been reported to mitigate PUP, although without a clear physical explanation[5]. Recent experiments at PTB Braunschweig further highlight the strong sensitivity of PUP to small geometric changes, sometimes accompanied by abrupt CBPR drops and particular acoustic signatures. These observations motivate refined numerical studies to clarify the underlying mechanisms and guide the design of nozzle geometries that could avoid PUP.

Objectives and conduct of the study

The present master's project will mainly aim to:

- conduct a comprehensive literature review of the intermittent unchoking phenomenon
- define a robust and reliable numerical strategy capable of reproducing both the expected steady-state features and unsteady flow structures based on reference experimental data available.
  The open-source mesh generator *Gmsh* (and/or alternative re-meshing libraries) and the CFD solver *SU2* will be used.
- carry out some parametric studies to determine the relevant ranges of geometrical and physical parameters influencing the intermittent unchoking phenomenon
- drawing some design recommendations in view of future detailed experimental characterization of PUP in more canonical configurations

References

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