# The Impact of Guide Tubes on Flow Separation in Rocket Nozzles

*Ralf Stark*[1⋆], *Carla Rieping*[2] *and Thomas Esch*[2]

[1]*German Aerospace Center, Langer Grund, D-74239 Lampoldshausen, Germany*
[2]*FH Aachen - University of Applied Sciences, Bayernallee 11, D-52066 Aachen, Germany*
⋆Corresponding author

## Abstract

Rocket engine test facilities and launch pads are typically equipped with a guide tube. Its purpose is to ensure the controlled and safe routing of the hot exhaust gases. In addition, the guide tube induces a suction that effects the nozzle flow, namely the flow separation during transient start-up and shut-down of the engine. A cold flow subscale nozzle in combination with a set of guide tubes was studied experimentally to determine the main influencing parameters.

## 1. Introduction

During the start-up and the shut-down of a rocket engine, the strong over-expansion of the flow in the nozzle leads to an unavoidable flow separation. During these transient processes, the separation position shifts axially,[1] depending on the nozzle pressure ratio (NPR). The NPR is defined as the quotient of combustion chamber pressure and ambient pressure, NPR=$p_{cc}/p_a$.

The flow separation leads to undesired side loads, stressing the nozzle itself, the rocket engine, the rocket structure, and the payload. Depending on the nozzle contour type, it occurs as free shock separation (FSS, Fig. 1 left) or even as restricted shock separation[2] (RSS, Fig. 1 right). The understanding of the separation position is crucial for rocket engine design. The separation position not only determines the maximum possible nozzle length, a deciding factor for the engine performance, but also the behaviour of the engine at test facilities and on launch pads.

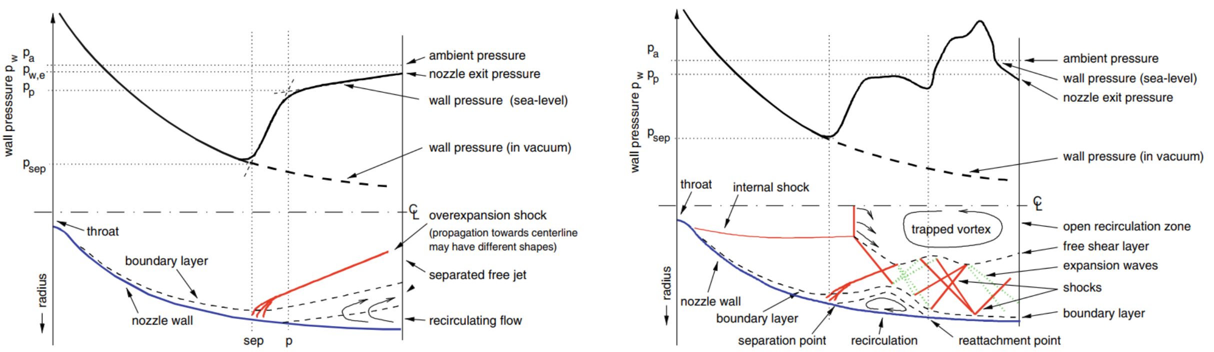


Figure 1: Characteristics[2] for free shock separation pattern (FSS, left) and restricted shock separation pattern (RSS, right)

Test facilities and launch pads are typically equipped with a guide tube. Its purpose is the controlled and safe routing of the hot exhaust gases. In recent times, the guide tube's acoustical interaction with the rocket nozzle exhaust jet has come into focus. Experimental studies[3] revealed geometrical dependencies as main influence parameters, in particular the ratio of the nozzle exit diameter vs. the guide tube inlet diameter, and the distance of nozzle exit and guide tube inlet. In addition to the acoustic coupling, the impact of the guide tubes on the transient progress of the flow separation was also determined. This study evaluates the separation data obtained.

## 2. Experimental Setup

Tests were realized at cold flow subscale test facility P6.2 in Lampoldshausen, which features dry gaseous nitrogen as working fluid, stored in 20 MPa high pressure vessels under ambient temperature. Nitrogen is used instead of air to minimize condensation effects. The subsequent supply system, consisting of an automatic valve, a filter, a pressure reducer, a regulation valve, and a mass flow meter, connects the fluid supply with a settling chamber that is mounted on a horizontal rig. The settling chamber is equipped with a set of grids and honeycombs to homogenize the flow. The mesh size is 4 mm$^2$, reducing the effective cross section down to 64%. The tested nozzle specimens were mounted downstream of the settling chamber. The facility features a maximum total pressure of $p_0$ = 6 MPa, with a maximum mass flow of 4.2 kg/s.

### 2.1 Nozzle Specimen

To study the interaction of a subscale rocket nozzle and different configurations of guide tubes, the already tested TICTOP B1 nozzle was chosen. The TICTOP B1 combines the internal shock free throat section of a truncated ideal contour nozzle (TIC) with a thrust optimized parabola nozzle extension (TOP).[4,5] The nozzle was made of acrylic glass, with a wall thickness of 8 mm (Fig. 2).

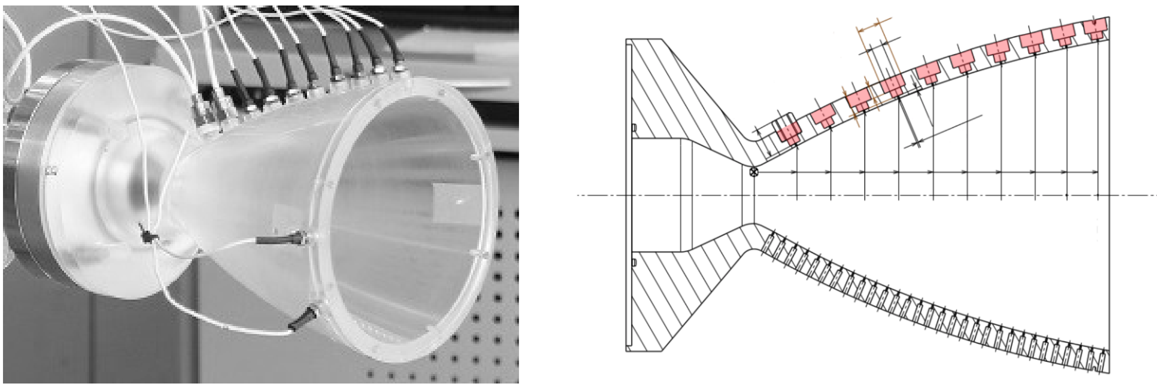

Figure 2: TICTOP B1 nozzle (left) and sketch with sensor positions 1-10 (marked in red, right)

To measure the static wall pressure distribution, the nozzle was equipped with an axial row of 10 piezoresistive XT-154-190M type Kulite pressure transducers, directly mounted into the nozzle wall. Two additional transducers, mounted in a cross section near the nozzle exit at different circumferential positions, completed the wall pressure measurements. All transducers were connected to the flow via orifices (0.5 mm), drilled perpendicularly into the nozzle wall.
The transducers have a measurement range of 0.1 MPa with an accuracy of 0.5% relative to the upper range limit. The natural frequency of the transducers' pressure-sensitive semiconductor membrane is higher than 50 kHz. However due to the eigenfrequency of the combination of orifice and cavity, the pressure signals were analogue filtered with a cut-off frequency of 8 kHz and recorded with a high frequency rate of 25 kHz.

### 2.2 Guide Tubes

Based on a reference guide tube, a set of 5 guide tubes was designed and manufactured. The guide tubes varied in diameter, length, and shape. The reference guide tube, in combination with the TICTOP B1 nozzle, was a geometrical downscaling of a typical rocket engine test bench configuration. Figure 3 (right) and Tab. 1 illustrate the geometrical proportions. The effect of the different specific heat ratios of hot and cold flow exhaust jets was not considered.

The guide tubes were made of polyamide (PA12) and directly printed in 3D by selective laser sintering (SLS). The design included plate mounts and sliders. The sliders enabled a horizontal adjustment of the guide tubes with regard to the nozzle exit. The experimental setup was completed by a circular plate around the guide tube inlet, representing a test cell floor, in order to mimic the inflow conditions of the full-scale guide tube (Fig. 3, left).

### 2.3 Test Sequence and Test Matrix

For comparison reasons, all configurations were tested with the same test sequence. Figure 4 illustrates the related total pressure profile. A steep total pressure increase was followed by a medium gradient phase, where the smooth

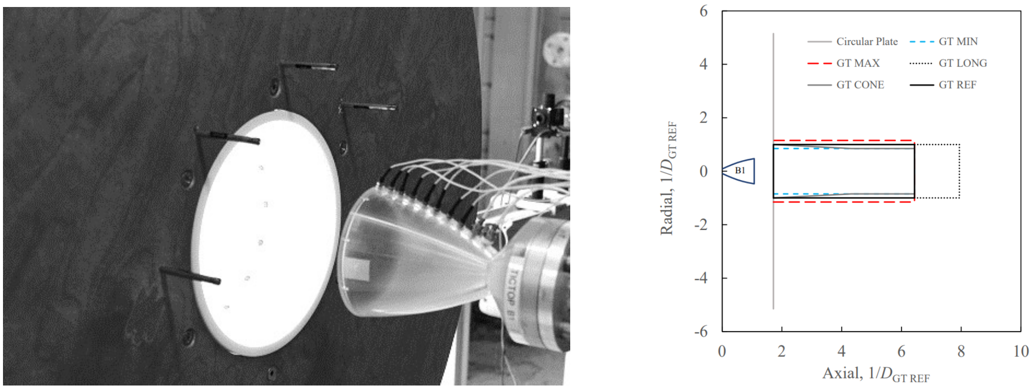


Figure 3: GT-Ref with circular plate (left) and guide tube scaling (right)

downstream shift of the flow separation was recorded. To study the behavior of the full-flowing nozzle, a pressure plateau completed the sequence, until the nozzle was shut down by closing all valves with maximum speed.

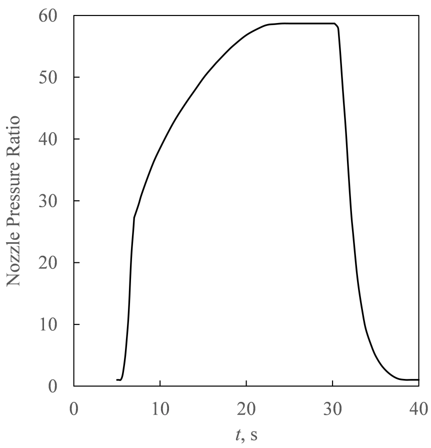


Figure 4: Test Sequence

After testing the nozzle free jet and its interaction with the reference guide tube for different distances in detail, the guide tube modifications were studied for selected configurations. Table 1 summarizes the test matrix.

Table 1: Test matrix

| Guide Tube | $D_{GT}/D_{eB1}$ | Tests | Configurations |
|---|---|---|---|
| Free Jet | - | 13 | 1 |
| GT-Ref | 2.4 | 22 | 8 |
| GT-Min | 2.04 | 10 | 5 |
| GT-Max | 2.76 | 8 | 4 |
| GT-Long | 2.4 | 5 | 3 |
| GT-Cone | 2.4 / 2.04 | 12 | 5 |

## 3. Results and Discussion

Ahead of testing the different guide tube configurations, the TICTOP B1 exhaust jet itself was studied under free-jet conditions. Figure 5 links the separation or, more precisely, the pressure port position (see Fig 2, right) with the NPR value that is necessary for the separation zone to pass over the respective position completely. That is, the lowest possible wall pressure $p_{sep}$ has been reached (see Fig. 1, left). Compared to wall pressure data, the NPR is better suited for clarifying the shift in the separation front during the transient start-up. As each test was carried out with the same test sequence, a reduced NPR meant that the pressure port position was reached earlier, i.e. the separation front was accelerated. The transient separation behavior under free-jet conditions is illustrated by the red line (triangles).

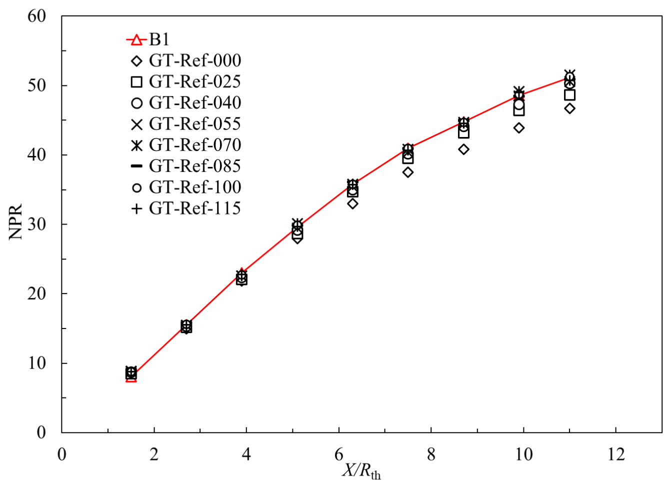


Figure 5: Impact of the reference Guide Tube (GT-Ref) on the flow separation

The reference guide tube GT-Ref was tested in 8 configurations (Tab. 1), with distances of 0-115 mm (Fig. 5). It can be seen that the first 3 pressure port data points didn't show any deviation from the free-jet behavior. The first significant deviations took place at port position 4 and continous further downstream. The clearest deviations were at a gap distance of 0 mm (GT-Ref-000), followed by the distances of 25 and 40 mm. The configurations with a larger gap continued to follow the free-jet trend of B1 and almost didn't deviate.

The expectation that the influence of a guide tube increases with decreasing gap distance was confirmed for GT-Ref. In particular, it could be seen that there was a significant influence if the gap distance was less than half the nozzle exit diameter ($d_{gap}$<55 mm).

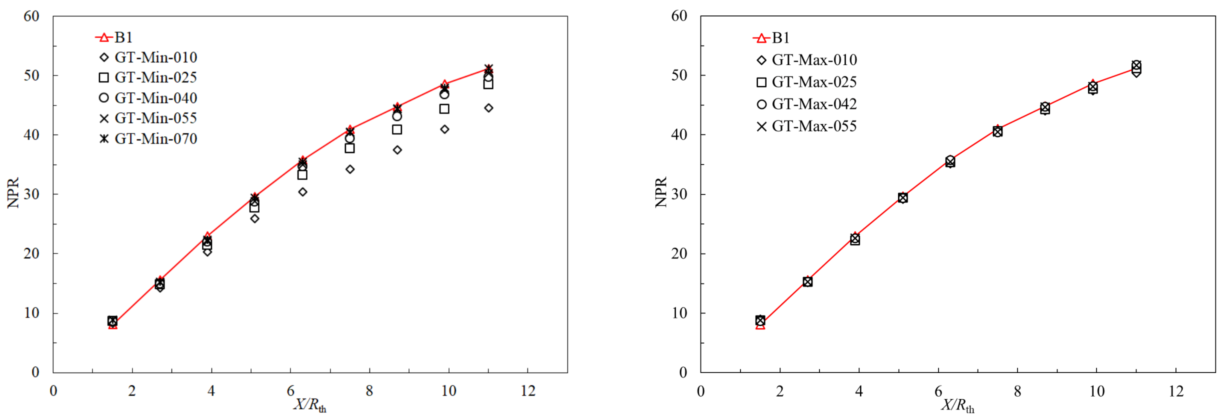


Figure 6: Impact on the flow separation by GT-Min (left) and GT-Max (right)

Figure 6 (left) shows the results for the guide tube GT-Min, which kept the length but which diameter was reduced by 15%. Here, the gap distances were 10-70 mm. In contrast to the reference guide tube, GT-Min influenced the flow separation from sensor position 3 onwards. Another difference appeared in the acceleration of the separation front. The impact was much more pronounced for the smallest gap distance (10 mm). The NPR values of the 25 mm and 40 mm configurations were also reduced. In summary, the reduced guide tube diameter meant that the suction effect started earlier and the flow separation was once more shifted significantly downstream compared to GT-Ref.

The guide tube GT-Max kept the reference guide tube length as well, but the diameter was increased by 15%. The gap distances were 10-55 mm. Figure 6 (right) shows the results. Guide tube GT-Max had no impact on the flow separation. Even at the last sensor position there were no significant differences.

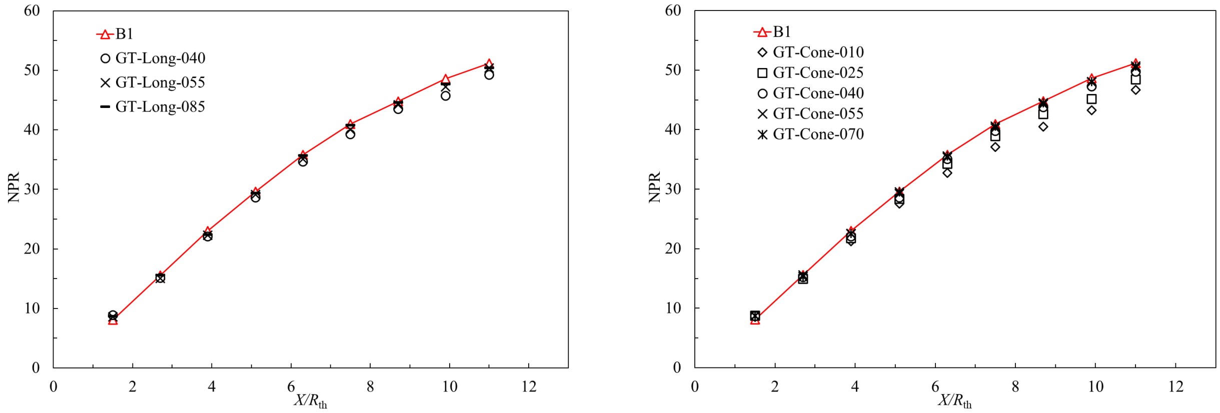


Figure 7: Impact on the flow separation by GT-Long (left) and GT-Cone (right)

Compared to the reference guide tube, GT-Long kept the same diameter but was enlongated by approximately 32%. Here, it was of interest whether an impact on the flow separation could also be shown for distances of more than half the nozzle exit diameter. It was not the case (Fig. 7, left).

Finally, GT-Cone was examined. The inlet diameter, as well as the length of this guide tube corresponded to GT-Ref. Its front half tapered to the diameter of GT-Min and remained cylindrical thereafter. The gap distances examined were between 10 and 70 mm. As with GT-Ref and GT-Min, the 55-70 mm gap configurations had no effect on the flow separation. Like for GT-Min, the first NPR deviation was determinable from the third sensor position. However, the subsequent deviations were less than those of GT-Min. Therefore, GT-Cone showed a combination of the behavior of GT-Ref and GT-Min. Table 2 summarizes the results.

Table 2: Impact of guide zubes on the flow separation

| **Guide Tube** | $\mathbf{D_{GT}/D_{eB1}}$ | **Impact below** | **NPR Reduction** |
|---|---|---|---|
| GT-Ref | 2.4 | 0.5 $D_{eB1}$ | 9.8% |
| GT-Min | 2.04 | 0.5 $D_{eB1}$ | 15.6% |
| GT-Max | 2.76 | - | - |
| GT-Long | 2.4 | 0.5 $D_{eB1}$ | 9.8% |
| GT-Cone | 2.4 /2.04 | 0.5 $D_{eB1}$ | 11.8% |

Up to here, the discussion has referred to flow separation. However, the test sequence also featured an NPR plateau that was reached after 23 s (see Fig. 4). It enabled to study the influence of the guide tubes on the overexpanded flow at the exit of the full-flowing nozzle. Although the nozzle was full-flowing, the wall pressure rose at the exit. This was due to the onset of the recompression to the ambiant pressure.

Figure 8 (left) shows the wall pressures of the TICTOP B1 with and without the impact of GT-Ref for all tested gap distances. The wall pressures were normalized with data taken from a numerical simulation of the vacuum wall pressure profile. For the first seven pressure ports, GT-Ref had no impact on the flow of the full-flowing nozzle. There were slight deviations for positions 8 and 9. Position 10, which was closest to the nozzle exit, showed clear changes depending on the gap distance. This correlation was expected.

Figure 8 (right) shows the related data of the additional pressure ports placed circumferential at the nozzle exit. From right to left: pressure ports 10 (180°), 11 (90°) and 12 (60°) (see also Fig. 2, left). The free-jet data (red triangles) revealed a three-dimensional distribution. The closer GT-Ref was to the nozzle exit, the more the pressure at the exit was lowered.

Values of up to 60%P have been achieved. Similar to the case of flow separation, gap distances above 55 mm had no effect on the flow at the nozzle exit. An exception was the gap distance of 115 mm that corresponded to the nozzle exit diameter. Pressure reductions of around 30%P were achieved there.

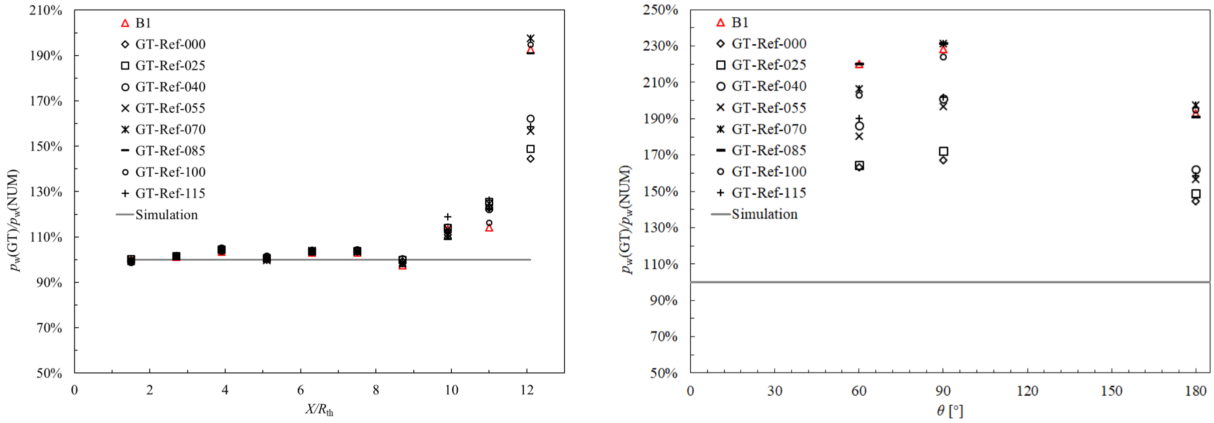


Figure 8: Wall pressure reduction by GT-Ref, axial reduction (left) and circumferential reduction (right)

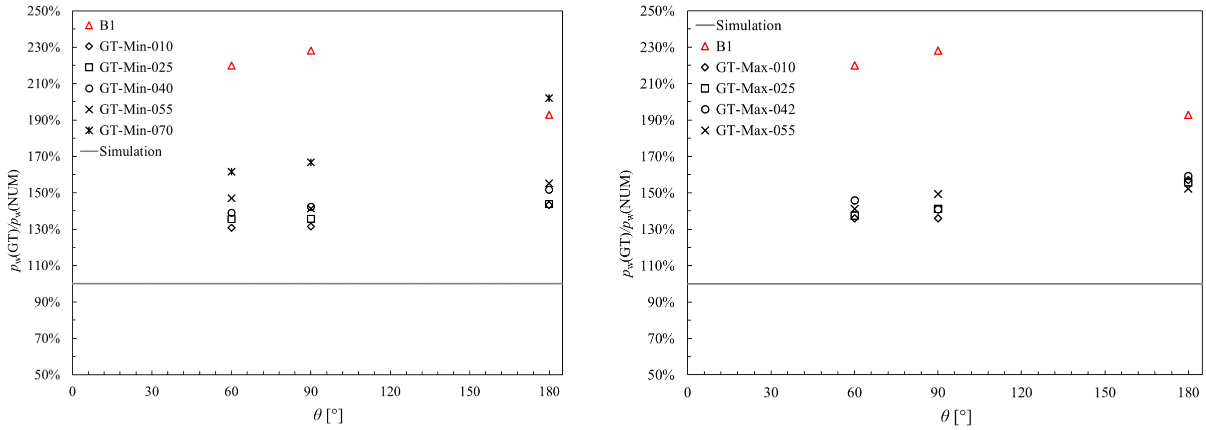


Figure 9: Exit wall pressure reduction by GT-Min (left) and GT-Max (right)

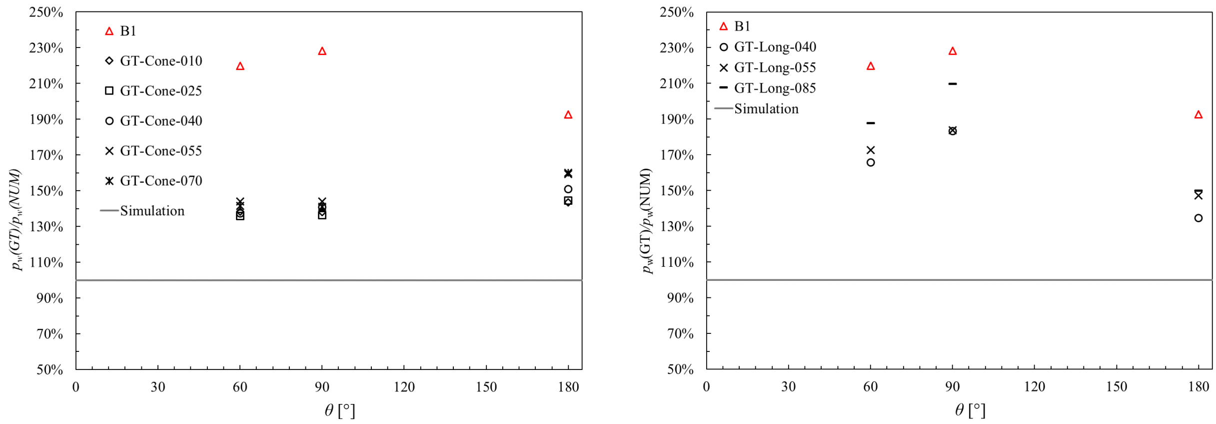


Figure 10: Exit wall pressure reduction by GT-Cone (left) and GT-Long (right)

The guide tube GT-Max had nearly no impact on the flow separation during transient start-up of the nozzle. An acceleration of the separation front was not found (Fig. 6, right). Therefore, GT-Max was not expected to have any impact on the nozzle exit pressure.

Figure 9 (left) gives the results for GT-Min. As awaited, the exit wall pressures were reduced compared to GT-Ref. Surprisingly, GT-Max revealed a comparable behavior (Fig. 9, right). The same was true for GT-Cone (Fig. 10, left), while GT-Long (Fig. 10, right) mirrored the behavior of GT-Ref. It turned out that all guide tubes, up to a certain gap distance, had an impact on the exit wall pressure. Table 3 summarizes the impact of the guide tubes on the recompression. The gap distance up to which the impact was measurable and the associated pressure reduction are listed.

Table 3: Impact of guide tubes on the recompression at the nozzle exit

| Guide Tube | Impact Up To | Pressure Reduction |
|---|---|---|
| GT-Ref | 0.5 $D_{eB1}$ | 45%P |
| GT-Min | 0.64 $D_{eB1}$ | 50%P |
| GT-Max | 0.5 $D_{eB1}$ | 40%P |
| GT-Long | 0.77 $D_{eB1}$ | 60%P |
| GT-Cone | 0.64 $D_{eB1}$ | 50%P |

## 4. Conclusions

Regarding their impact on the flow separation during transient nozzle start-up, the guide tubes behaved as expected. Somewhat unexpected was their impact on the wall pressure at the exit of the full-flowing nozzle. In summary, the following can be stated:

◦ The suction effect of the guide tubes could accelerate the separation front during transient start-up of the nozzle.
◦ The smaller the gap distance, the stronger the acceleration was. If the gap distance exceeded half the exit diameter of the nozzle, the acceleration stopped.
◦ A narrower guide tube increased the suction effect. A conical guide tube combined the properties of the respective cylindrical guide tubes. Above a certain increase in diameter, the guide tubes lost their influence on the flow separation.
◦ All guide tubes, regardless of their diameter, affected the pressure at the nozzle exit if close enough to the nozzle exit.

The last point in particular is crucial, because the recompression at the end of the nozzle is automatically accompanied by an increase in wall temperature. During repeated endurance tests on a test bench, this can lead to permanent deformation or even failure of the nozzle extension. Lowering the temperature could be very beneficial here.

## 5. Acknowledgments

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## References

[1] M. Frey. Behandlung von Strömungsproblemen in Raketendüsen bei Überexpansion. Ph.D. thesis, *Universität Stuttgart*, 2001.

[2] G. Hagemann and M. Frey. Shock pattern in the plume of rocket nozzles: needs for design consideration. *Shock Waves*, **17**, 387-395, 2008.

[3] R. Stark, C. Wick, S. General, C. Möller, T. Aichner, S. Köglmeier and M. Frey. Experimental Study of the Acoustical Interaction of a Subscale Rocket Nozzle Exhaust Jet and different Guide Tubes. *International Journal of Energetic Materials and Chemical Propulsion*, **22**, 4:43-57, 2023.

[4] M. Frey, K. Makowka, T. Aichner, R. Stark, and C. Génin. The TICTOP nozzle - first experimental results. *EUCASS, 7th European Conference for Aerospace Sciences*, No. 359, DOI 10.13009/EUCASS2017-359, 2017.

[5] R. Stark and C. Génin. Experimental Study of TICTOP Nozzles. *31st International Symposium on Shock Waves (ISSW31)*, No. 45, 2017.