Flow Separation in Rocket Nozzles, a Simple Criteria

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Cold and hot flow tests were conducted to investigate the flow separation in rocket nozzles. The results are presented. A separation data base including a wide range of literature data is established to evaluate the influence of propellant combination and nozzle design on flow separation. As a result a simple separation criteria is suggested.

Nomenclature

p	=	pressure
c_f	=	friction coefficient
Ma	=	wall Mach number
Ma_{des}	=	design Mach number
k	=	adiabatic exponent
q	=	deflection angle
s	=	oblique shock angle
u, U	=	velocity
d	=	boundary layer thickness
d^*	=	displacement thickness
d^{**}	=	momentum loss thickness
a	=	ambient
c	=	combustion chamber
p	=	plateau
w	=	nozzle wall
e	=	exit area
0	=	total condition
$¥$	=	edge of boundary layer
sep	=	incipient separation
TIC	=	truncated ideal contour
TOP	=	thrust optimized parabola
DLR	=	German Aerospace Center

I.   Introduction

The design of today's launchers has changed from a classical tandem to a parallel configuration and the main stage engine therefore has to fulfill a wider range of operation conditions during ascent from sea-level to high altitude. A significant payload gain can be achieved if the main stage engine features a high specific impulse. As its contribution to the launchers total sea-level thrust, compared to the boosters, is of minor importance its nozzle is designed to be just full flowing under sea-level conditions to avoid flow separation resulting in undesired side loads. For that reason designing and test engineers need an easy to implement tool to estimate the separation location.

DLR performed test series to investigate the flow separation in rocket nozzles[10,14,19,29] under various conditions like cold or hot flow, with and without film cooling. Of interest are the position of the separation, its length, its flow structure, its fluctuating nature and its increased heat load. Methods of flow separation visualization were evaluated and developed. Comparing the obtained flow separation data to values of common separation criteria a difference was observed. An upgraded separation data base combined with the obtained test data is used to define a simple separation criteria.

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II.   Experimental Program

Two exemplary test campaigns illustrate the investigation of flow separation and its visualization.

A. Cold Flow Tests

A test campaign was conducted to evaluate the capability of the optical pressure measurement method PSP (Pressure Sensitive Paint) to detect the location of flow separation[30]. The subscale cold flow tests were performed at test facility P6.2[17] using dry nitrogen as operating gas. The advantage of nitrogen compared to air is the absence of water vapor that tends to condense. Nitrogen can be easily modeled in attendant CFD calculations as a perfect gas.
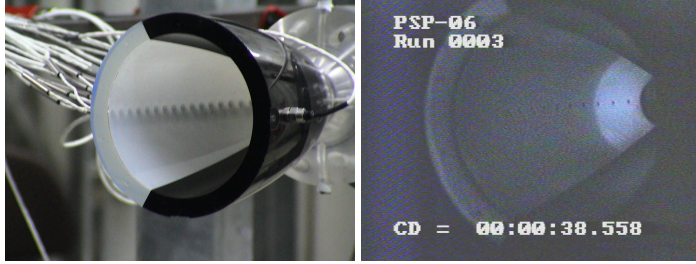

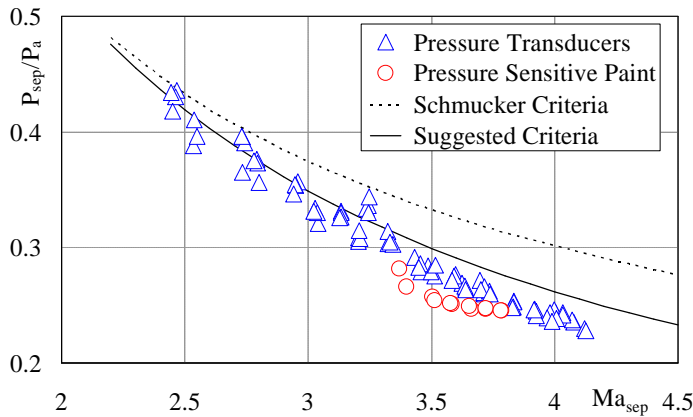**Figure 1.   PSP test specimen (left), test run (right)**

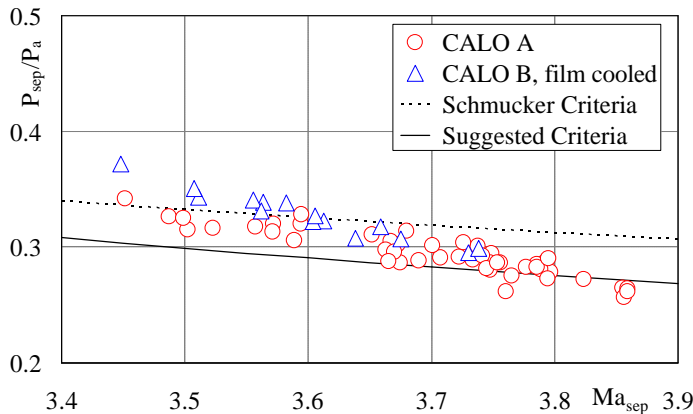**Figure 2.   Comparison of wall pressure and PSP data**

Figure 3.   Flow separation with and without film-cooling

PSP bases on the physical properties of luminophores: Activated by light these organic molecules can achieve a higher energetic level. Luminophores return to their basic level by emitting light (fluorescence). The deactivation can also be effected by collisions of suitable molecules like oxygen. In this case the luminophores react with phosphorescence.

During test the region of the attached nitrogen flow pronounces bright (fig. 1), whereas the separated backflow region clouds. The intensity change marks the separation of the boundary layer, fading into the shear layer of the free jet. In combination with the constant vacuum wall pressure profile (P_w/P_0) a related wall pressure can be obtained.
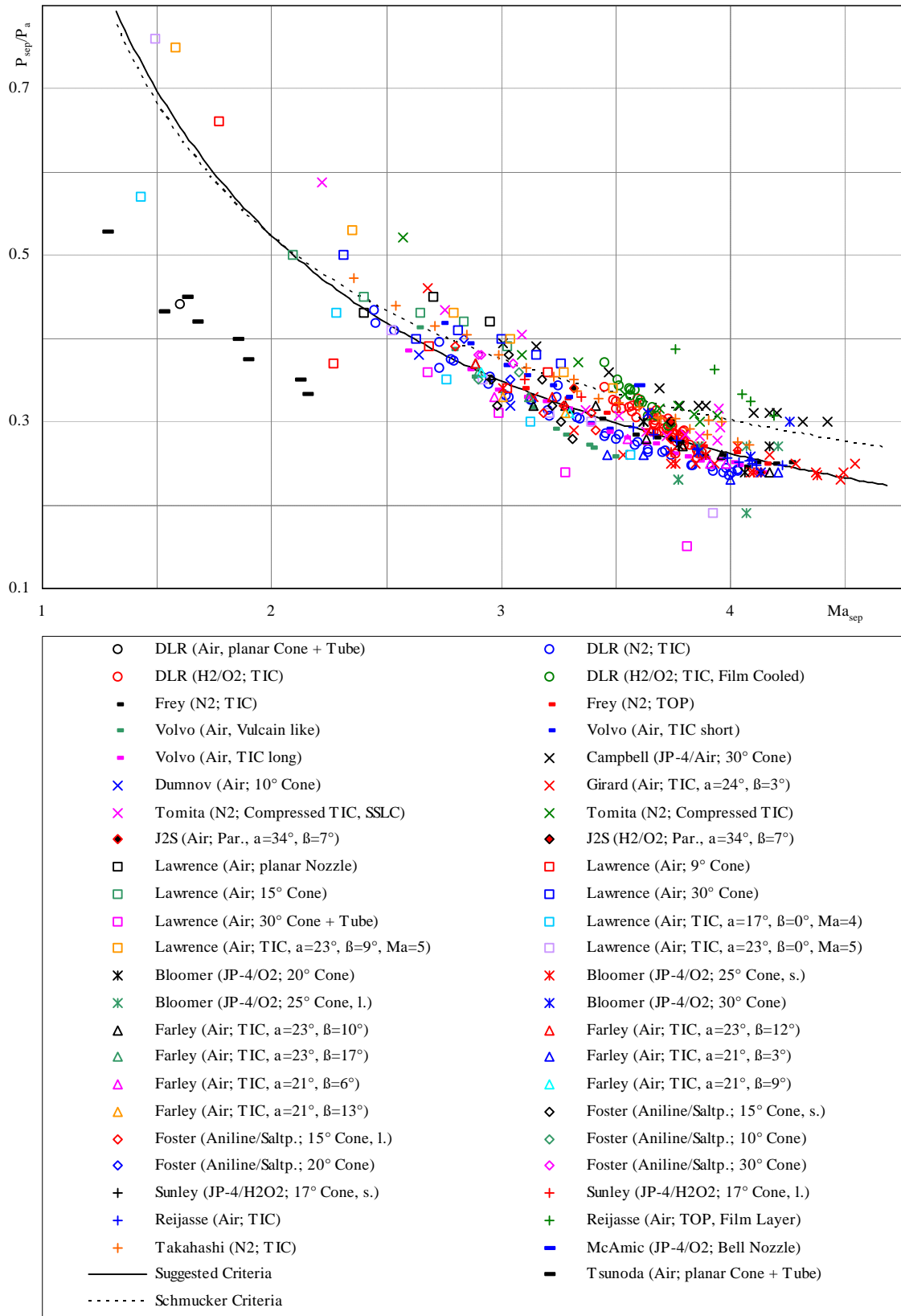
The test data evaluation showed that PSP detects the downstream border of the fluctuating separation zone. Compared to wall pressure measurements, where the lowest value determines the position of the incipient separation (fig. 8), PSP overestimates the location of the flow separation (fig. 2).

B. Hot Flow Tests

In cooperation with EADS ST and Volvo Aero Corporation hot-firing tests were conducted at test facility P8[15]. The objective was to establish a data base of wall pressure and wall heat flux for separated nozzle flows. Three configurations were tested, including regenerative and film cooled nozzles. The tests were performed with hydrogen-oxygen mixture ratios from 5 to 7.6 and combustion chamber pressures up to 11.5 MPa.

C. Separation data base

The obtained cold and hot gas data as well as actual publications[23,26,34,35,37] enhance a separation data base that was introduced by M. Frey[11], including a wide literature survey[2,3,6,8,9,13,20,24,32,36].

Figure 4. Separation data base

The figure legend contains the following entries:

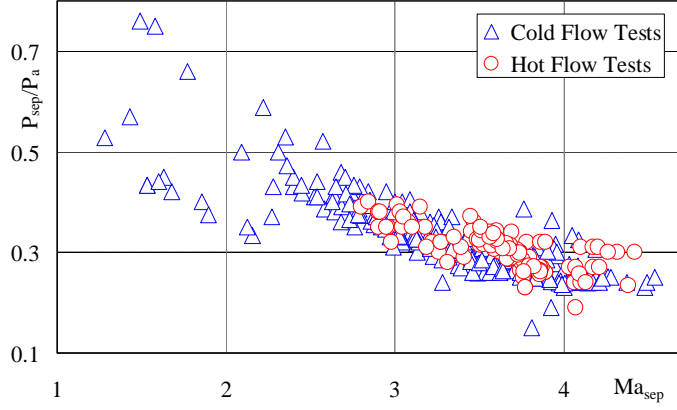| Symbol	Description	Symbol	Description
○	DLR (Air, planar Cone + Tube)	○	DLR (N2; TIC)
○	DLR (H2/O2; TIC)	○	DLR (H2/O2; TIC, Film Cooled)
▪	Frey (N2; TIC)	▪	Frey (N2; TOP)
▪	Volvo (Air, Vulcain like)	▪	Volvo (Air, TIC short)
▪	Volvo (Air, TIC long)	✕	Campbell (JP-4/Air; 30° Cone)
✕	Dumnov (Air; 10° Cone)	✕	Girard (Air; TIC, a=24°, ß=3°)
✕	Tomita (N2; Compressed TIC, SSLC)	✕	Tomita (N2; Compressed TIC)
◆	J2S (Air; Par., a=34°, ß=7°)	◆	J2S (H2/O2; Par., a=34°, ß=7°)
□	Lawrence (Air; planar Nozzle)	□	Lawrence (Air; 9° Cone)
□	Lawrence (Air; 15° Cone)	□	Lawrence (Air; 30° Cone)
□	Lawrence (Air; 30° Cone + Tube)	□	Lawrence (Air; TIC, a=17°, ß=0°, Ma=4)
□	Lawrence (Air; TIC, a=23°, ß=9°, Ma=5)	□	Lawrence (Air; TIC, a=23°, ß=0°, Ma=5)
✳	Bloomer (JP-4/O2; 20° Cone)	✳	Bloomer (JP-4/O2; 25° Cone, s.)
✳	Bloomer (JP-4/O2; 25° Cone, l.)	✳	Bloomer (JP-4/O2; 30° Cone)
△	Farley (Air; TIC, a=23°, ß=10°)	△	Farley (Air; TIC, a=23°, ß=12°)
△	Farley (Air; TIC, a=23°, ß=17°)	△	Farley (Air; TIC, a=21°, ß=3°)
△	Farley (Air; TIC, a=21°, ß=6°)	△	Farley (Air; TIC, a=21°, ß=9°)
△	Farley (Air; TIC, a=21°, ß=13°)	◇	Foster (Aniline/Saltp.; 15° Cone, s.)
◇	Foster (Aniline/Saltp.; 15° Cone, l.)	◇	Foster (Aniline/Saltp.; 10° Cone)
◇	Foster (Aniline/Saltp.; 20° Cone)	◇	Foster (Aniline/Saltp.; 30° Cone)
+	Sunley (JP-4/H2O2; 17° Cone, s.)	+	Sunley (JP-4/H2O2; 17° Cone, l.)
+	Reijasse (Air; TIC)	+	Reijasse (Air; TOP, Film Layer)
+	Takahashi (N2; TIC)	▬	McAmic (JP-4/O2; Bell Nozzle)
——	Suggested Criteria	▬	Tsunoda (Air; planar Cone + Tube)
·····	Schmucker Criteria		

III.   Discussion of Results

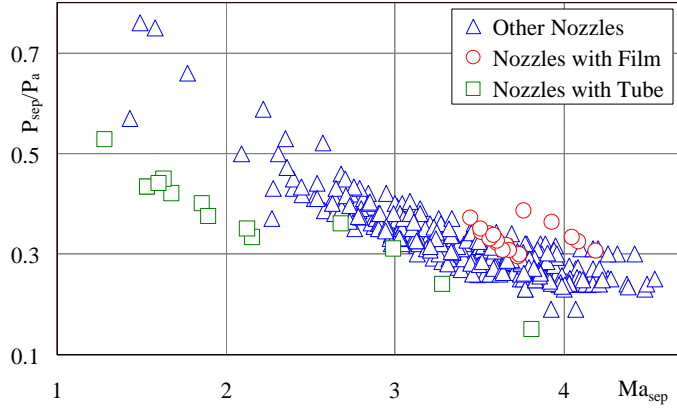**Figure 5. Cold and hot flow tests**

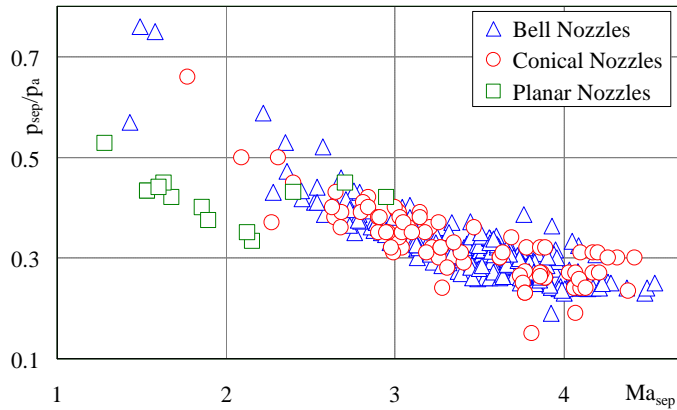**Figure 6. Film layer injection and attached tubes**

Figure 7. Nozzle design

The obtained cold gas test data (fig. 2) clearly fall below the expected trend and illustrate that common separation criteria like Schmucker's under predict the separation location. The hot gas data differ less but show an increasing difference with increasing wall Mach number Ma_{sep} too (fig. 3). The hot gas separation is superimposed by total pressure fluctuations causing a comparatively high variance of wall pressure data p_{sep}/p_a. This interaction is damped if a cooling film is injected. The data also point out that this film causes a premature separation. With proceeding evolution the film looses its efficiency and the flow separation normalizes.

Examining the data base the distribution of hot and cold flow data don't differ (fig. 5), except a small region around Mach 3.5 where data are dominated by the obtained hot gas data. The wall Mach number reproduces the influence of the adiabatic exponent κ (and therefore the propellant combination) on the separation location in a sufficient manner.

In Fig. 6 the data are split up to visualize the influence of injected film layers and attached tubes. Apparently attached tubes cause a delayed separation. Especially Tsunoda's data differ. These data were verified using a small blow down wind channel build up for DLR education purpose. Its planar conical nozzle is three times smaller scaled than Tsunoda's setup. It was enhanced with a flat plate to achieve a tube like characteristic. The spacing of the available wall pressure sensors allows only one measuring point in the relevant Mach number interval. This single data point overlaps with Tsunoda's data.

An inverse influence on separation can be observed for film layers. As already mentioned the obtained hot gas data indicate a premature separation. This is verified by the cold flow data of Reijasse[26]. A comparable film layer influence is reported by Dumnov[6] and well known from Europe's Vulcain 2 rocket engine.

An influence of the nozzle design on separation is not given (fig. 7).

Based on the data of fig. 4 the following separation criteria is suggested:

$$\frac{p_{sep}}{p_a} = \frac{\Pi}{3 \cdot Ma_{sep}}$$

Where p_a is the ambient pressure, p_{sep} is the wall pressure of the incipient separation and Ma_{sep} the related wall Mach number.

IV. Conclusions

Cold as well as hot flow subscale tests were conducted and presented. The obtained separation location data don't match with the expected values. For this reason an existing separation data base was enhanced to setup a separation criteria. The data show no evident influence of propellant combination or basic nozzle design on flow separation. The separation is affected by attached tubes and injected film layers.

Flow separation is a result of adaptation on ambient conditions. Even though this adaptation can be divided in two regions (the oblique shock recompresses the wall pressure p_{sep} to plateau pressure p_p, followed by a system of recompression waves in the separated backflow region where plateau pressure p_p is adapted to ambient condition p_a, fig. 8) it is not necessary to establish a separation criteria that considers this dichotomy, as suggested by some authors[1,4,5,11,16,18,20,25,33]. For designing purpose it is sufficient to derive the lowest achievable wall pressure for given system parameter like ambient pressure p_a, total pressure p_0 and nozzle contour. The suggested separation criteria fulfils this requirement.

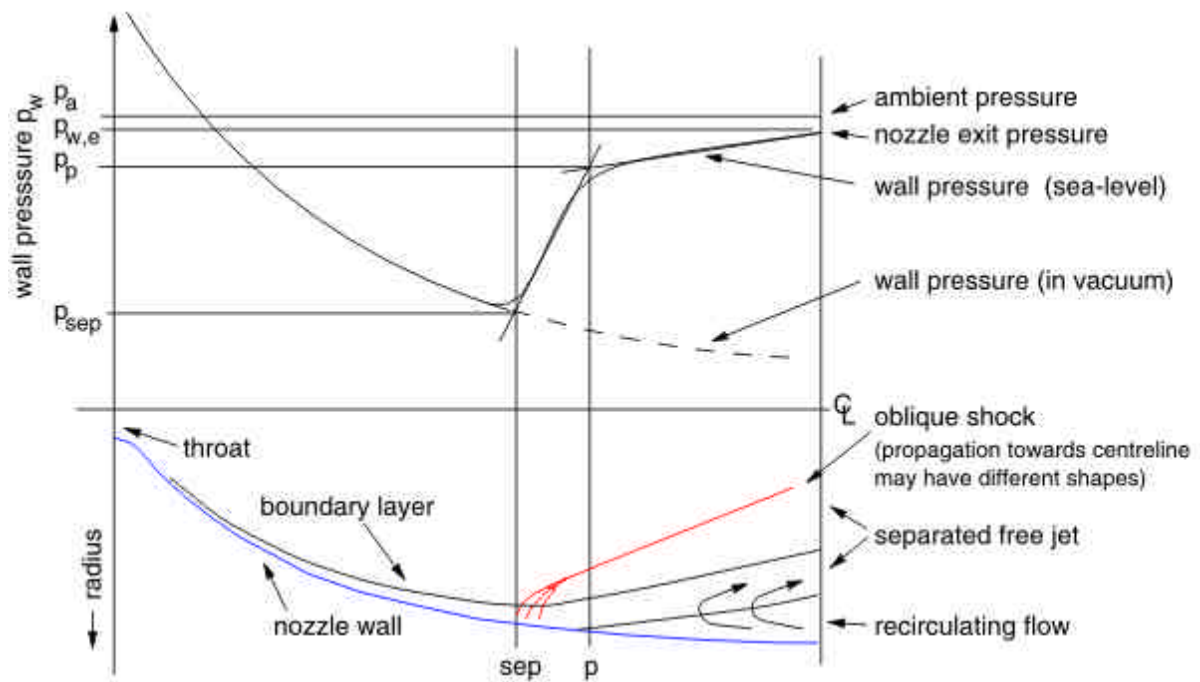As an appendix some separation criteria are given.

Appendix

Figure 8. Free Shock Separation in over-expanding rocket nozzles (taken from Ref.11)

Arens & Spiegler	$$\frac{p_{sep}}{p_p} = \frac{\left[1 + \frac{k-1}{2}Ma_{sep}^2\left(1-k_A^2\right)\right]\left\{0.5Ma_{sep}^2\left[(k+1)k_A^2 - \frac{(k-1)^2}{k+1}\right] - \frac{k-1}{k+1}\right\}^{\frac{1}{k-1}}}{\left[\frac{k+1}{2}Ma_{sep}^2 \cdot k_A^2\right]^{\frac{k}{k-1}}} \quad,\ k_A = u/U_\infty$$
Crocco-Probstein	$$\frac{p_p - p_{sep}}{k \cdot p_{sep}}\left[\frac{k_{1sep}}{Ma_{sep}^2} + \frac{k-1}{2}\left(k_{1sep}-1\right)\right] =$$ $$1 - \frac{k_{2p}}{k_{2sep}}\sqrt{\left(\frac{2}{k-1}\right)} \cdot \frac{1}{Ma_{sep}}\sqrt{\left(1 + \frac{k-1}{2}Ma_{sep}^2 - \left(\frac{k+1}{k-1} + \frac{p_p}{p_{sep}}\right)\left(\frac{k+1}{k-1} + \frac{p_{sep}}{p_p}\right)\right)}$$ $$k_1 = 1 \Big/ \left(1 - \frac{d^*}{d} - \frac{d^{**}}{d}\right)$$ $$k_2 = \left(1 - \frac{d^*}{d} - \frac{d^{**}}{d}\right)\Big/\left(1 - \frac{d^*}{d}\right)$$
Donaldson & Lange	$$\frac{p_p}{p_{sep}} = 1 + k_3 \cdot \frac{k}{2} \cdot Ma_{sep}^2 \cdot c_f \quad,\ k_3\text{: constant determined from analysis of experimental data}$$
Frey	$$\frac{p_{sep}}{p_p} = \left(1 + \frac{2 \cdot k}{k+1} \cdot \left[Ma_{sep}^2 \cdot \sin^2\left(44.5° - 4.7° \cdot Ma_{sep}\right) - 1\right]\right)^{-1}$$
Kalt & Badal	$$\frac{p_{sep}}{p_a} = \frac{2}{3} \cdot \left(\frac{p_c}{p_a}\right)^{\frac{1}{5}}$$
Kudryavtsev	$$\frac{p_a}{p_p} = 1 + \left(\frac{0.192}{\sin a} - 0.7\right)\left(1 - \frac{Ma_{sep}}{Ma_{des}}\right) \text{; Proposed for air in conical nozzles, } \alpha < 15°$$
Lawrence	$$\frac{Ma_p}{Ma_{sep}} = 0.8$$
Mager	$$\frac{p_{sep}}{p_a} = \left[1 + \left(\frac{k}{2}Ma_{sep}^2 \frac{1-k}{1 + \frac{k-1}{2}Ma_{sep}^2}\right)\left(1 + 0.328\frac{k \cdot Ma_{sep}^2 \cdot k^2 \cdot \Theta}{1 + \frac{k-1}{2}Ma_{sep}^2 \cdot k^2}\right)\right]^{-1} \text{; } k = Ma_p/Ma_{sep}$$
Östlund	$$s = -3{,}764° \cdot Ma_{sep} + 42{,}878°$$ $$q = 1{,}678° \cdot Ma_{sep} + 9{,}347°$$
Schilling	$$\frac{p_{sep}}{p_a} = 0.583 \cdot \left(\frac{p_c}{p_a}\right)^{-0.195} \text{; Suggested for short bell nozzles}$$
Schmucker	$$\frac{p_{sep}}{p_a} = \left(1.88 \cdot Ma_{sep} - 1\right)^{-0.64}$$
Suggested Criteria	$$\frac{p_{sep}}{p_a} = \frac{\Pi}{3 \cdot Ma_{sep}}$$
Summerfield	$$\frac{p_{sep}}{p_a} = 0.35...0.4$$

Tagirov	$\dfrac{p_p}{p_{sep}} = \left(\sqrt{A_1^2 + A_2\left(1 + \dfrac{k-1}{2} Ma_{sep}^2\right)} - A_1 \right) / A_2$
	$A_1 = \dfrac{k+1}{4}(A_3 - 1) \cdot Ma_{sep}^2$
	$A_2 = 1 + \dfrac{k-1}{2} \cdot A_3 \cdot Ma_{sep}^2$
	$A_3 = \left(\dfrac{Ma_p}{Ma_{sep}} \right)^2$
Zukoski	$\dfrac{p_{sep}}{p_a} = \dfrac{2}{Ma_{sep} + 2}$; Forward-Facing Step

Acknowledgments

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