Film cooling mass flow rate influence on a separation shock in an axisymmetric nozzle

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Abstract. The influence of the mass flow rate of a film cooling upon the free shock-induced separation inside an over-expanded axisymmetric slot nozzle has been experimentally investigated in the Onera R2Ch wind tunnel. The characteristics of the shock wave – turbulent boundary layer interaction are differently affected depending on whether the film mass flow rate is greater or smaller than a critical value. Above this critical value the laminar nature of the film governs the interaction, which leads to a more precocious flow separation in the nozzle. Beneath the critical value, the interaction properties are weakly affected by the presence of the film. Even, for very weak film mass flow rates, one can observe a slight favourable influence upon the separation position. One suggests that the film -not energetic enough- breaks up into the turbulent boundary layer and reinforces it by adding momentum.

Key words: flow separation, shock wave-boundary layer interaction, film cooling, nozzle.

1. Introduction

The film cooling effectiveness has been largely investigated in supersonic and hypersonic regimes for application to gas turbine blades or scramjet combustors. From this abundant literature some studies have focused onto the film cooling influence either in the presence of bump-induced adverse pressure gradients as seen by Teekaram et al. [8] and by Zakkay et al. [9], or with a fixed incident shock induced by a shock generator as seen by Juhany and Hunt [3] and by Kanda and Ono [4].

Wall film cooling is also a technology used in rocket engine nozzles to prevent intense convective heat fluxes. In addition to thermal protection, film cooling may improve engine performance by reducing skin friction and providing thrust in the high Mach number domain. At ignition and at low altitudes rocket engine nozzles run in over-expansion regime. This leads to the presence of an oblique shock interfering with the nozzle boundary layer and the wall cooling film. In this paper, the effect of the film cooling mass flow rate upon the free shock-induced separation has been investigated in a subscale axisymmetric over-expanded slot nozzle through the analysis of wall pressure properties.

2. Test set-up and model

The test campaign has been executed in the ONERA R2Ch blowdown wind tunnel of Meudon Center [1]. The nozzle model is shown in Figure 1. The nozzle throat and exit diameters are d=20mm and D=112.9mm, respectively. The throat-to-exit distance is L=125mm. The nozzle set-up allows to independently feed the main nozzle and its annular injection slot (Figure 2). A calibrating throat mounted upstream of the film injection device determines the mass flow rate q_{film} to be symmetrically distributed into 4 pipes. The pipes thus feed an annular settling chamber upstream of the wall film injection slot. The ratio of the nozzle jet stagnation pressure over the ambient pressure is close to 47. This nozzle pressure ratio (NPR) value leads to the overexpansion of the supersonic nozzle flow with an extended shock-induced separation zone. The film-to-nozzle jet stagnation pressure ratio $p_{st,film}/p_{st}$ can vary from 1% to 8%. As the nozzle jet conditions (NPR) are fixed, the variation of the ratio $p_{st,film}/p_{st}$ is equivalent to the variation of the film mass flow rate relatively to that one of the nozzle jet.

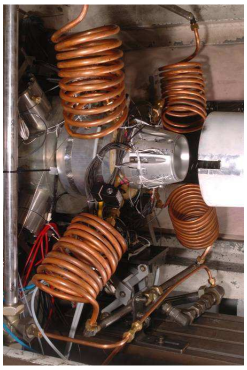


Figure 1. Mounting in the R2Ch wind tunnel

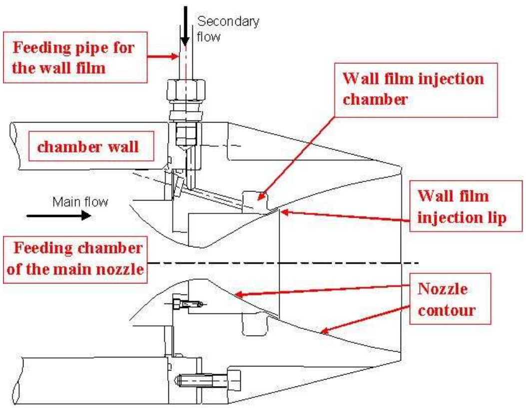


Figure 2. Principles of the nozzle set-up with the film injection slot device

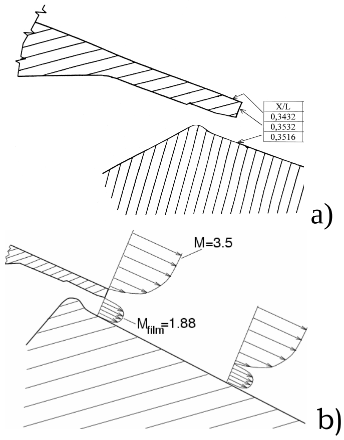


Figure 3. Injection slot
a)pressure taps
b)local Mach numbers

The nozzle jet Mach number at the slot is close to M=3.5. The nominal wall film Mach number at the slot injection exit is M_{film}=1.88 (Figure 3b). The height of the sonic throat of the injection slot is 0.58mm. The film Reynolds number based on the injection slot throat conditions varies from 3.34 10^3 to 2.41 10^4. For a fixed film injection mass flow rate of 8%, former theoretical studies [6, 7] of the flow separation in this nozzle have shown that the film is laminar.

3. Experimental data analysis

3.1. FILM ADAPTATION

The co-flowing of the two supersonic flows downstream of the injection slot base geometry (Figure 3a) leads the film to adapt to the main flow static pressure along a certain distance. As shown in Figure 4 the adaptation is obtained at X/L=0.45 whatever the level of the film stagnation pressure $p_{st,film}$ is.

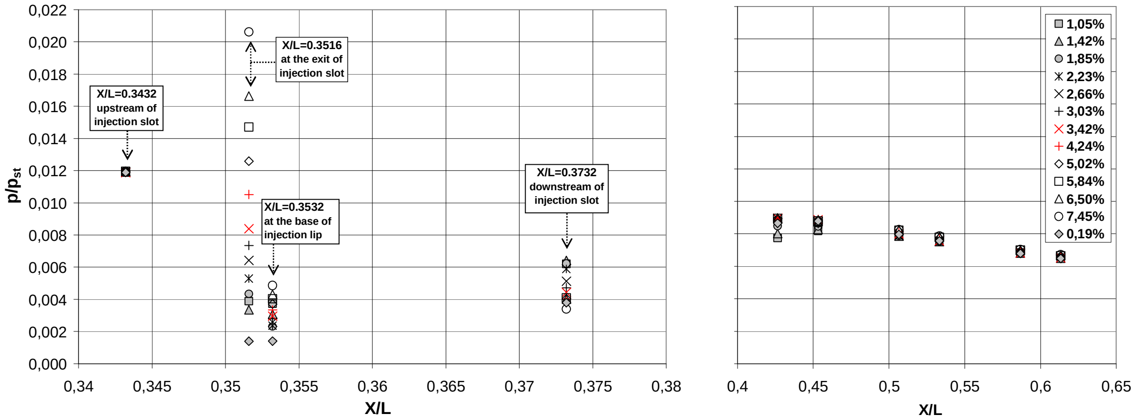


Figure 4. Wall pressures in the vicinity of the injection slot for different film stagnation pressures

3.2. WALL PRESSURE DISTRIBUTIONS

The wall pressure distributions are severely affected by the film mass flow rate q_{film} (Figure 5). The two characteristics which are notably changed are a)the pressure slope $\Delta p/\Delta X$ induced by the pressure jump by crossing the shock foot and b)the streamwise position X_0 of the pressure curve.

One can distinguish two types of pressure slope values as shown in Figure 6. Sharp rises of wall pressures are seen for small film mass flow rates as for no-film configurations. For q_{film} values above 1% the maximum values of the pressure slopes decrease. This can reveal whether the film exercises an influence on the shock foot by spreading it or not.

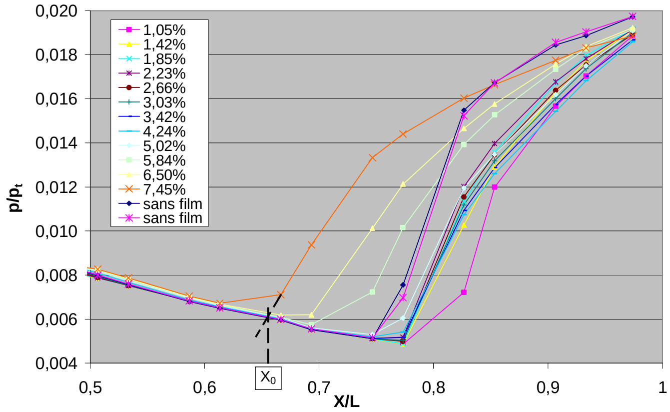


Figure 5. Wall pressure distributions (NPR=47) for different film mass flow rate ratios

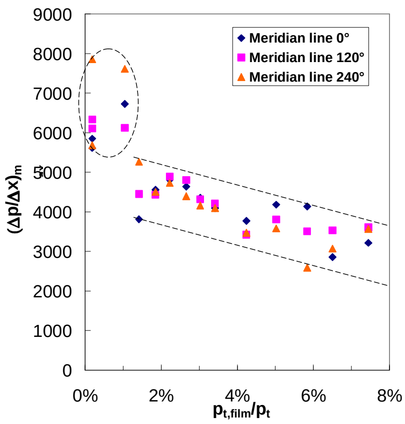


Figure 6. Pressure slopes (NPR=47) for different film mass flow rate ratios

The streamwise position X_0 of the pressure curves has been roughly evaluated as shown in Figure 5. Then one defines a distance DX which is the difference between the $X_{0,film}$ values obtained in the presence of the film relatively to the X_0 values obtained without film. The distance DX/X_0 is plotted versus the film mass flow rate ratio (Figure 7). The value DX=0 is thus a reference to discuss the influence of the film. Three types of pressure curve positions versus film mass flow rate ratios are observed. Positive values of DX which indicate a less extended separation zone in the nozzle are obtained for the smallest film mass flow rate ratios (q_{film} less than 2%). For q_{film} in the range 2%-4%, there is no influence upon the flow separation position. For q_{film} greater than 4%, DX is negative and the separation region is thus more extended than in the case without film.

The behaviour (DX<0 when q_{film} greater than 4%) is coherent with the fact that the film is laminar, thus less resistant to an adverse pressure gradient. An explanation for DX values greater than 0 is that the film -weakly energetic- should break up into the nozzle boundary layer. Thus its non-zero momentum adds to the one of the nozzle turbulent boundary layer which becomes thus more resistant. In the intermediate range where DX is close to 0 one can suggest that it results from the balance between the two antagonistic facts relatively to the separation position: the film momentum contribution and the laminar nature of the film sub-layer.

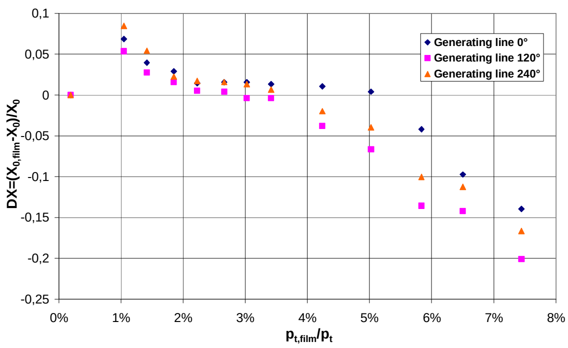


Figure 7. Pressure curves positions vs. film mass flow rate ratios (NPR=47)

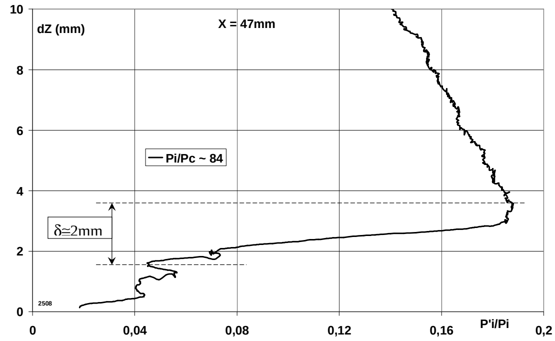


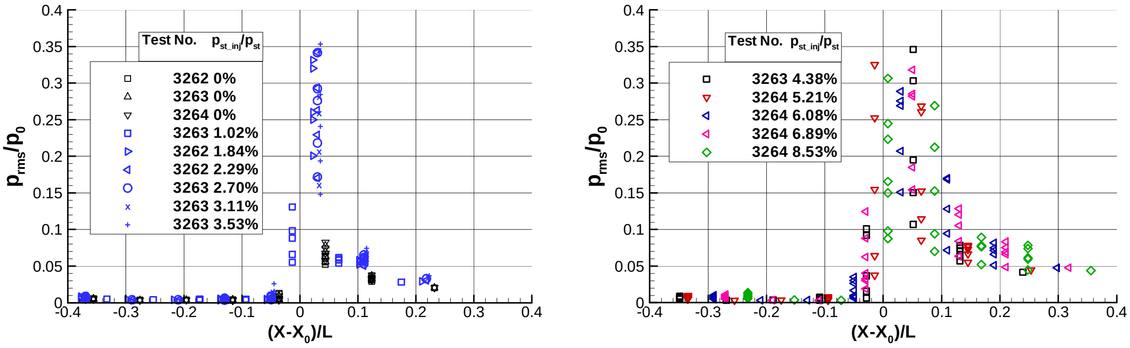
Figure 8. Pitot pressure probings of the flows at 2mm downstream of the injection slot. (the height of the injection slot is 1.8mm)

3.2. PRESSURE FLUCTUATIONS LEVELS

The pressure fluctuations levels normalized by the local wall pressure p_0 have been plotted versus the normalized streamwise coordinate $(X-X_0)/L$ (Figure9). One clearly observes the three zones which characterize a shock wave – boundary layer interaction:

- The attached flow region where p_{rms} is small and does not exceed 1% of the mean local wall pressure p_0.
- The interaction region where p_{rms} rapidly increases and reaches the highest values, representing 35% of the mean local wall pressure p_0. This level is about twice the maximum of p_{rms} values measured in supersonic compression ramps at Mach 3 [2], [5].

- The fully separated flow region where p_{rms}/p_0 values are nearly constant at a level smaller than 10%, a level which is comparable to the values measured on compression ramps.



a)film mass flow rates < 4% *b)film mass flow rates >4%*

Figure 9. Pressure fluctuations levels normalized by the local wall pressure p_0 vs the normalized streamwise coordinate.

Two classes of pressure rms distributions have been distinguished (Figures 9a and 9b) according to the film mass flow rate ratio q_{film}.

For q_{film} smaller than 4% the pressure rms distributions obtained are better correlated than those for q_{film} greater than 4%. Even for the cases q_{film}<4% one can evaluate An order of magnitude of the interaction length is about 10% to 20% of the nozzle length L, which represents 6 to 12 times the nozzle boundary layer height δ evaluated by Pitot probing at about 2mm (Figure 8).

4. Conclusions

The effect of the film cooling mass flow rate upon the characteristics of a free oblique shock wave – boundary layer interaction has been investigated in a subscale axisymmetric over-expanded slot nozzle through the analysis of wall pressure properties. The test campaign has been executed in the ONERA R2Ch blowdown wind tunnel of Meudon Center. The film-to-nozzle jet stagnation pressure ratio $p_{st,film}/p_{st}$ can vary from 1% to 8%.

The characteristics of the interaction are differently affected depending on whether the film mass flow rate is greater or smaller than a critical value. In the present study, the critical value is q_{film} 4%. For q_{film}>4% the film keeps its laminar nature all along the nozzle wall which induces the expected changes (pressure slope more gentle, separation more precocious, interaction length larger) relatively to the case of the nozzle turbulent boundary layer without film. For q_{film}<4% the interaction properties are weakly affected by the presence of the film, and for very weak values of q_{film} (<1%) one can observe a slight favourable influence upon the separation position. One suggests that, in the latter case, the film is not energetic enough and breaks up into the turbulent boundary layer, but reinforces it by adding momentum.

Acknowledgements

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References

1. Coponet, D., Influence of a film cooling on flow separation and side loads in propulsive nozzles. R2Ch wind tunnel. *(translation of the French title)*. Onera report, 2/10515 DAFE, October 2006.
2. Dolling, D.S. and Or, C.T., ”Unsteadiness of the Shock Wave Structure in Attached and Separated Compression Ramp Flow Fields”, AIAA 83-1715, July 1983.
3. Juhany, K.A. and Hunt, M.L., Flow-field measurements in supersonic film cooling including the effect of shock wave interaction. *AIAA 92-2950*.
4. Kanda, T. and Ono, F., Experimental studies of supersonic film cooling with shock wave interaction (II). *J. Thermophysics, Vol.11, No.4 (1997) 590-593*.
5. Muck, K., Dussauge, J.-P. and Bogdonoff, M., ”Structure of the Wall Pressure Fluctuations in a Shock-Induced Separated Turbulent Flow”, AIAA 85-0179, january 1999.
6. Reijasse, P., Morzenski, L., Blacodon, D. and Birkemeyer, J., Flow Separation Experimental Analysis in Overexpanded Subscale Rocket-Nozzles. *AIAA paper 2001-3556*.
7. Reijasse, P., Aerodynamics of overexpanded propulsive nozzles : free separation and side loads in stabilized regime. Ph. D. thesis, University of Pierre-et-Marie-Curie (Paris 6-Jussieu, Paris, France), (2005).
8. Teekaram, A.J.H., Forth, C.J.P. and Jones, T.V., Film cooling in the presence of mainstream pressure gradients. *ASME 90-GT-334* (1990).
9. Zakkay, V., Wang, C.R. and Miyazawa, M., Effect of adverse pressure gradient on film cooling effectiveness. *AIAA-73-0697.*