2. Film cooling in rocket engines

In a high performance rocket engine a significant reduction of the thermal and structural loads can be reached by the application of film cooling with an acceptable loss in performance and specific impulse. Typical for film cooling is a cooling effect not only at the position of the film injection but also farther downstream[3,5].

Modern first stage rocket engines use film cooling not only in the immediate vicinity of the injector head (e. g. Vulcain 2, SSME), either with slot injection of the gaseous or liquid coolant or by a reduction of the mixture ratio *ROF* in the nearness of the wall (e. g. SSME), but also in the region of the nozzle throat section (e. g. RD-170) (see fig. 1)[8,16–18].

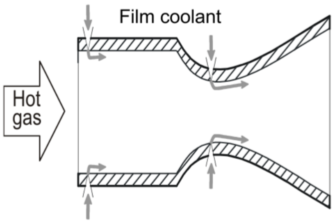


Fig. 1. Film cooling in rocket engines

To make a conclusion about film cooling efficiency, non-dimensional efficiency η is a widely used parameter to describe and compare film cooling results[5,7,9,14,19]. The difference between adiabatic wall temperature T_{ad} and hot gas temperature T_{c} is referred to the maximum difference between coolant temperature at injection point T_2 and hot gas temperature:

$$\eta = \frac{T_{\mathrm{ad}} - T_{\mathrm{c}}}{T_2 - T_{\mathrm{c}}} \tag{1}$$

However, this definition of efficiency is not applicable in a rocket engine combustion chamber due to the high temperatures of the combustion gases. Adiabatic wall temperatures would exceed operating temperatures of all known combustor materials by far. Hence, for a high pressure combustion chamber regenerative and film cooling will be used in combination. It is advantageous to establish a new temperature ratio to describe film cooling efficiency in a film cooled rocket engine. This temperature ratio can be used as a degree of efficiency for film cooling processes.

The local temperature difference due to the application of film cooling will be compared with the maximal achievable temperature difference, where $T_{\mathrm{W,0}}$ designates the wall temperature without and $T_{\mathrm{W,f}}$ the wall temperature with film cooling:

$$\Theta(x) = \frac{T_{\mathrm{W,0}}(x) - T_{\mathrm{W,f}}(x)}{T_{\mathrm{W,0}}(x) - T_2} \tag{2}$$

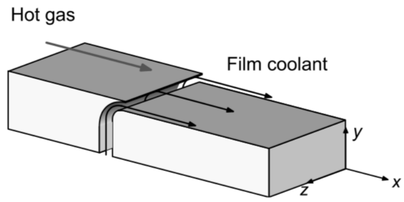
For comparing differential experimental data the non-dimensional film cooling length x/s (based on the slot height s) instead of distance x is a widely used parameter.

The efficiency of film cooling in a rocket engine is dependent on a multitude of parameters like slot geometry, injection angle, temperature and velocity ratios between film and hot gas stream, turbulence ratio as well as boundary layer thicknesses. The blowing rate M is a main parameter to characterize film cooling. It describes the mass flow momentum ratio between coolant and hot gas stream:

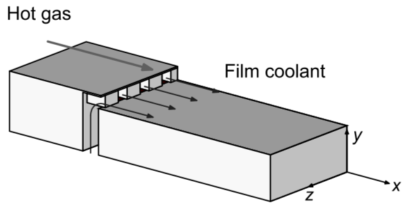
$$M = \frac{(\rho u)_2}{(\rho u)_{\mathrm{c}}} \tag{3}$$

Experimental work in the past has shown a clear connection between blowing rate and film cooling effectiveness for $M \leq 1$ as well as for $M > 1$[10,11,13]. An increase of the blowing rate M up to $M \approx 3$ indicates a better film cooling effectiveness for tangential slot injection. This also applies for foreign gas injection in place of the well examined case of air injected into air.

Fig. 2 shows two different specifications of tangential film injection. While in terms of a homogeneous distribution of the film coolant in the combustion chamber a continous injection (see fig. 2 (a)) would be the best choice, nevertheless for construction reasons this cannot be achieved in any case (see fig. 2 (b)).



(a) Continuous injection



(b) Slot injection

Fig. 2. Tangential film injection

3. Experimental setup

All investigations presented in this paper were performed at the European Research and Technology Test Facility P8 at DLR Lampoldshausen using the subscale combustion chamber "B"[12,15].

3.1 Subscale combustion chamber "B"

Subscale combustion chamber "B" (see fig. 3) is a modular built-up of several watercooled segments (each with a length of 50 mm) and a newly developed watercooled measurement segment with a length of 100 mm. The combustion chamber features a diameter of 50 mm with a nozzle throat diameter of 28 mm. For film cooling investigations it is possible to vary the axial position of the measurement segment between the 50 mm standard segments. Thereby it had been possible to capture a detailed axial temperature distribution inside the combustion chamber.