Evolution of cooling-channel properties for varying aspect ratio

M. Pizzarelli, F. Nasuti and M. Onofri
Sapienza University of Rome
Department of Mechanical and Aerospace Engineering
Via Eudossiana 18, I-00184 Rome, Italy

Abstract

High performance liquid rocket engines are often characterized by rectangular cooling channels with high aspect ratio (channel height-to-width ratio) because of their proven superior cooling efficiency with respect to a conventional design. However, the identification of the optimum aspect ratio is not a trivial task. In the present study a trade-off analysis is performed on a cooling channel system that can be of interest for rocket engines. This analysis requires multiple cooling channel flow calculations and thus cannot be efficiently performed by CFD solvers. Therefore, a proper numerical approach, referred to as quasi-2D model, is used to have fast and accurate predictions of cooling system properties. This approach relies on its capability of describing the thermal stratification that occurs in the coolant and in the wall structure, as well as the coolant warming and pressure drop along the channel length. Results of the analysis show the existence of an optimum channel aspect ratio that minimizes the requested pump power needed to overcome losses in the cooling circuit.

1. Introduction

Cooling channels with high aspect ratio of the cross section $\lambda = h/b$, often referred to as HARCC (high-aspect-ratio cooling channels), have the potential to reduce the thermal strain in the wall material and to increase the material strength by substantially reducing its maximum temperature. For this reason HARCC have been studied by NASA since many years [1, 2, 3, 4] and introduced in engines like the European Vulcain [5]. In fact, reducing wall temperature allows increasing engine life and cost of fabrication, as resulted during development and production of Space Shuttle main engine and thus studied subsequently. However, it has been demonstrated [6] that if the channel aspect ratio is too high, the cooling efficiency vanishes. In fact, in case of strongly asymmetric distributed heat fluxes around the channel perimeter and cooling geometries with high aspect ratios, limited coolant mixing and inhomogeneous temperature distribution (also referred to as "thermal stratification") are expected. This, in turn, can lead to cooling inefficiency of HARCC.

Aim of the present study is to emphasize that the optimum aspect ratio exists and depends on the set of assigned constraints. In particular, the constraints that characterize the cooling system are divided in two families: those related to the realization of the device (weight, dimensions, manufacturing capability, etc.) and those related to the system operation (maximum allowable wall temperature and coolant pressure drop, available coolant mass flow rate, coolant power loss, etc.). The present trade-off analysis is performed on cooling channel conditions representative of those occurring in liquid rocket engines. In this study, the cooling channel aspect ratio that would minimize the coolant power loss is found with the constraint of fixed weight and channel height. The trade-off analysis is performed by means of a numerical approach presented and validated in [7, 8]. This approach, which is based on a quasi-2D model, permits to have fast and complete information on the thermal evolution in cooling systems characterized by HARCC, because of its capability to describe the thermal stratification as well as the temperature distribution along the whole cooling channel structure.

2. Test case description

The considered cooling system is composed of straight rectangular passages which contour a cylindrical chamber with an internal radius r = 150 mm, a length L = 400 mm, and an internal wall thickness s_w = 1 mm. The reference cooling channel geometry is characterized by rib and channel thickness $t_w = b$ = 2 mm, and height h = 16 mm, which corresponds to $\lambda = 8$. The resulting number of cooling channels is $N = 236$. Of course, for a given internal radius, the circumferential length of the cooling circuit, $2\pi r = N(b + t_w)$, is constant for every channel geometry. The selected criterion to vary the channel aspect ratio is obtained considering the constraints of $h = \text{const}$ (which means, same overall dimensions) and $N \cdot h \cdot t_w = \text{const}$ (which means, for a given material, same weight). The dependency of the geometric parameters on channel aspect ratio λ is shown in Fig. 1.

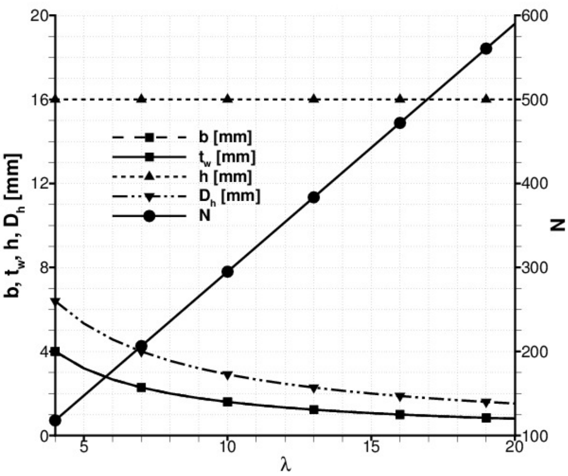


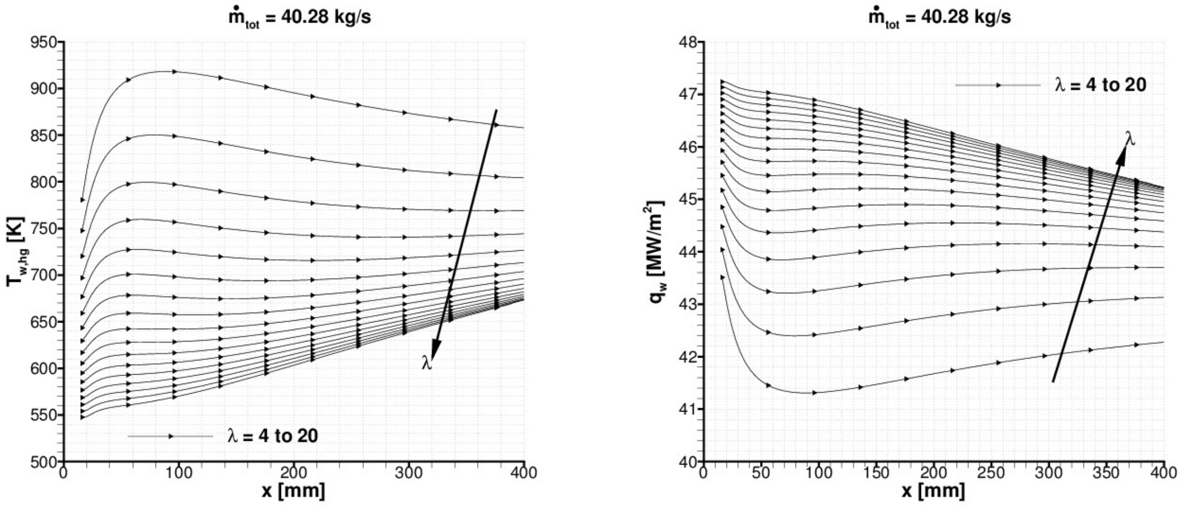
Figure 1: Dependency of the cooling circuit geometric parameters to channel aspect ratio.

In this analysis, the solid material is assumed to have a hydrodynamically smooth surface and a thermal conductivity $k_w = 390$ W/m K, that is a typical value of the copper alloys used in rocket engine applications, such as AMZIRC or OFHC-copper [9]. The hot-gas is characterized by a constant value of heat transfer coefficient and adiabatic wall temperature along the chamber length: $h_{w,hg} = 16000$ W/m^2 K and $T_{aw,hg} = 3500$ K, which are representative of conditions of high-performance rocket engines thrust chambers. The external wall is assumed adiabatic. The coolant is supercritical hydrogen and the inlet coolant conditions are $T_{in} = 80$ K and $p_{in} = 80$ bar. Finally, for the reference case of $\lambda = 8$, the mass flow rate of the single channel is $\dot{m} = 0.171$ kg/s; thus, the resulting Reynolds number of the turbulent flow is $Re = 4 \cdot 10^6$.

3. Results

With reference to the cooling channel design of Fig. 1, two different parametric studies with variable channel aspect ratio are performed. The first parametric study refers to the case of constant coolant mass flow rate $\dot{m}_{tot} = 40.28$ kg/s, which is the value used for the reference case of $\lambda = 8$. Also inlet coolant temperature and pressure are the same for all the considered channel aspect ratios. The aspect ratio is varied from 4 to 20. The resulting wall temperature and the heat flux at the hot-gas side, obtained with the quasi-2D model, are presented in Fig. 2.

The wall temperature decreases and the heat flux increases for increasing channel aspect ratio. Moreover, it is worth emphasizing a peculiar thermal behavior for increasing channel aspect ratio. In fact, if $\lambda \leq 8$ the wall temperature, after the flow development close to the channel inlet, reaches a maximum between $x \sim 50$ mm and ~ 100 mm and then decreases (Fig. 2(a)). This is explained by the heat transfer decrease in the flow development region and the subsequent heat transfer increase due to the increasing coolant thermal conductivity with temperature; the minimum heat transfer coefficient reached after flow development causes the maximum wall temperature. The decrease is nearly 60 K in case of $\lambda = 4$ while, in the reference case of $\lambda = 8$, the wall temperature is nearly constant all along the channel length for $x \gtrsim 50$ mm. A further increase of the aspect ratio implies that the wall temperature progressively increases in the streamwise direction. The temperature increase is nearly 125 K in case of $\lambda = 20$. Note that the wall temperature increase is limited by the channel length; that is, the longer the channel the larger the temperature increase. Thus, even if the wall temperature level of $\lambda = 20$ is well below that of $\lambda = 8$, it must be considered that a marked increase of the wall temperature is not wanted in the actual application because of the possible excess of the maximum allowable wall temperature after a certain channel length. The deterioration of the cooling capability in case of very high aspect ratio can be easily related to the heat flux decrease along the channel length (see Fig. 2(b)). This effect, which is due to the limited mixing and thermal stratification within the coolant



(a) Wall temperature.

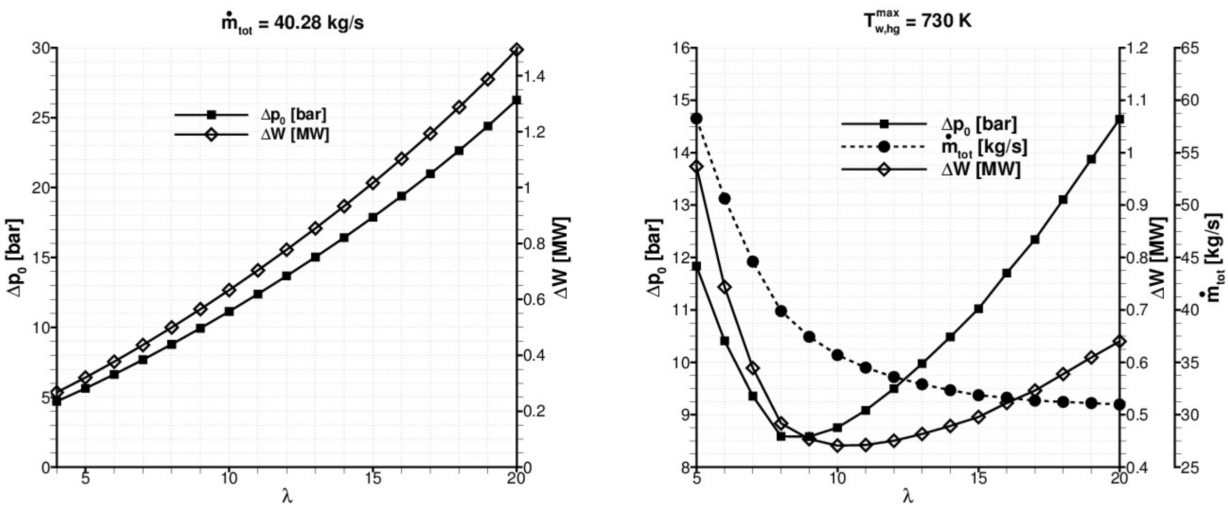
(b) Wall heat flux.

Figure 2: Hot-gas side parametric behavior.

that takes place in case of high aspect ratio and has been already noticed in Ref. [10, 6], cannot be described with a one-dimensional model because of the absence of the coolant and wall thermal conduction in the radial direction.

In Fig. 3(a) the coolant pressure drop, Δp_0, and the power loss, $\Delta W = \dot{m}_{tot} \Delta p_0$, that is the requested coolant pump power to overcome pressure loss in the cooling circuit, is shown for the considered aspect ratio range. The results highlight that in case of constant coolant mass flow rate the reduction of maximum wall temperature with increase of channel aspect ratio is offset by the increase of both pressure drop and power loss. Passing from $\lambda = 4$ to $\lambda = 20$ these variables increase by a factor of about 13.

The second parametric study is performed considering variable coolant mass flow rate with the constraint of maximum hot-gas side wall temperature. The selected value is $T_{w,hg} = 730$ K, which pertains to the reference case of $\lambda = 8$ and $\dot{m}_{tot} = 40.28$ kg/s. Searching for the required coolant mass flow rate is made iteratively so that the wall temperature satisfies the constraint $T_{w,hg}^{max} = 730$ K. Of course, due to the effect of limited coolant mixing and thermal stratification in case of high aspect ratios seen in Fig. 2(a), the maximum wall temperature is encountered in the initial part of the channel length if $\lambda < 8$ or at the channel exit if $\lambda > 8$.



(a) Constraint of imposed coolant mass flow rate.

(b) Constraint of imposed maximum wall temperature.

Figure 3: Cooling channel parametric behavior.

The behavior of the coolant pressure drop, mass flow rate, and power loss, is shown in Fig. 3(b) as a function of channel aspect ratio, within the range $5 \leq \lambda \leq 20$. Note that the cases of aspect ratio lower than 5 are not considered because they are not able to satisfy the constraints of $T_{w,hg}^{max} = 730$ K and subsonic flow. The required constraint of imposed maximum wall temperature can be achieved with decreasing coolant mass flow rate as channel aspect ratio increases. In particular, passing from $\lambda = 5$ to 20, the mass flow rate almost halves, ranging from 58 kg/s to 31 kg/s. The coolant pressure drop exhibits a minimum for $\lambda = 8$, which is $\Delta p_0 = 8.6$ bar; the pressure drop for smaller or larger aspect ratios is consistently higher, being $\Delta p_0 = 11.8$ bar for $\lambda = 5$ and $\Delta p_0 = 14.6$ bar for $\lambda = 20$. The minimum pressure drop is due to the fact that the coolant heat transfer coefficient increases with λ because of the hydraulic diameter reduction but this behavior is limited by the "thermal stratification" that occurs for very high aspect ratios. These conflicting phenomena, for a given maximum wall temperature, lead to a minimum pressure drop. As a consequence, also the power loss through the cooling circuit presents a minimum value. This minimum is located around $\lambda = 10$; with respect to $\lambda = 5$ and $\lambda = 20$, the power loss is reduced by 55% and 31%, respectively.

4. Conclusions

A trade-off analysis has been carried out to study the performance of cooling channel for varying channel aspect ratio. Considering different aspect ratios and coolant mass flow rates such that the wall temperature remains below a threshold value, an optimum value is finally identified as the channel configuration that yields the minimum power loss or the minimum pressure drop in the cooling circuit. The analysis has followed the strategy in varying channel aspect ratio by assuming constant weight and height of the channels. This strategy has led to a minimum of power loss at $\lambda = 10$, which is about half the value at $\lambda = 5$. Finally, the analysis has emphasized that, in case of aspect ratios larger than $\lambda > 10$, the beneficial effect of HARCC is reduced because of the excessive coolant thermal stratification in the radial direction..

References

[1] Quentmeyer, R. J., 1977. Experimental Fatigue Life Investigation of Cylindrical Thrust Chambers. AIAA Paper 1977-893, 13th AIAA/SAE Propulsion Conference.

[2] Quentmeyer, R. J., 1990. Rocket Combustion Chamber Life-Enhancing Design Concepts. AIAA Paper 1990-2116, July 1990, 26th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[3] Carlile, J. A. and Quentmeyer, R. J., 1992. An Experimental Investigation of High-Aspect-Ratio Cooling Passages. AIAA Paper 1992-3154, 28th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[4] Wadel, M. F., 1997. Comparison of High Aspect Ratio Cooling Channel Designs for a Rocket Combustion Chamber. AIAA Paper 1997-2913, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[5] LeBail, F. and Popp, M., 1993. Numerical Analysis of High Aspect Ratio Cooling Passage Flow and Heat Transfer, AIAA Paper 1993-1829, 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[6] Woschnak, A., Suslov, D., and Oschwald, M., 2003. Experimental and Numerical Investigations of Thermal Stratification Effects, AIAA Paper 2003-4615, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[7] Pizzarelli, M., Carapellese, S., and Nasuti, F., 2011. A Quasi-2D Model for the Prediction of Wall Temperature of Rocket Engine Cooling Channels. *Numerical Heat Transfer, Part A: Applications*. 60:1–24.

[8] Pizzarelli, M., Nasuti, F., and Onofri, M., 2013. Coupled Wall Heat Conduction and Coolant Flow Analysis for Liquid Rocket Engines. *Journal of Propulsion and Power*. 29:34–41.

[9] Esposito, J. J. and Zabora, R. F., 1975. Thrust Chamber Life Prediction. Volume 1: Mechanical and Physical Properties of High Performance Rocket Nozzle Materials. NASA CR-134806, Final Report Boeing Aerospace Co., Seattle, WA.

[10] Woschnak, A. and Oschwald, M., 2011. Thermo and Fluidmechanical Analysis of High Aspect Ratio Cooling Channels. AIAA Paper 2001-3404, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference.