Optimization of Aspect Ratio for Cooling Channels in Rocket Engines

A Parametric Study on the RL10 Engine

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Introduction

- **Objective**: Find the optimal mass flow rate and aspect ratio (AR) for the cooling channels at the throat section of the RL10 engine.
- **Context**: Importance of aspect ratio in enhancing cooling performance and minimizing pump power loss.

Methodology

- **Parametric Study**: Conducted to determine the optimal AR by varying mass flow rate and observing the resulting pressure drop and power loss.
- **Design**: Channel height constant, width is twice the rib thickness.

Key Equations and Concepts (1/2)

- **Aspect Ratio (AR):** Ratio of channel height to width.
- **Heat Transfer Coefficient**:
  - Coolant: Explained through the Dittus-Boelter correlation for the Nusselt number
  - Hot gas: Bartz correlation
- **Wetted Perimeter and Hydraulic Diameter**: Their role in pressure drop and heat transfer.

Key Equations and Concepts (2/2)

(1) Pressure drop: $\Delta p_0 \sim \frac{G^2}{D_h}$

(2) Channels hydraulic diameter: $D_h = \frac{4A}{P} = \frac{4A_{tot}}{P_{tot}}$

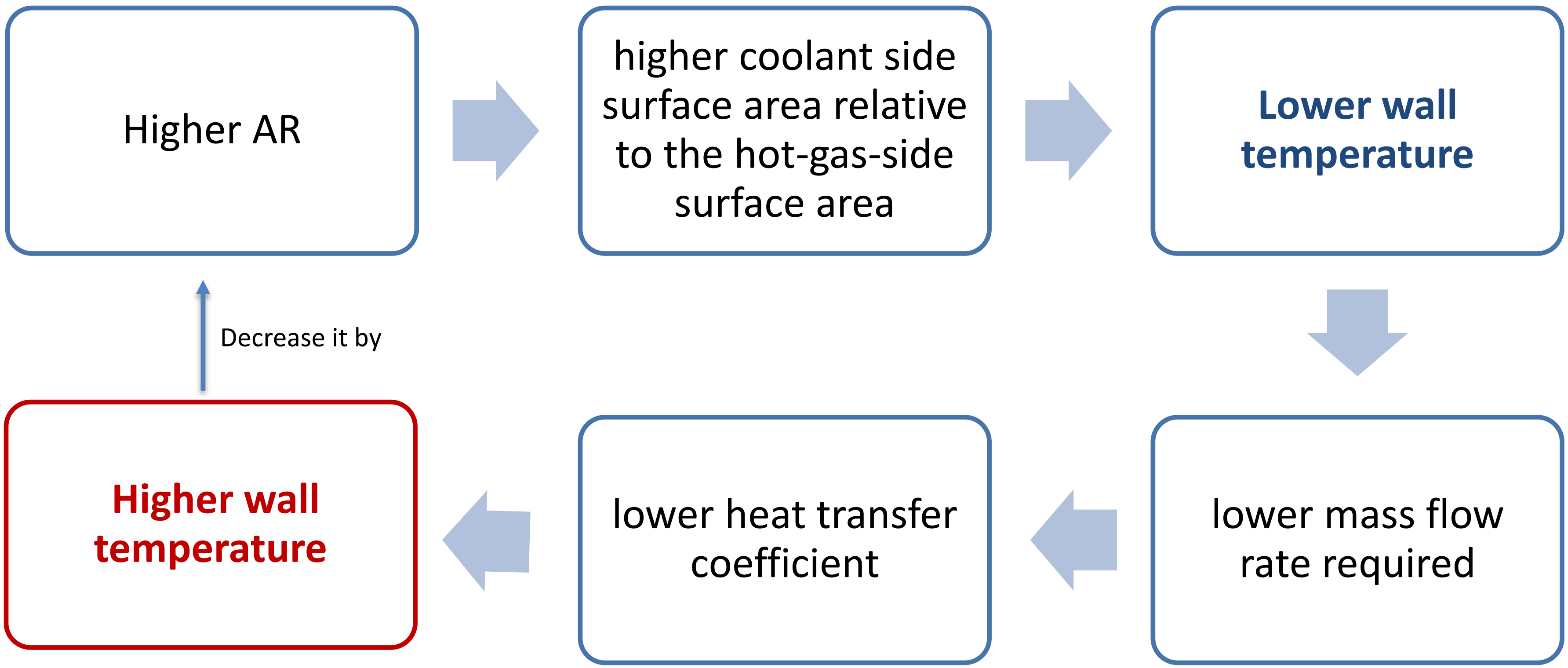
(3) Coolant heat transfer coefficient: $h_w \sim \frac{G^{0.8}}{D_h^{0.2}}$

- For a given coolant mass flow rate, the wall temp can be reduced by increasing the coolant-side surface area relative to the hot-gas-side surface area. This means increasing the wetted perimeter (P_tot), which means more cooling jackets.
- Increasing P_tot will decrease the hydraulic diameter, and consequently increase the pressure loss. (equations 1 and 2)
- The heat transfer will decrease if the hydraulic diameter increases.

Note: G is the mass flow rate per unit area [kg/s/m^2]

Reference: Pizzarelli, Trade-off analysis of high-aspect-ratio-cooling-channels for rocket engines.

Need for a parametric study



Requirements (ref.[2])

- Cooling jackets outlet pressure: 5.6 Mpa
- Wall temperature < 880K
- Coolant is subsonic in the cooling channels

Algorithm

1. Geometry inputs, define $P_{pump_{f_{in}}}$, $T_{pump_{f_{in}}}$, $P_{pump_{ox_{in}}}$,$T_{pump_{ox_{in}}}$

$For\ loop\!: \ Aspect\ ratio = 1\!:\!20$

$For\ loop\!: \ mass\ flow\ rate = 3\!:\!6$

While loop: error > tolerance (bisection method)

2. Define bounds, $P_{IN,l}$, then $P_{IN,u}$ for the cooling jacket inlet pressure

3. Calculate average $P_{IN,mid}$

4. Determine P_{out} with *regen_cooling_rl10.m* function

5. Error = $(P_{OUT,mid}$ - $P_{OUT,l})$

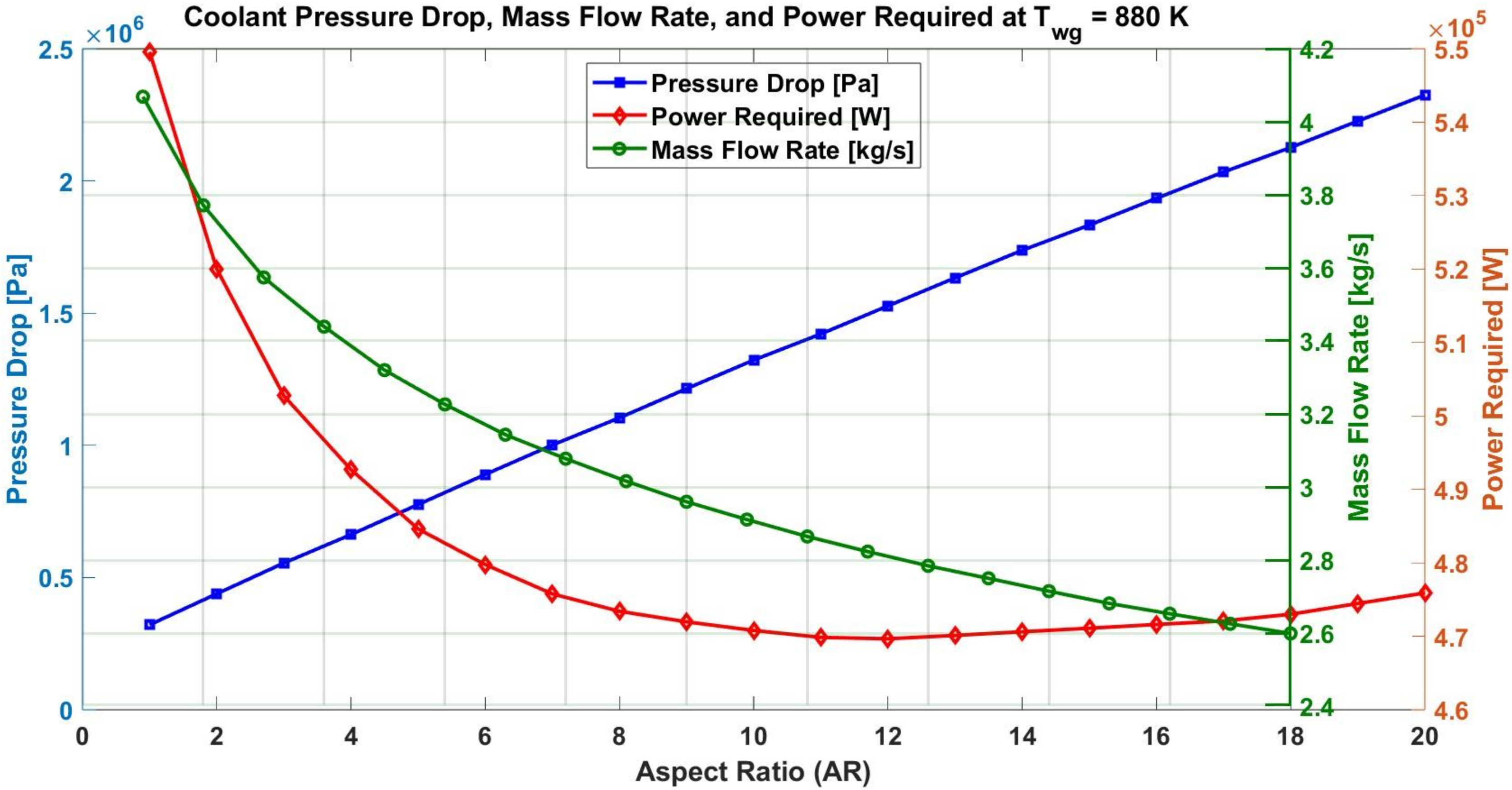
6. Bisection interval boundaries update

end

Results Overview

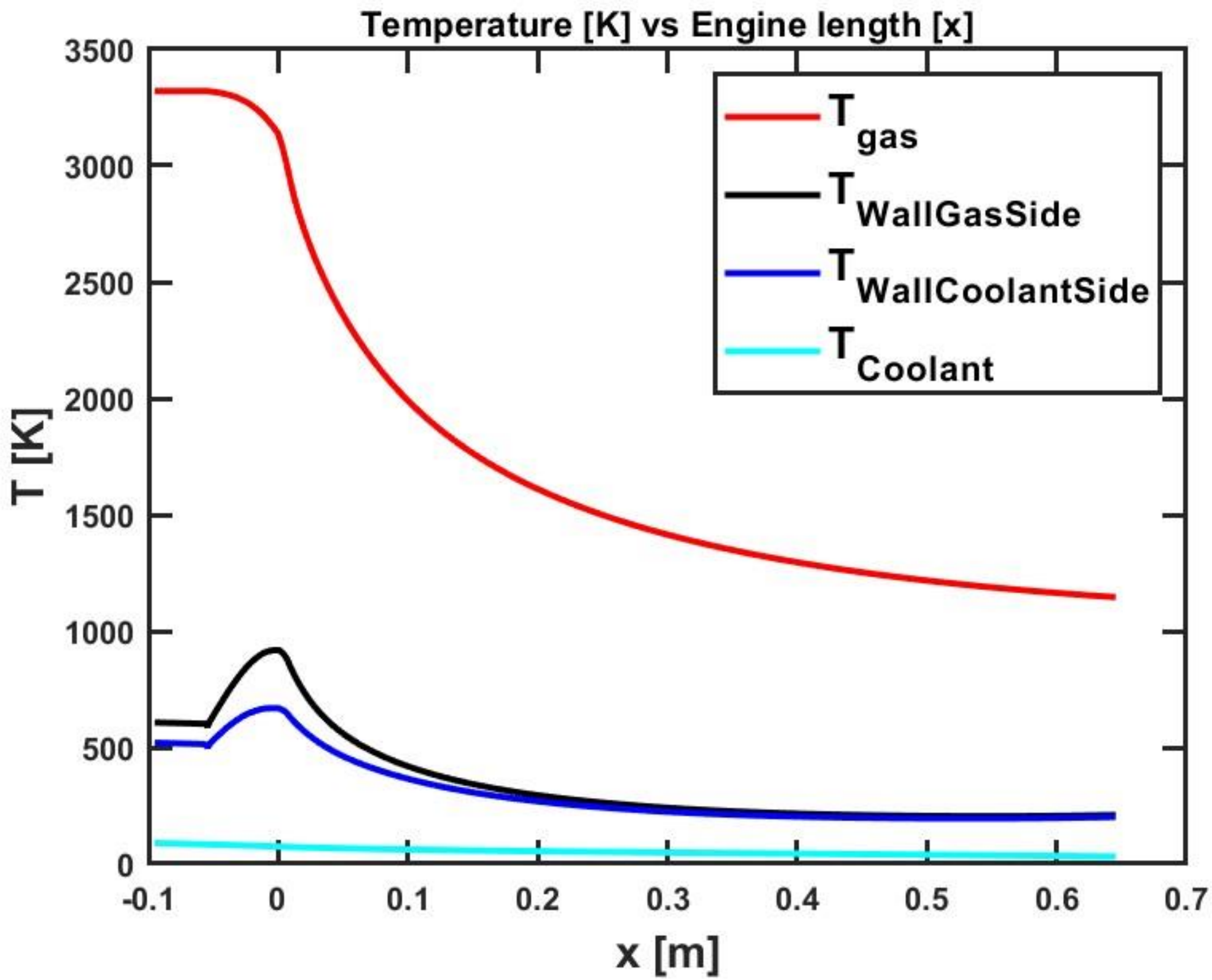
- Minimum pressure drop at AR=1, minimum power loss at AR=12.
- Current RL-10
  - H_2 mass flow rate = 2.7 kg/s
  - Power consumption: 0.50 MW
- Optimized RL10
  - Hydrogen mass flow rate = 2.6 kg/s
  - Power consumption = 0.47 MW
- Power saving with optimized AR: 6%

Graphical Results



Coolant pressure drop, mass flow rate, and power required as a function of AR.

Temperature distribution in the engine



Discussion

- **Trade-offs**: Higher AR improves cooling but increases pressure losses.
- **Manufacturing Considerations**: Challenges in achieving high AR with conventional machining.

Conclusion

- **Optimal AR**: Identified as AR=12 for minimizing power loss while maintaining acceptable cooling, and subsonic flow in the channels
- **Future Work**: Suggestions for further parametric studies with more variables.

References

1. Pizzarelli, Trade-off analysis of high-aspect-ratio-cooling-channels for rocket engines.
2. Binder, RL10A-3-3A Rocket Engine Modeling Project
3. Haberbusch, Modeling the RL1O with Densified Liquid Hydrogen and Oxygen Propellants.
4. NASA SP8107, Turbopump systems for liquid rocket engines.
5. Bartz, Technical notes.

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