Quantification of Heat Loads for Rotating Detonation Combustor with Gas Turbine Conditions

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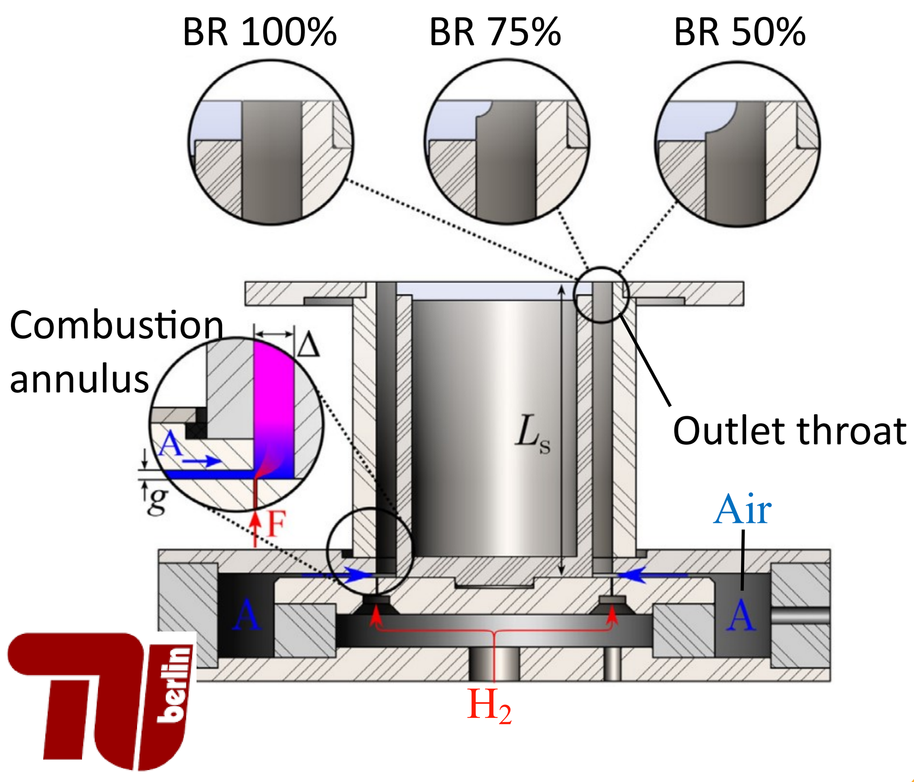
Abstract

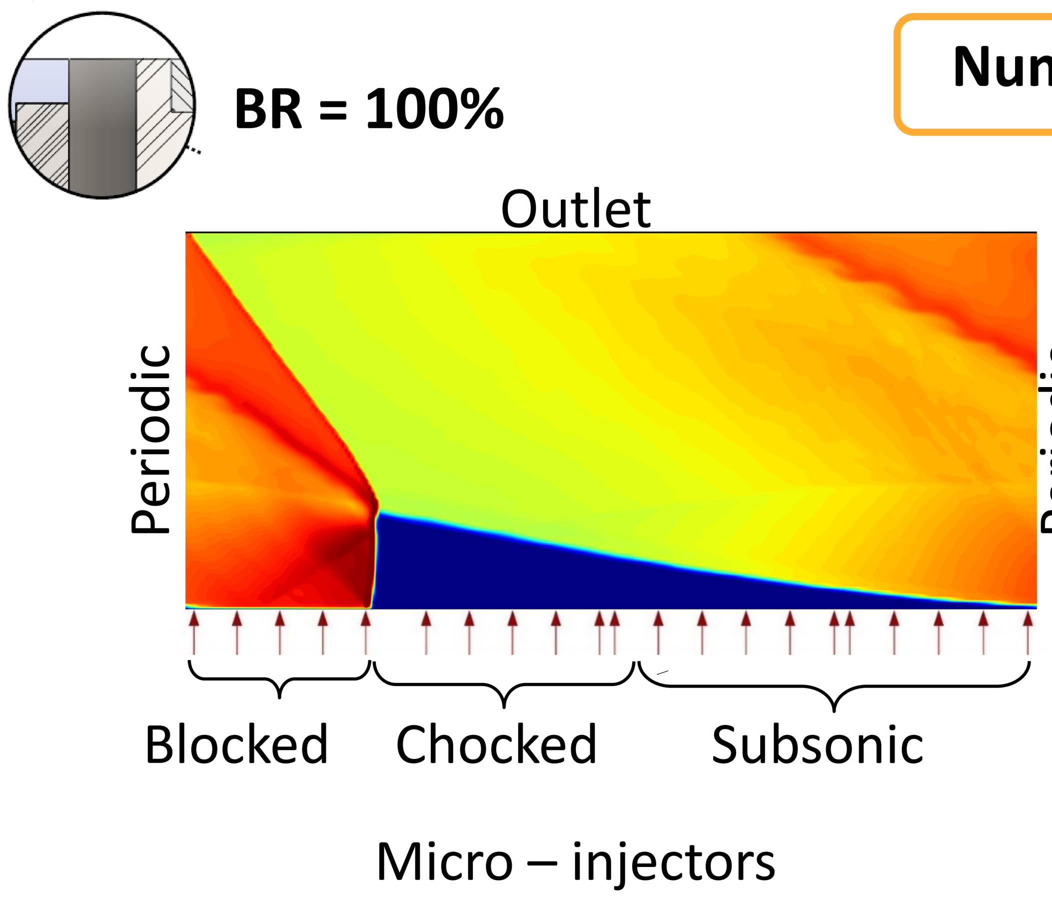
Rotating Detonation Combustors (RDC) offer a very high-power density compared to other combustors. Although they must overcome many challenges to be integrated into a gas turbine (GT), it is certainly a promising solution for increasing cycle efficiency. Among the many challenges, cooling the RDC is one of the most predominant, due to the high heat loads generated by the combustion process. Most of the available numerical and experimental data in the literature about RDC heat loads are obtained for laboratory conditions (i.e. at atmospheric pressure). However, in order to design a cooling system for an RDC that allows for its sustainable operation and aids its integration to GT engines, a quantification of the heat loads of an RDC with GT conditions is necessary. The presence of a detonation wave/boundary layer interaction and a small annulus width leads to a very high heat transfer when compared to a conventional GT combustor.

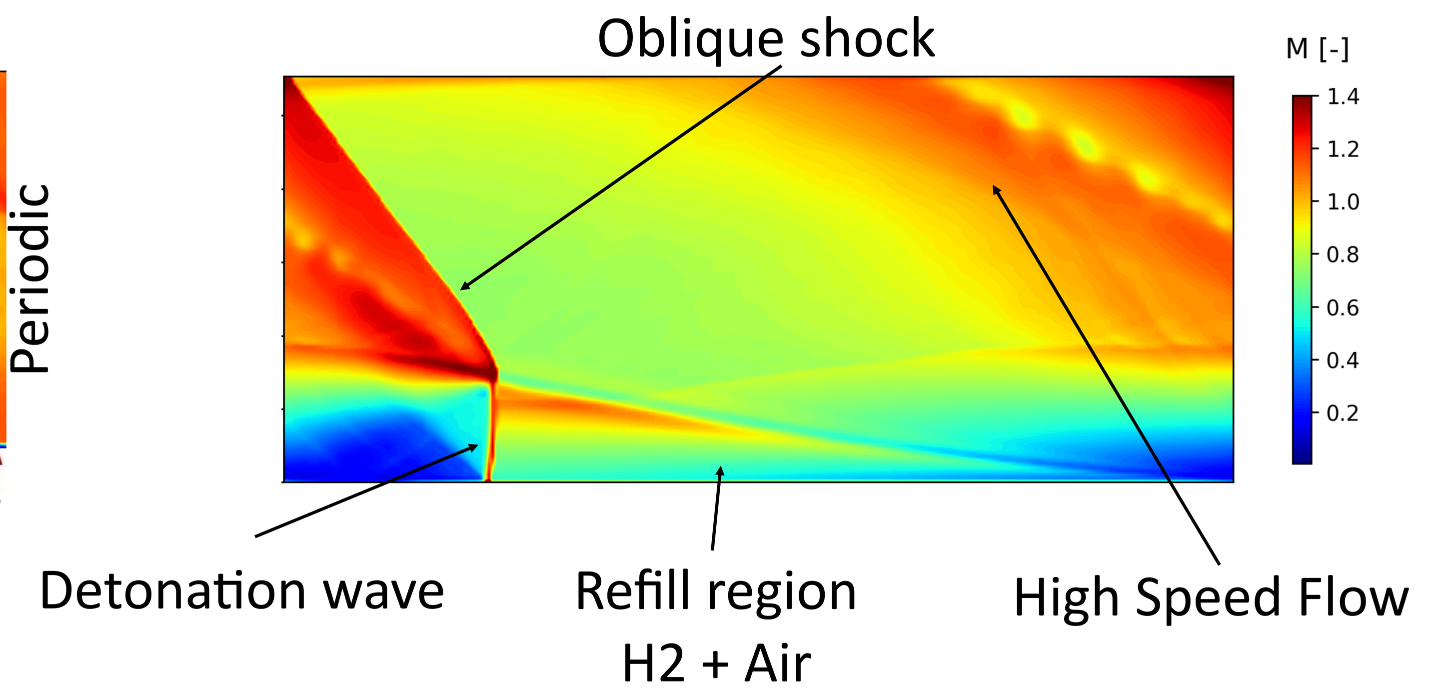
Experimental Setup

A combustor integrated into a turbine experiences mass flow restrictions due to the reduction of the flow area. One simple way to consider this is to add outlet area restrictions to the combustor [1].



Numerical Methodology





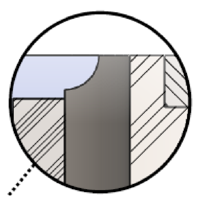
Premixed Hydrogen — Air mixture is injected as sources. The mass, momentum and energy sources are calculated from the isentropic mass flow rate equation. P_o and T_o are plenum pressure and temperature, P_x is the static pressure in each injection cell.

$$\dot{m} = \frac{Ap_o}{\sqrt{T_o}}\sqrt{\frac{\gamma}{R}}M\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

$$V_x = \sqrt{\frac{2\gamma_R}{\gamma_R-1}R_R T_o\left[1-\left(\frac{P_x}{P_o}\right)^{\frac{\gamma_R-1}{\gamma_R}}\right]}$$

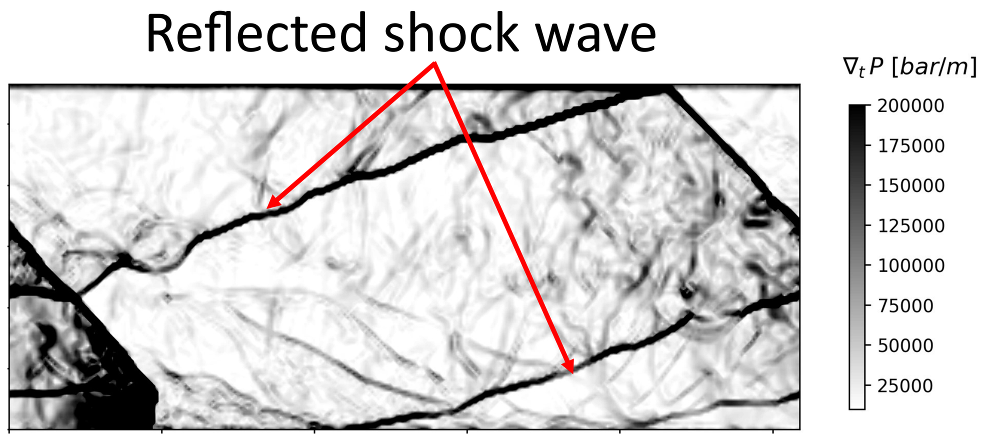
- Quasi 2D mesh—unrolled RDC.
- Pressure Based solver (Fluent).
- Navier Stokes equation.
- No Turbulence models.
- Species transport.
- Single step reaction mechanism [2].

BR = 50%

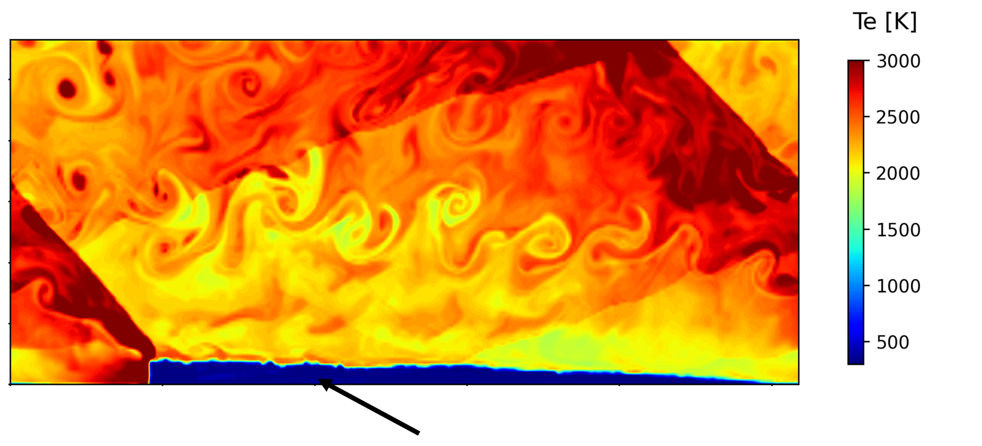


The simulation is performed for a mass flux of 500 kg/s m^2. Because of the restricted output, the oblique shock reflects from the output and impinges on the injectors, further reducing the mass flow rate. The increase in chamber pressure causes the compression of the refill region leading to a very dense initial mixture which results in a stronger detonation.

Reflected shock wave

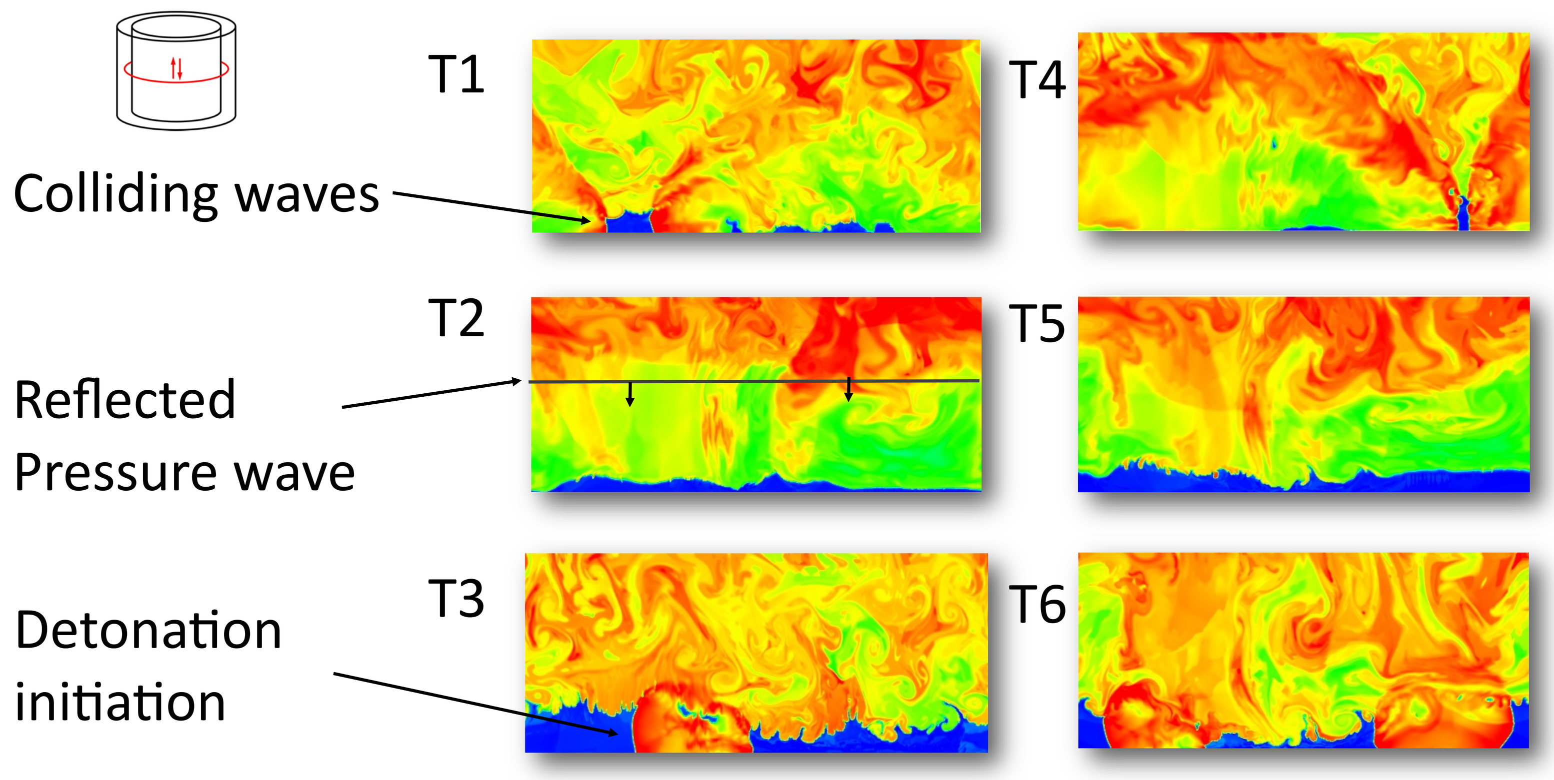


Pressure gradient contour



Compressed refill region

With outlet restrictions the dynamics of the combustor change completely. At certain mass flux and area restrictions the single wave quickly transits to clapping waves and axially pulsating waves which are not desired for GT applications.



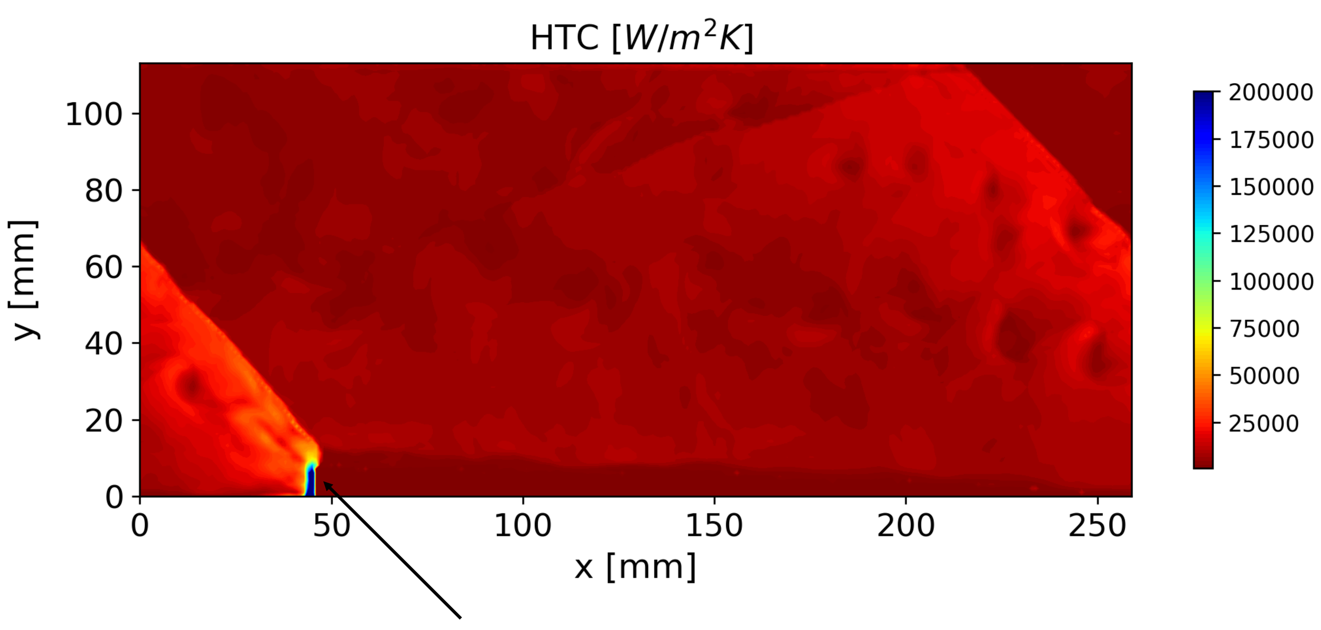
Heat Flux Modelling

The wall heat flux is calculated with the following equation [3].

$$St = \frac{0.123e^{-1.151H_{i,fp}}\left(\frac{T_e}{T_{ref}}\right)^{0.732}}{\left(\frac{T_0}{T_e}\right)^{0.268}\left(\frac{M_e a_0 \theta_{tr}}{\nu_0}\right)^{0.268}}Pr_{ref}^{-2/3}$$

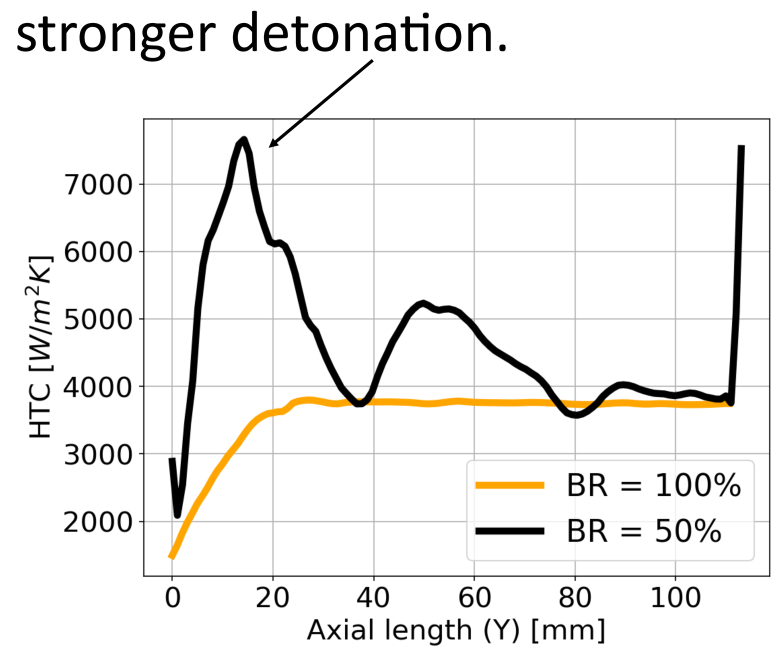
$$q_{wall} = \mathrm{St}\ \rho_e u_e (h_{aw} - h_w)$$

The flow fields obtained from RDC simulations are split into numerous 1D arrays, and the equations are applied.



The detonation front induces an extremely high heat transfer. Shock wave boundary layer interaction with hot gases results in elevated heat loads.

Elevated heat transfer caused by a stronger detonation.



Laterally-averaged HTC for Mass Flux of 500 kg/s m^2.

References:

[1]Bach, E., Stathopoulos, P., Paschereit, C. O., & Bohon, M. D., *Performance analysis of a rotating detonation combustor based on stagnation pressure measurements. Combustion and Flame, 217, 21–36 .2020.03.017*

[2]Nassini Pier Carlo, *High-fidelity Numerical Investigations of a Hydrogen Rotating Detonation Combustor, PhD Thesis, UniFI, 2022*

[3]Braun et al., *Numerical assessment of the convective heat transfer in rotating detonation combustors using a reduced-order model. Applied Sciences, Applied Sciences (Switzerland), 8(6).*

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