Low-Order Model of the Impact of Combustion Inefficiencies in RDCs

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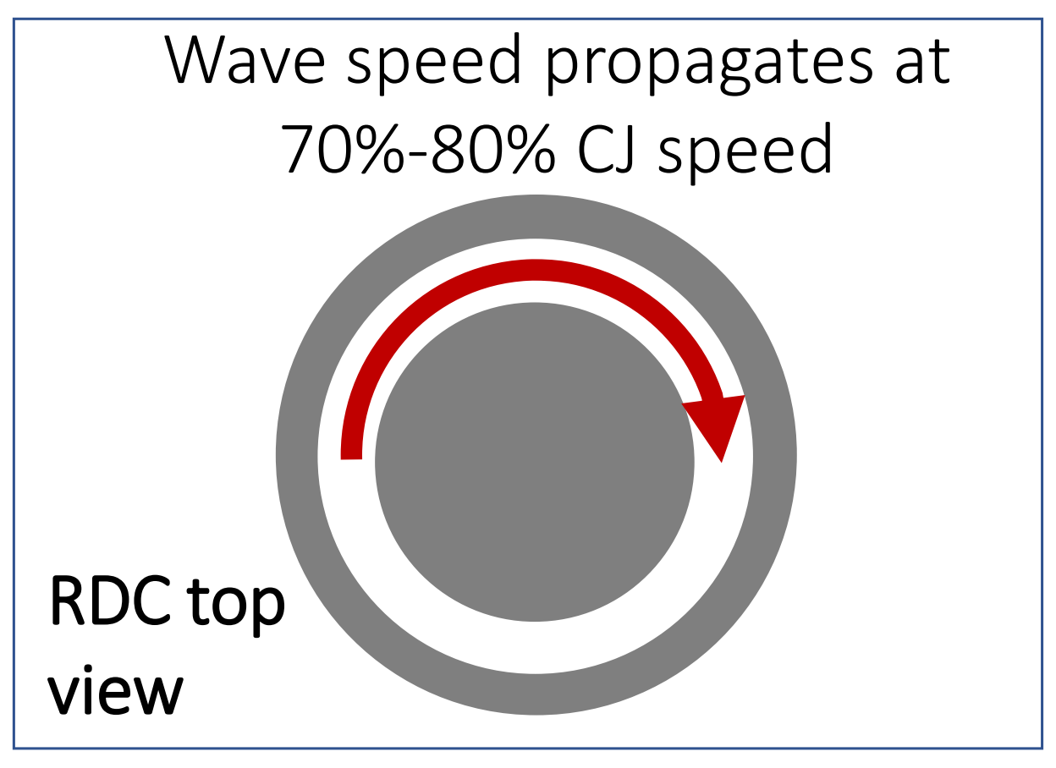
Motivation


Wave speed propagates at 70%-80% CJ speed

RDC top view

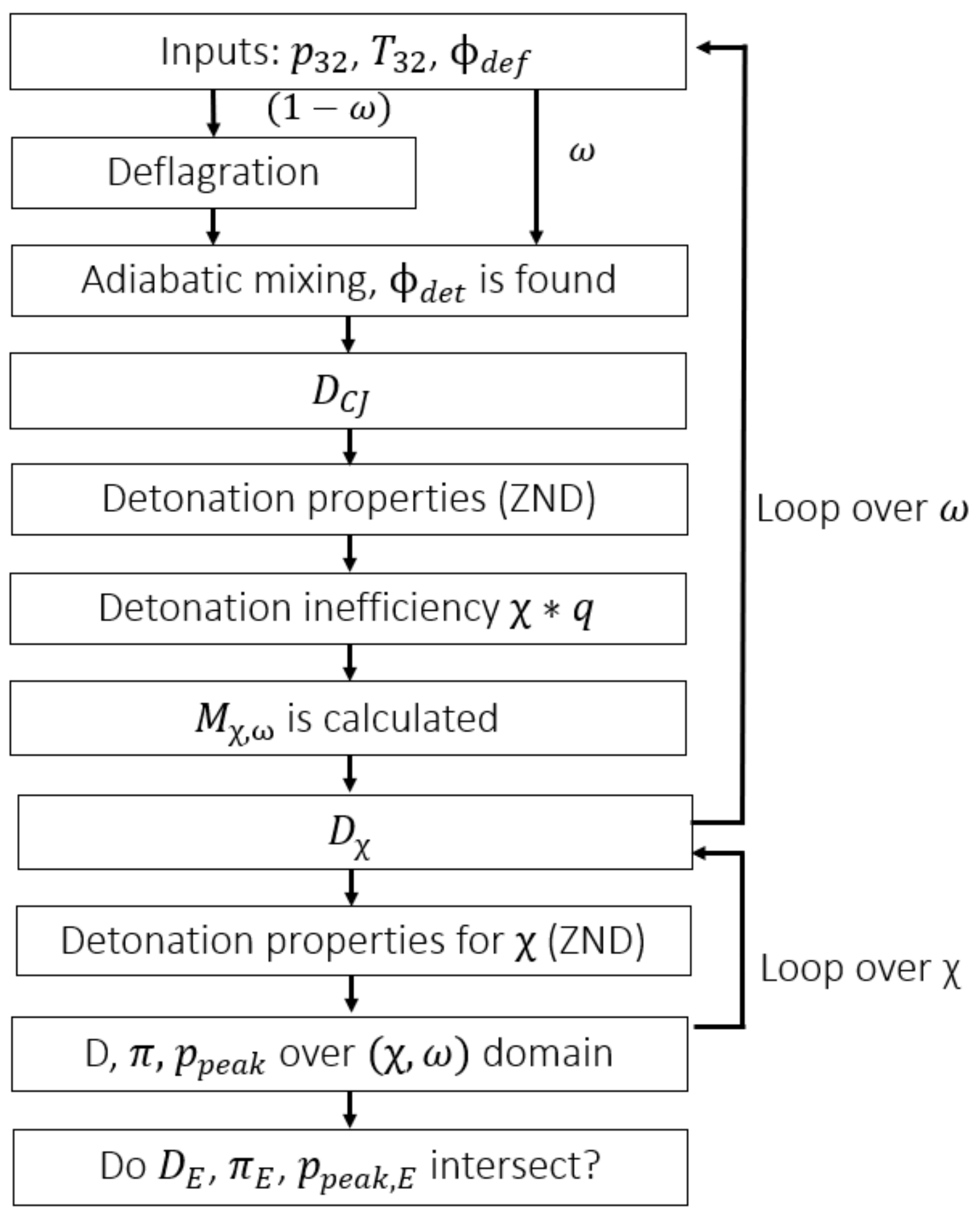
Figure 1 Typical observations in experimental RDCs

- In experimental rotating detonation combustor (RDC) studies, the detonation wave often propagates at 70 – 80% of the Chapman–Jouguet (CJ) speed.
- This discrepancy between experiments and theory partly stems from idealized flow assumptions of Zeldovich-von Neumann-Döring (ZND) theory, which does not account for losses.
- It is hypothesized that the differences in detonation characteristics between experiments and theory are due to a partial heat release generated by these loss mechanisms.
- Injection loss mechanisms (non-ideal mixing, backflow of products into the plenum and interaction of products with fresh reactants) affect detonation characteristics and pre-detonation gas states.
- The objective of this study is to estimate the impact these mechanisms may have on the combustion and detonation properties.

Low-order heat release algorithm

Boundary Conditions:

- There are three inputs to the model: the pressure just before the arrival of the detonation wave, p_{32}, the temperature in the annulus, T_{32} and the global equivalence ratio, ϕ.
- The global equivalence ratio, ϕ_g is determined by the relative proportion of the total mass flow rates.
- The local equivalence ratio for the detonation process is impacted by both ψ and ω.
- Convergence is determined by the comparison of wave speed, D, pressure ratio, π, and peak pressure p_{peak}.


Inputs: p_{32}, T_{32}, Φ_{def}

$(1-\omega)$

ω

Deflagration

Adiabatic mixing, Φ_{det} is found

D_{CJ}

Detonation properties (ZND)

Detonation inefficiency $\chi * q$

$M_{\chi,\omega}$ is calculated

D_{χ}

Detonation properties for χ (ZND)

D, π, p_{peak} over (χ, ω) domain

Do D_E, π_E, $p_{peak,E}$ intersect?

Loop over ω

Loop over χ

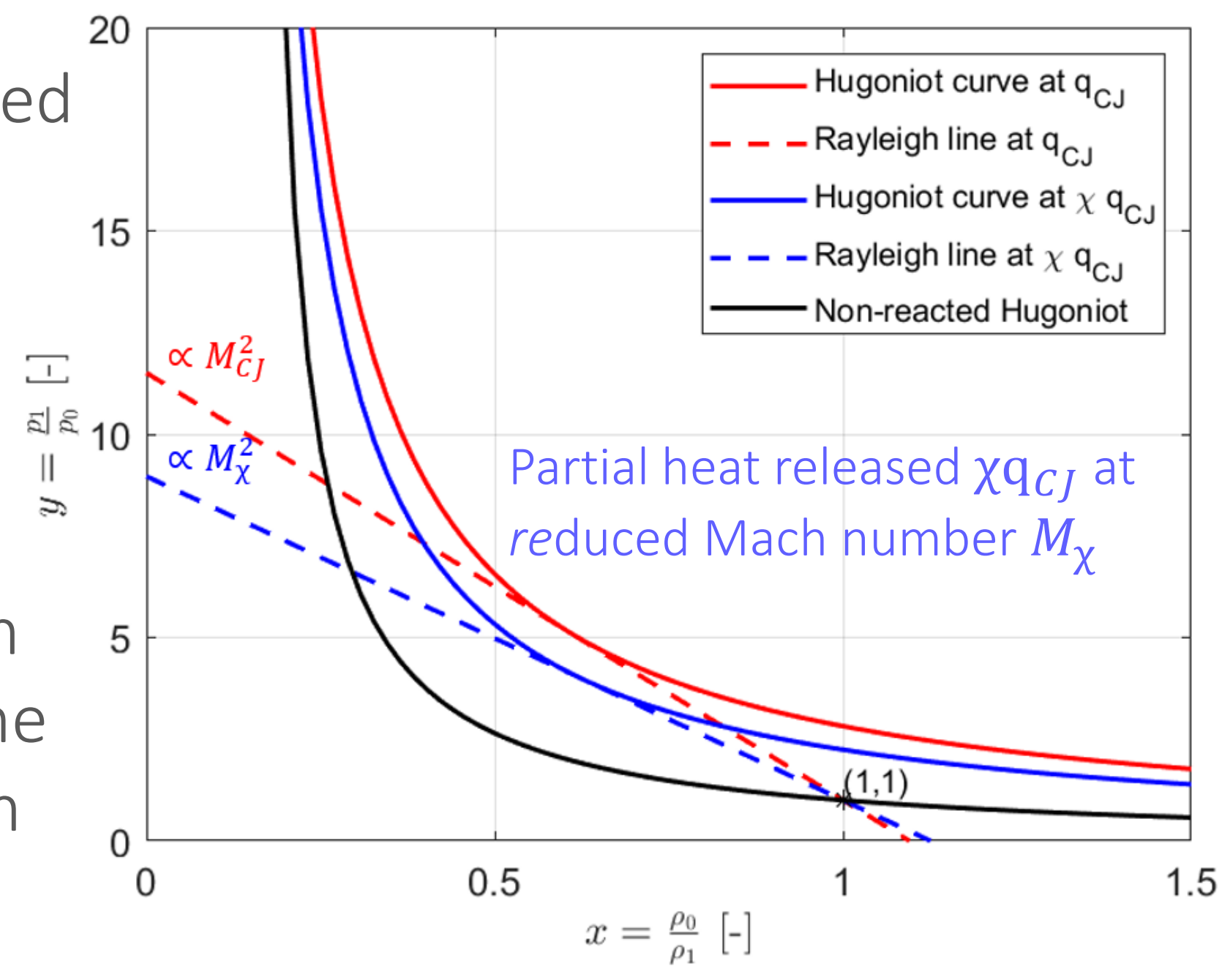
Figure 3 Outline of low-order heat release algorithm

Reduced Mach Number:

- The detonation velocity is obtained from CJ theory, and the heat release that drives the product gases to the sonic condition , q_{CJ}, is calculated from ZND theory.
- The parameter χ is then used to scale q_{CJ} such that $\chi\, q_{CJ}$ represents the modified heat release.
- The reduced Mach number, $M\chi$, is obtained from the following equation:

$$2\left(\gamma^2-1\right)\frac{\chi q_{\mathrm{CJ}}}{c_0^2}=\frac{\left(M_\chi^2-1\right)^2}{M_\chi^2\left(1+\frac{\gamma-1}{2}M_\chi^2\right)}$$

- $M\chi$ accounts for the reduced contribution of heat release in the detonation wave, the impact of pre-combustion, and the shift in the local equivalence ratio due to the formation of a buffer region.



Partial heat released χq_{CJ} at reduced Mach number M_{χ}

Figure 4 calculated RH curves

- Preliminary results using an experimental stable detonation run with D = 1480 m/s and π = 2.06 converge at (χ, ω) = (0.7, 0.5).

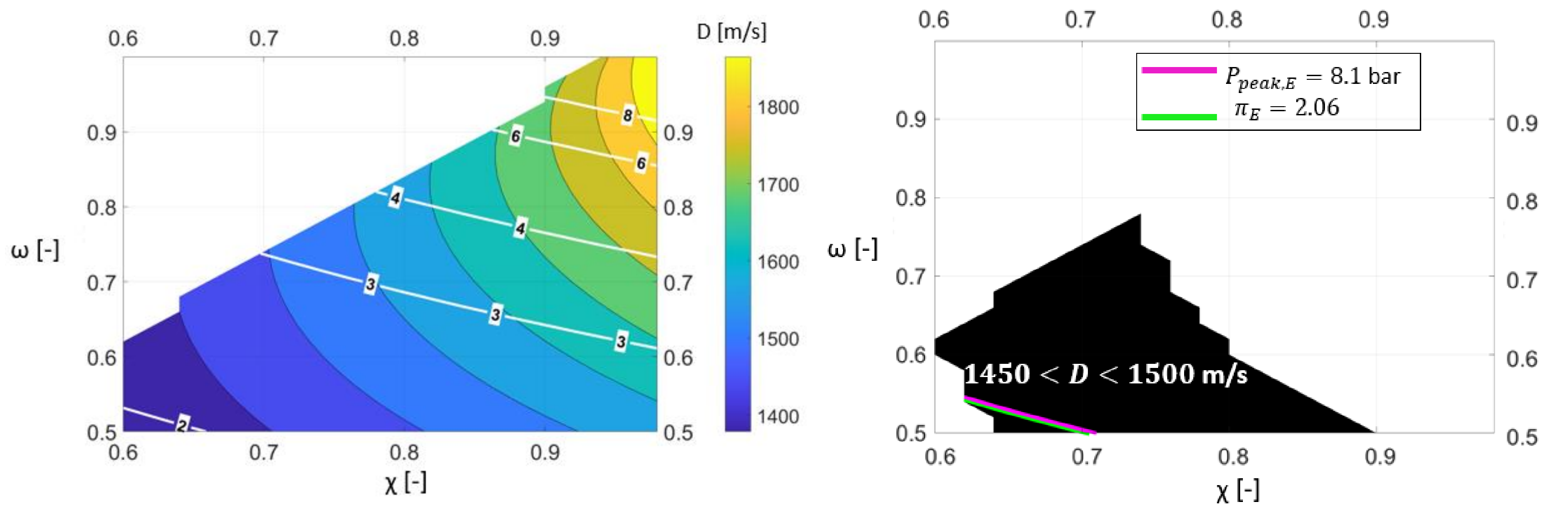
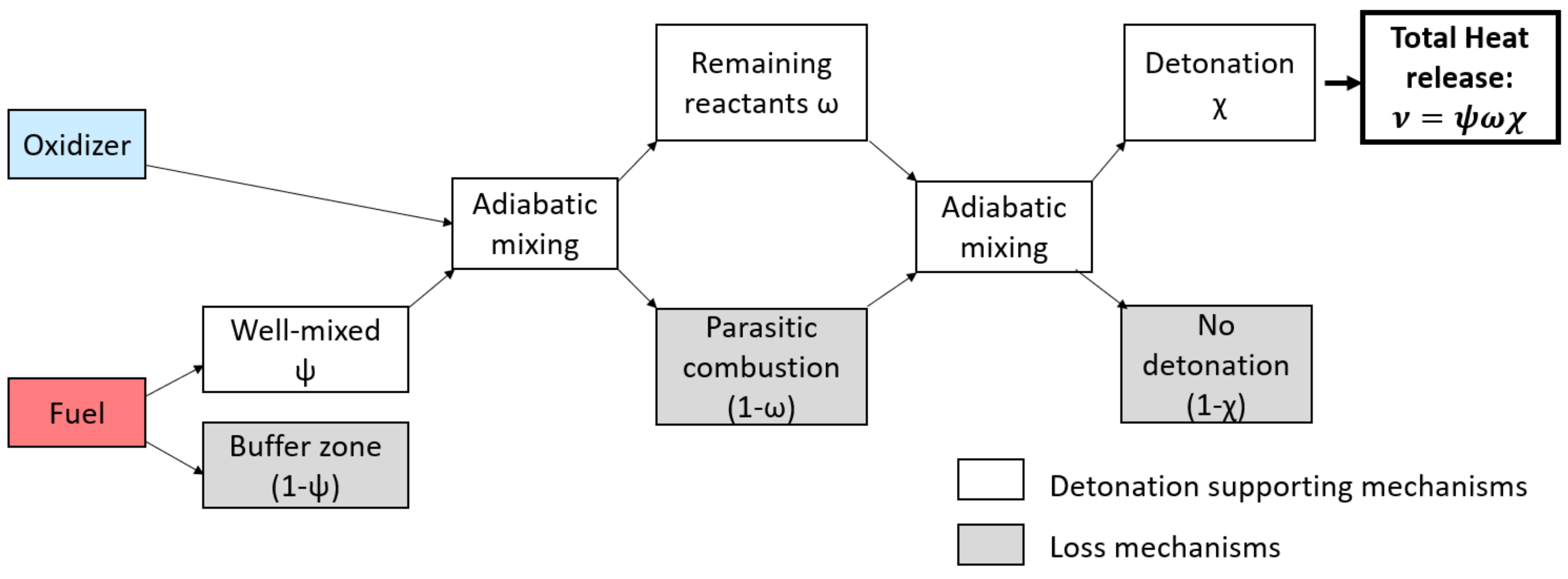


Figure 5 a) Variation of the detonation wave speed and pressure on the $(\boldsymbol{\omega}, \boldsymbol{\chi})$ domain b) Region of convergence between experimental and theoretical parameters.

Loss Mechanisms


Oxidizer

Fuel

Well-mixed ψ

Buffer zone $(1-\psi)$

Adiabatic mixing

Remaining reactants ω

Parasitic combustion $(1-\omega)$

Adiabatic mixing

Detonation χ

No detonation $(1-\chi)$

Total Heat release: $\nu = \psi\omega\chi$

☐ Detonation supporting mechanisms

▨ Loss mechanisms

Figure 2 Non-ideal heat release processes

Domain parameters:

- A three-parameter domain is defined (ψ, ω, χ) with $\psi, \omega, \chi \in [0, 1]$.

ψ	Proportion of fuel that is well-mixed
$(1-\psi)$	Proportion of fuel in the buffer zone
ω	Proportion of fuel that survives the injection and mixing period
$(1-\omega)$	Proportion of fuel burned through parasitic deflagration heat release
χ	Proportion of heat release within the detonation
$(1-\chi)$	Proportion of heat release not within the detonation (wall heat loss, friction)

- The fraction of heat release that supports the detonation wave propagation and is $\nu = \psi\omega\chi$. For a CJ detonation, (ψ, ω, χ) = (1, 1, 1).

Preliminary results

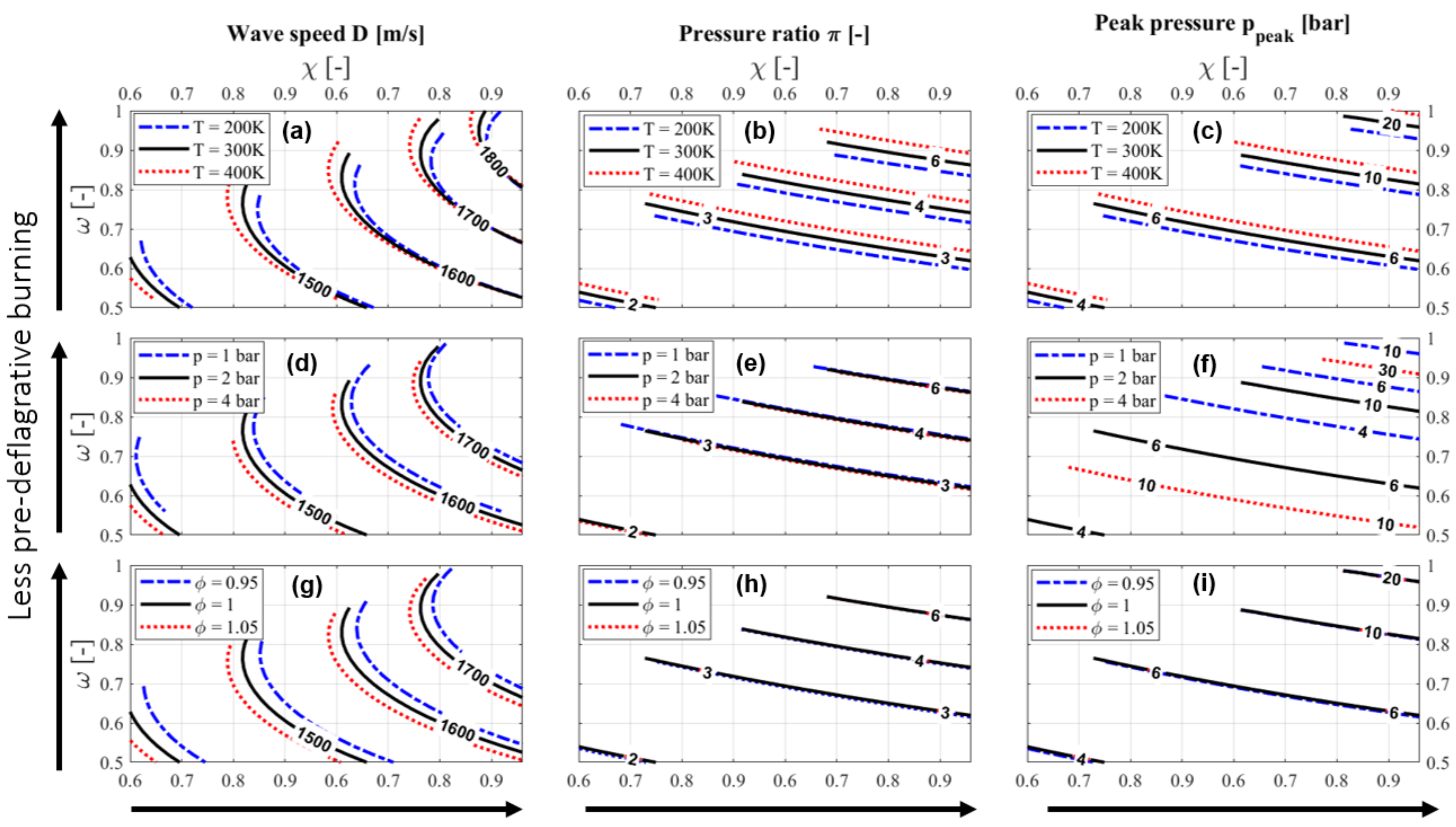


Figure 6 Sensitivity study

- The impact of the three inlet parameters, T_{32}, p_{32} and φ on the wave speed, pressure ratio and pressure peak is studied.
- The wave speed, D, is sensitive to small changes in the equivalence ratio, φ (g).
- The inlet pressure p_{32} significantly affects the peak pressure, p_{peak} (f). Uncertainties in inlet pressure measurements could significantly affect the convergence between calculated and measured peak pressure values.
- The results give insight on which parameters can be used to find the convergence between experimental and computed values. Particularly, given an inlet pressure, the pressure ratio is a more robust measure of convergence.

Conclusions

- Preliminary results using an experimental stable detonation run with D = 1480 m/s and π = 2.06 converge at (χ, ω) = (0.7, 0.5), implying that almost half of the heat release undergoes parasitic combustion.
- To estimate the size of the buffer zone, the individual air and fuel injector response times will be calculated from a dynamic inlet model. From this, the equivalence ratio of the deflagration can be updated in the heat release model.
- A parametric study is currently underway to determine the impact of boundary conditions on characteristic parameters in the RDC.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956803".