Hydrogen-Oxygen Rotating Detonation Rocket Engine Development

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What is a Detonation Engine?

- Detonation is defined as the supersonic propagation of combustion wave through a medium, in contrast to a typical combustion process that travels at subsonic speeds, otherwise known as deflagration [1]. Detonation engines operate a pressure-gain combustion cycle, where the combustible medium is compressed by a leading shockwave, compared to traditional gas turbines and rocket engines which operate as constant-pressure combustion where a pre-compressed fuel mixture is combusted [2].
- *Pulse Detonation Engines* operate cyclically, similar in concept to an internal combustion engine where the air-fuel mixture is injected and combusted. This limits the upper threshold of operational frequency [2].
- *Rotating Detonation Rocket Engines (RDREs)* operate continuously; as the combustion chamber is filled with fresh air-fuel while combustion wave(s) simultaneously travel around the annular combustion chamber.
- Pulsed, and Rotating, Detonation Engine cycles can be approximately represented by the Humphrey and Fickett-Jacobs cycles, respectively.

Table: Theoretical efficiencies of various combustion cycles [3]

Fuel	Brayton (%)	Humphrey (%)	Fickett-Jacobs (%)
Hydrogen (H_2)	36.9	54.3	59.3
Methane (CH_4)	31.4	50.5	53.2
Acetylene (C_2H_2)	36.9	54.1	61.4

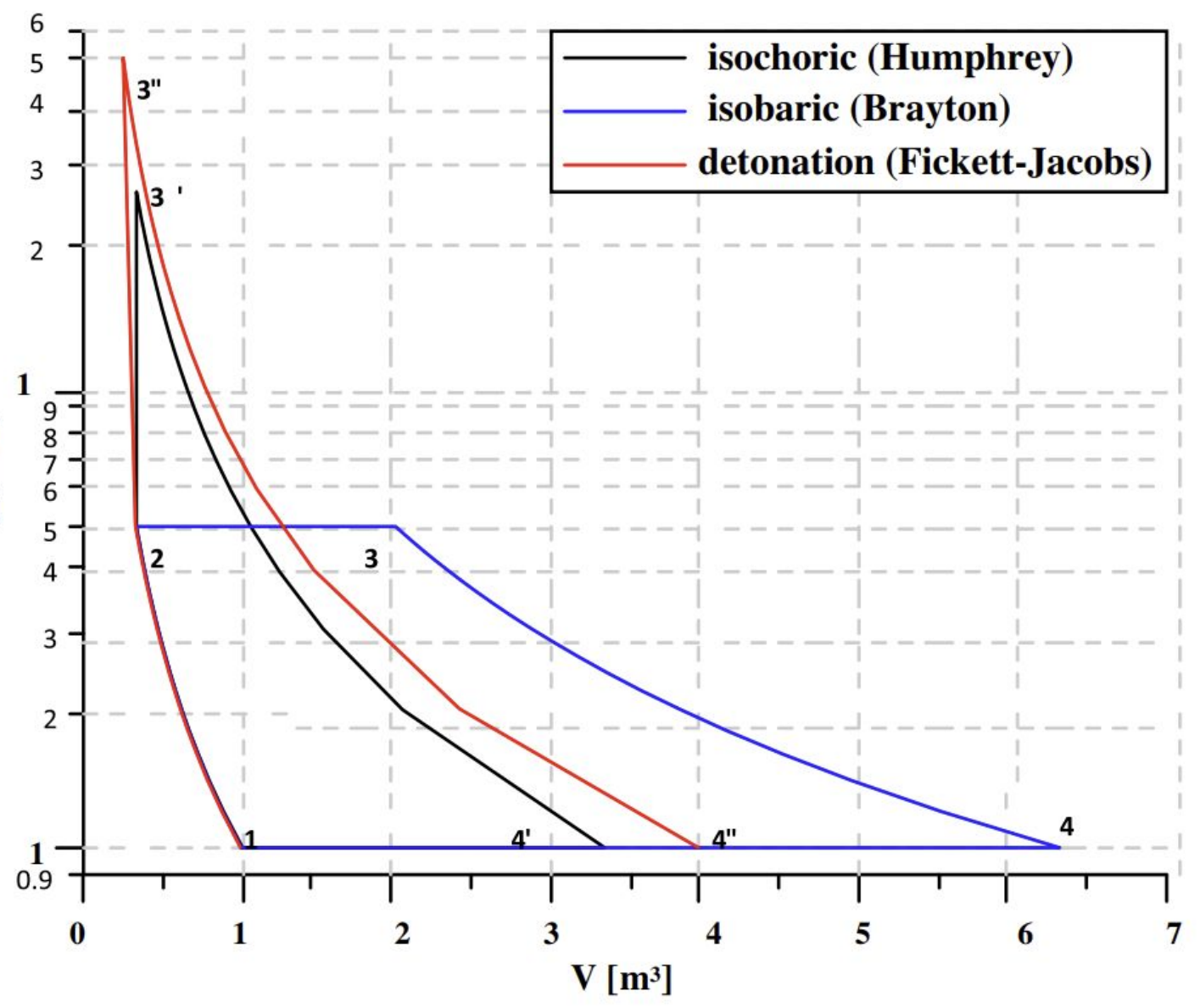

Figure: PV Diagram showing various combustion cycles [4]

- Peak theoretical cycle efficiencies based on fuel source are described in the table above; showing a significant mean efficiency gain of 22.9% comparing Fickett-Jacobs to Brayton cycle efficiencies across the three presented fuel sources.

Project Objectives

- Develop a functional Rotating Detonation Rocket Engine prototype to conduct hot-fire testing.
- Designed to be easily comparable to other engines in the RDRE research community.
- Research bed for further detonation research at MUN.
  - Modular design to allow for easy modification of critical geometry.
- Specific design constraints and objectives are shown on the right hand side.

Table: Qualitative (- minimize; + maximize) and Quantitative Engine Design Constraints

Parameter	Qualitative Objective	Quantitative Objective
Stagnation Pressure P_0	-	$\sim$ 1 MPa
Stagnation Temperature T_0	-	$\sim$ 18° C
Mass Flow-rate $\dot{m}$	-	One canister of propellant
Thrust Output	+	$\sim$ 1000 N
Engine Diameter (OD)	+	$\sim$ 100 mm

Numerical Modelling of Detonation

- Chapman [5] Jouguet [6] (CJ) and Zel'dovich [7], von Neumann [8] and Döring [9] (ZND) detonation theories are employed to understand chemical reaction across the detonation wave.
- The proposed engine sizing routine uses a top-down, iterative approach. Initial parameters, pressure, P_0, temperature, T_0, and equivalence ratio, Φ, drive calculations for downstream parameter as described in the flowchart on the right hand side.
- Three high-level iterations are completed to ensure that 1) detonation has been achieved, 2) that peak downstream pressure and temperature are suitable, 3) that the proposed mass flow-rate of propellant is realistic at the proposed input temperature and pressures.
- Reaction kinetics, and low level CJ and ZND iterative calculations are facilitated using open-source tools: Cantera (MIT) and SDToolbox (CalTech) for MatLab.
- Written to output engine geometry, and expected pressure and thermal loads, thrust, and specific impulse for a given set of input parameters: $400\text{kPa} < P_0 < 2\text{MPa}$, $285_{\circ}\text{K} < T_0 < 500_{\circ}\text{K}$, $0.1 < \Phi < 10$.

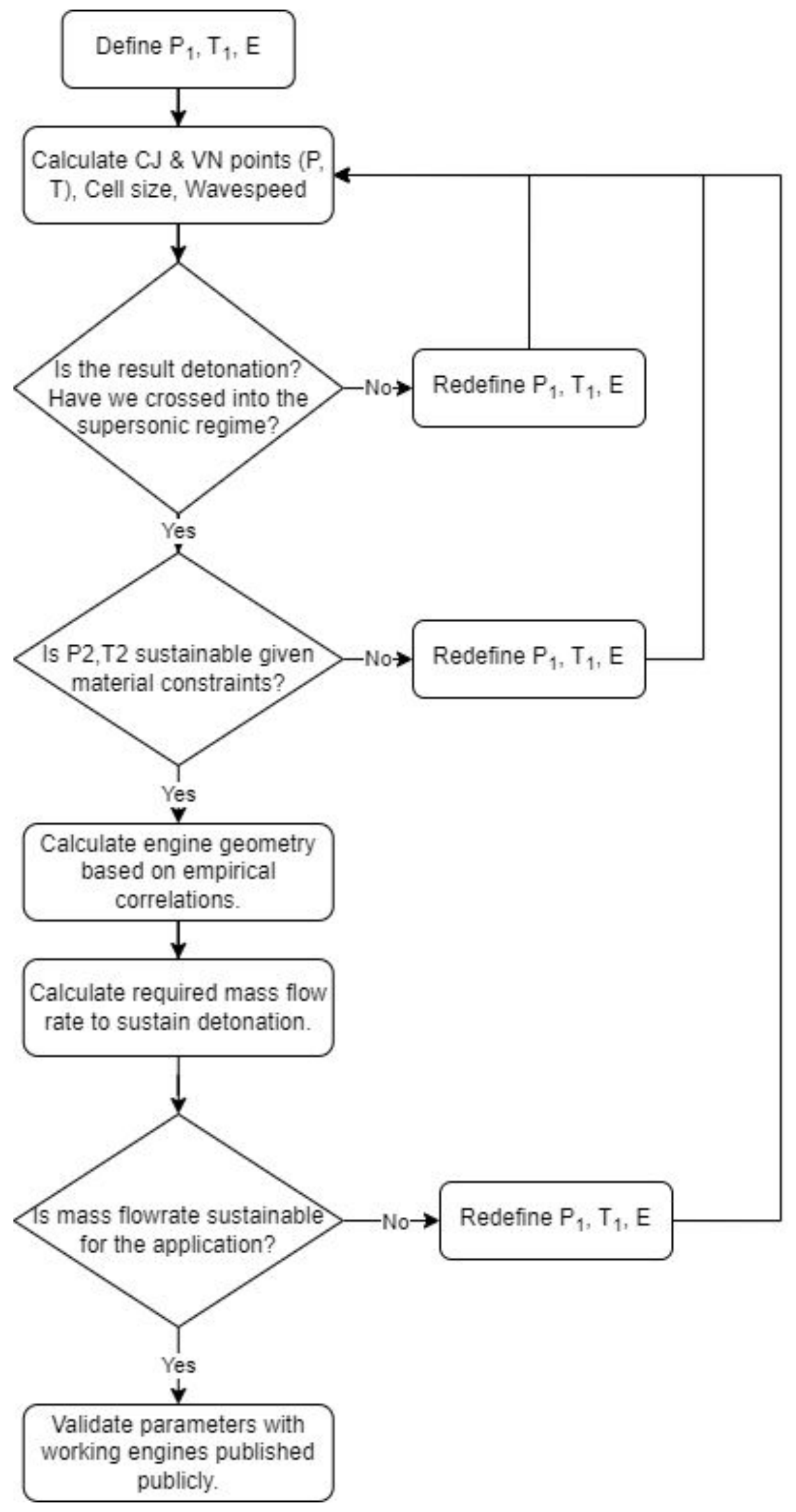

Figure: Proposed Engine Sizing Procedure

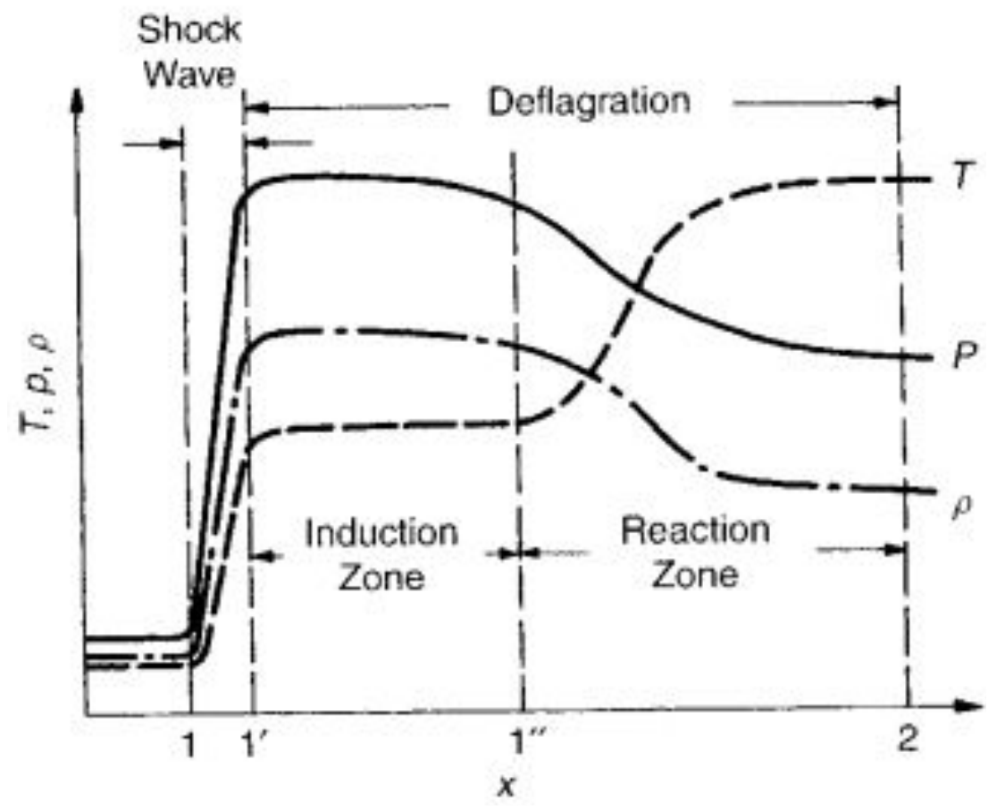

Figure: ZND Description of Temperature, Pressure & Density Across Detonation Wave [10]

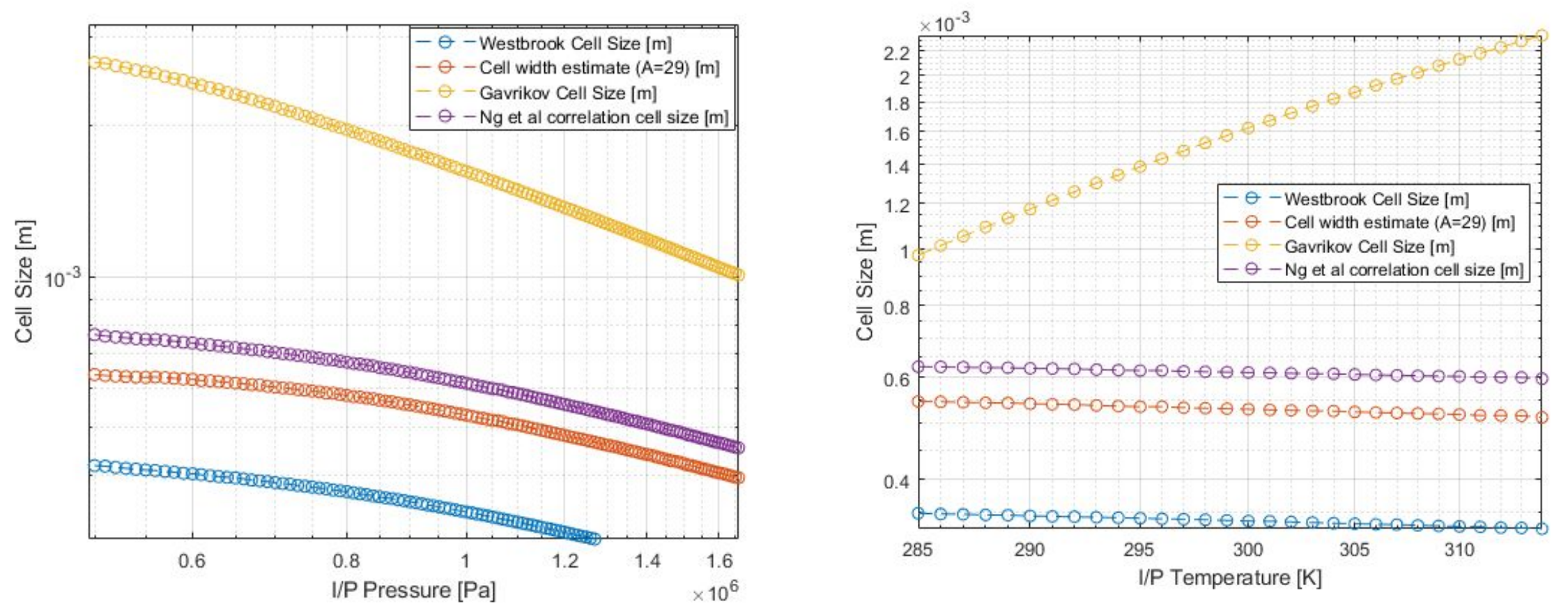

Figure: a) Detonation Cell Size, λ, varying P_0 b) Detonation Cell Size, λ, varying T_0

- Previously shown figures depict detonation cell size, λ, for a given input pressure and temperature. According to Bykovskii [11], Voitsekhovskii [12] the minimum detonation cell size needed in order to reach and sustain detonation combustion in a stoichiometric Hydrogen, Oxygen combustion reaction is 1.6mm. This threshold is shown in the figure below.
- According to these figures, thresholds for detonation are as follow: $T_0 \geq 300_{\circ}\text{K}$, $P_0 \geq 1.01$ MPa and $1.015 \leq \Phi \geq 1.300$ for the input parameter ranges considered.
- Following published empirically derived rules of thumb for engine geometry yielding detonation based on detonation cell size, λ, the below table can be presented with the input parameters: $P_0 = 1$ MPa, $T_0 = 300_{\circ}\text{K}$, $\Phi = 1.00$.

Table: Suggested Engine Geometry Ranges

Parameter	Selected Value
Minimum Fill Height, h^* [mm]	27.55
Minimum Diameter OD_{min} [mm]	$45.38 < OD_{min} < 64.84$
Minimum Channel Width δ_{min} [mm]	$3.89 < \delta < 5.51$
Minimum Length L_{min} [mm]	$38.90 < \phi < 55.11$

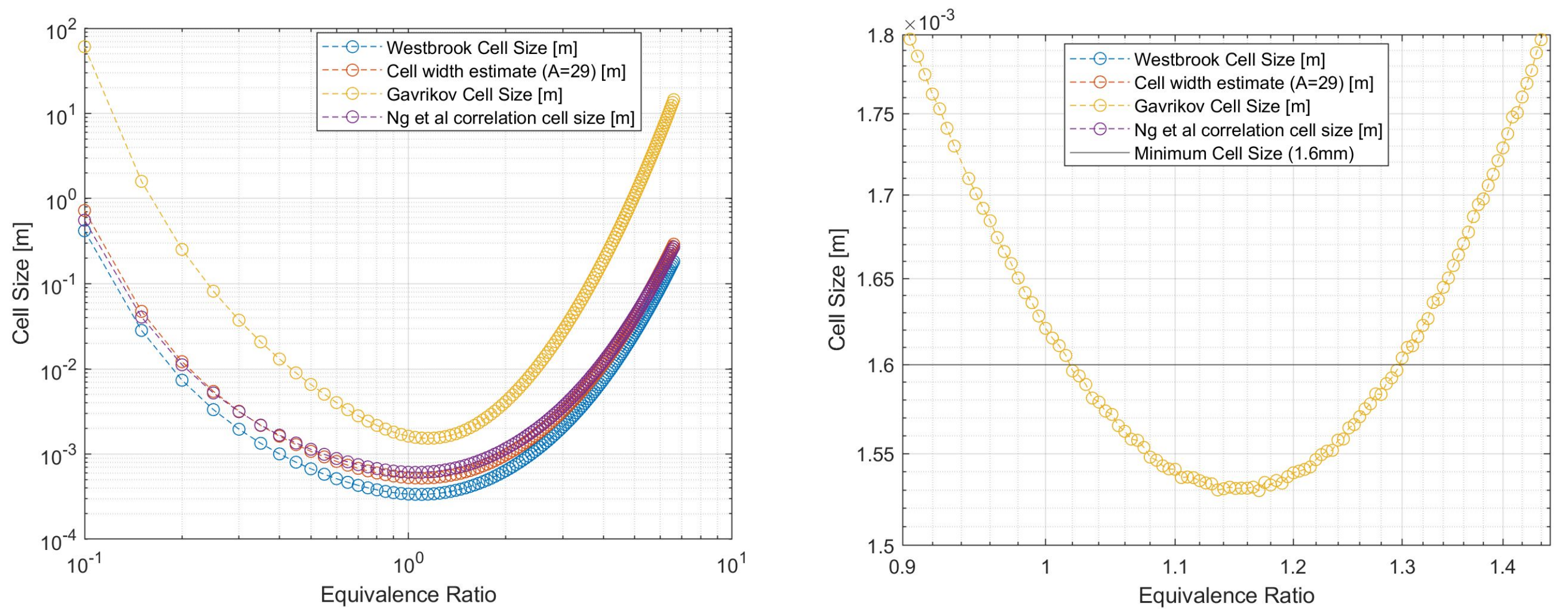

Figure: Detonation Cell Size, λ, Varying Equivalence Ratio, Φ

Computational Fluid Dynamics

- Through partnership with Convergent Science (CONVERGE CFD), we have been provided an example 2D unrolled RDRE model, which has been modified to meet our engine design, and will be used to validate the analytical model, and determine operating parameters for our hot fire testing
- To date, the CONVERGE model has been transitioned from air-hydrogen to oxygen-hydrogen fuel, and refinement of input parameters is ongoing
- Following injector geometry validation, the CONVERGE model will be updated with the in-fabrication engine design of DETechnologies, and work will begin on selecting ideal operating parameters to meet the goals of the project
- The 2D setup of the simulation requires a specific region initialization to properly simulate the DDTT, which initiates the detonation wave.

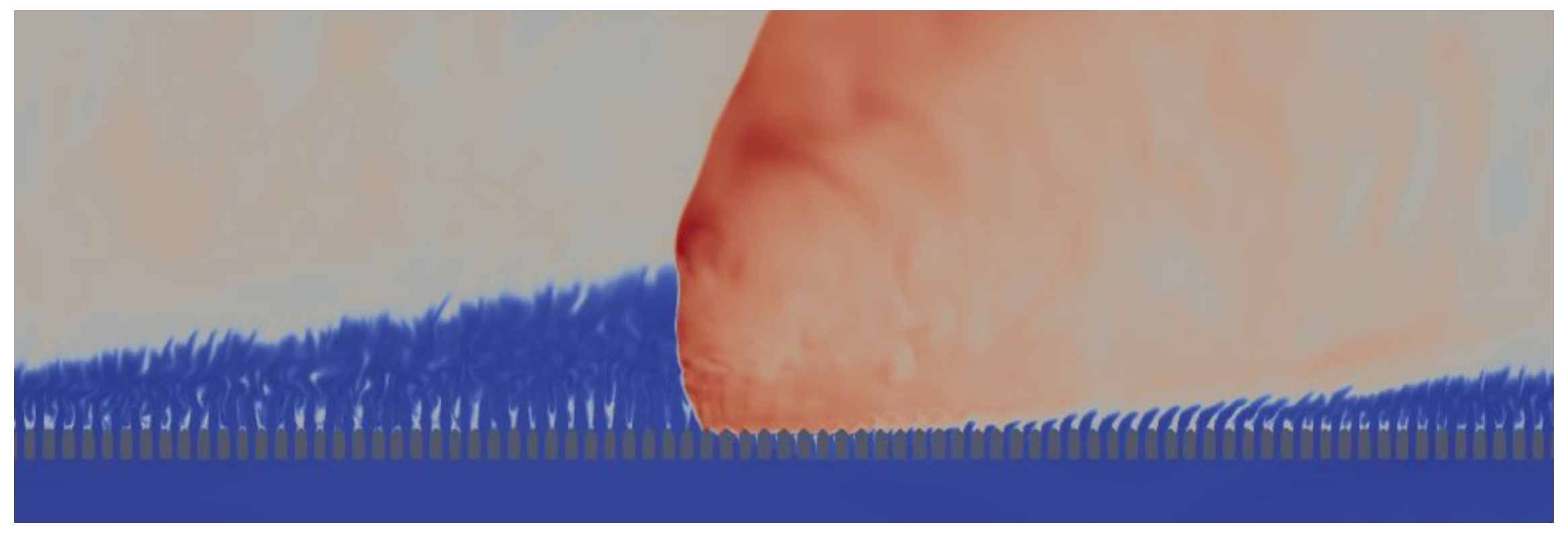

Figure: 2D RDE Temperature Plot

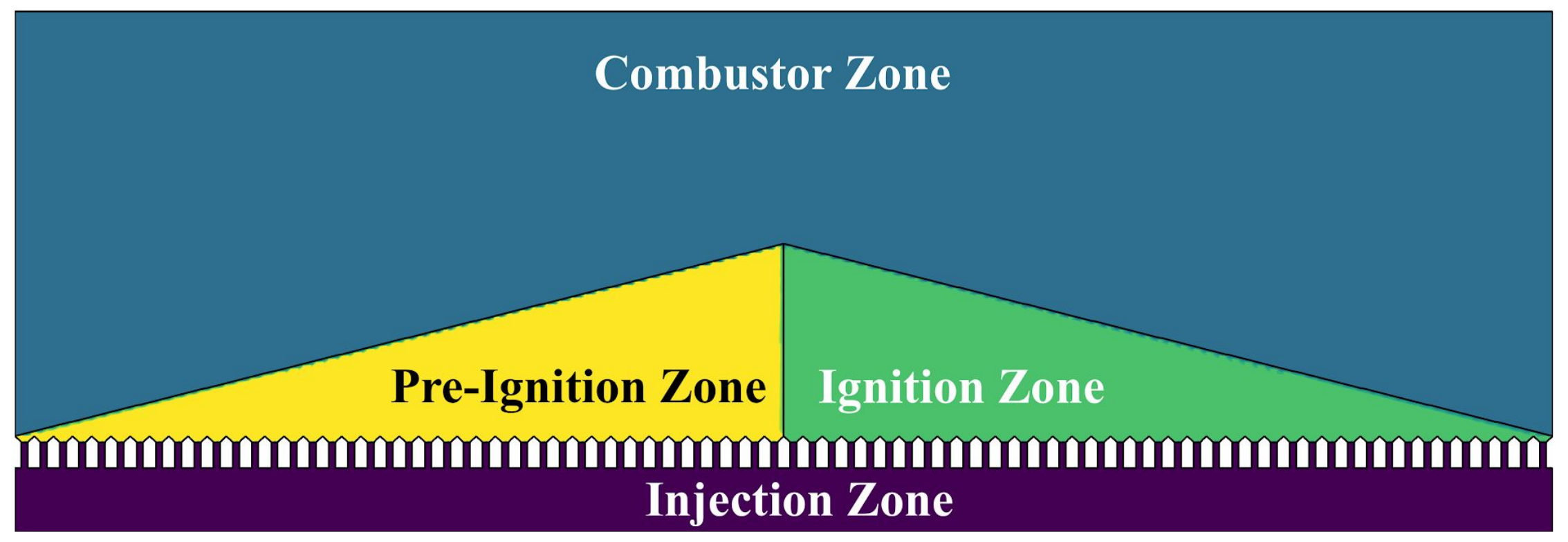

Figure: 2D Unrolled RDE Region Initialization

Conclusions and Next Steps

- Chosen engine geometry, and anticipated downstream wave parameters are shown in the right hand side table.
- Numerical results discovered are an inoperable region in the slightly rich combustion realm, between $1.015 > \Phi > 1.300$. This region is earmarked for further discovery during continued CFD and experimental testing.
- Peak temperature and pressures are nearly instantaneous by nature; oblique shock wave angle and temperature rundown axially are also earmarked for discovery.
- The next steps beyond this analysis is finalizing validation procedure using Computational Fluid Dynamics to ensure that chosen parameters are realistic and attainable in this situation. Secondary design and validation of propellant injection features is required to ensure that desired mass flow rate is attainable with the proposed pressure differential.

Table: Chosen Engine Design

Parameter	Value
Mass Flow Rate	0.3049 kg/s
Thrust	1350 N
Specific Impulse I_{SP}	430.34 s
Stagnation Pressure P_0	1 MPa
Initial Temperature T_0	300 K
Equivalence Ratio ϕ	1
Peak Pressure P_{VN}	35.72 MPa
Peak Temperature T_{CJ}	4136.94 K
Minimum Fill Height, h^*	27.55 mm
Minimum Diameter OD_{min}	55.11 mm
Minimum Channel Width δ_{min}	4.70 mm
Minimum Length L_{min}	47.00 mm

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