Numerical study of Rotating Detonation Combustion (RDC) for Stationary Power Generation

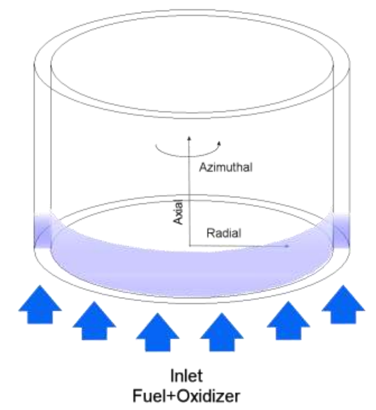
Sergio Escobar[1,2º], S. Raju Pakalapati[1,2*] & Ismail Celik[1,2◊]
[1]DOE National Energy Technical Laboratory, Morgantown, WV, USA (Sponsor Agency)
[2]Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, USA.
ºGraduate Student: sescobar@mix.wvu.edu, *Post Doct. & ◊Academic Advisor

Abstract

Recently pressure gain supersonic combustion has received renewed interest among the combustion researchers as it offers higher efficiency and lower emissions. Among the possible technology concepts that employ this mode of combustion **Rotating Detonation Combustion (RDC)** is thought to be most suitable for stationary power. However, most research on RDC is focused on propulsion applications. The overall objective of this study is to assess, through computational modeling, the feasibility of RDC for power generation.
A commercial Computational Fluid Dynamics (CFD) code is used for the simulations along with several custom built sub-models to emulate the chemical reactions and boundary conditions of the RDC.
The complex supersonic flow and combustion phenomena in an RDC are captured in these simulations. Future simulations will be performed using the model to evaluate the efficiency and emissions for RDC and to estimate the design specifications for a stationary gas turbine to be used in conjunction with the RDC.

Introduction

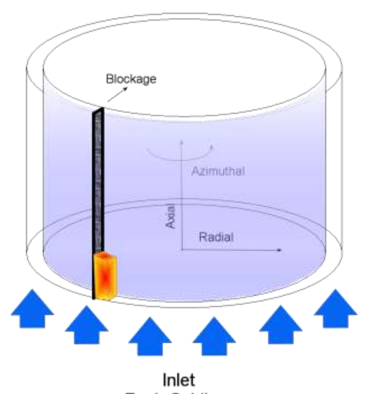
- Rotating detonation combustion concept:



FILLING OF COMBUSTION CHAMBER

- Inlet mixture from high pressure (5 atm) reservoir [1].
- Fuel injected through array of small 1x1 mm orifices [2].
- Oxidizer enters chamber through 1.25 mm annular slot [2].
- Stoichiometric Hydrogen, Oxygen and Nitrogen.
- Free exhaustion of combustion products

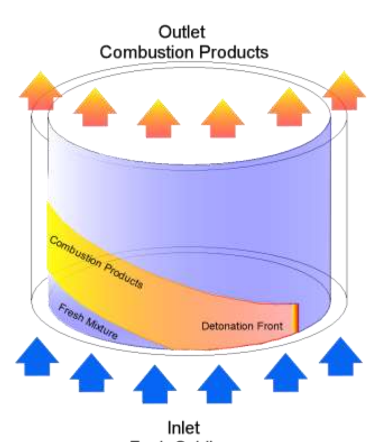
- Ignition through explosive wire.
- Critical detonation energy must be delivered. For $2H_2+O_2$ ~2MJ.
- Blockage is removed as the wave is close to complete its first cycle.



FORCED IGNITION

- Blockage membrane guarantees propagation of detonation wave in one direction during ignition.

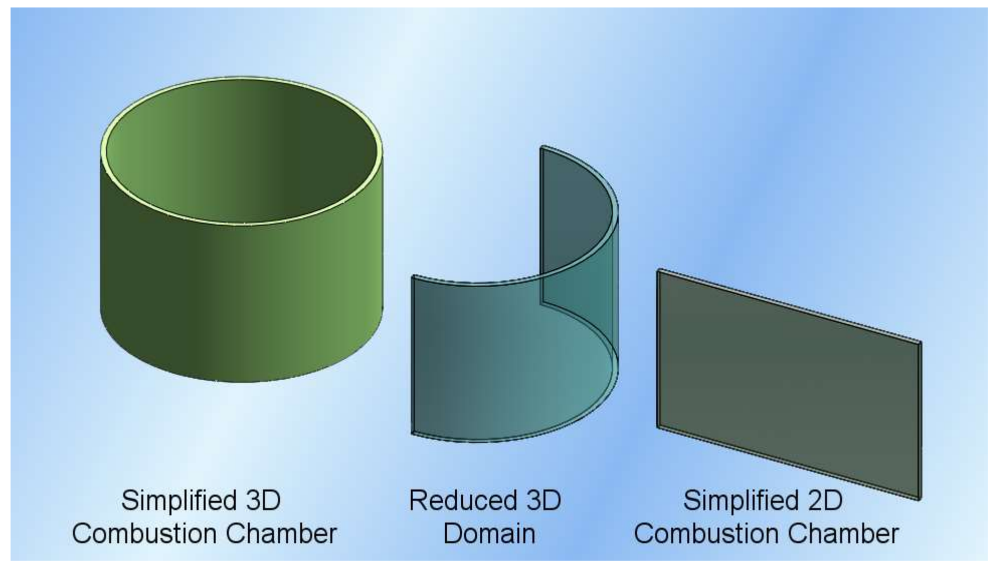
- At steady operation the detonation front travels in the azimuthal direction.
- Fresh mixture is continuously injected into the chamber.
- Products leave combustion chamber at elevated temperatures and pressures.



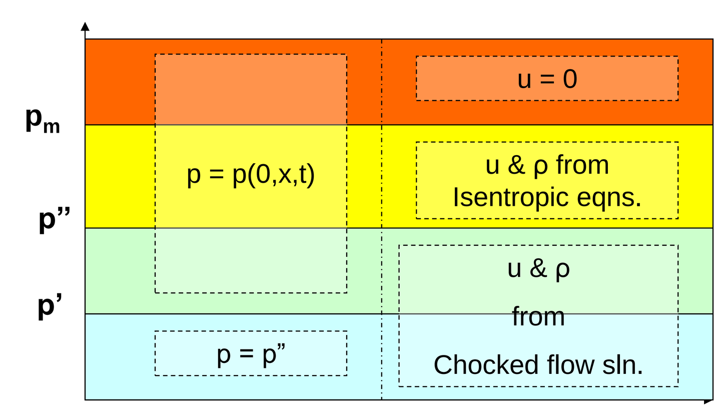
PROPAGATION OF ROTATING DETONATION WAVE

Methodology

- Initial simulations were performed for inert and reacting shock tubes.
- Domain simplification.



- Treatment of Boundary Conditions (B.C.)
  – Vertical faces: Periodic boundary.
  – Outlet: Pressure Outlet with static pressure < critical pressure
  – Inlet: Micro Laval nozzles injecting premixed fuel and oxidizer [1].



$$If\ p_m \le p(0,x,t), then\ p = p(0,x,t) \,\&\, v = 0;$$

$$If\ p'' \le p(0,x,t), then\ p = p(0,x,t),$$

$$u = u_{max}\left[1-(p/p_m)^{(\gamma-1)/\gamma}\right]^{1/2},$$

$$\rho = \rho_m\left(1-\frac{u^2}{u_{max}^2}\right)^{1/(\gamma-1)}$$

$$If\ p' \le p(0,x,t) < p'', then\ p = p(0,x,t);$$

$$If\ p(0,x,t) < p', then\ p = p',$$

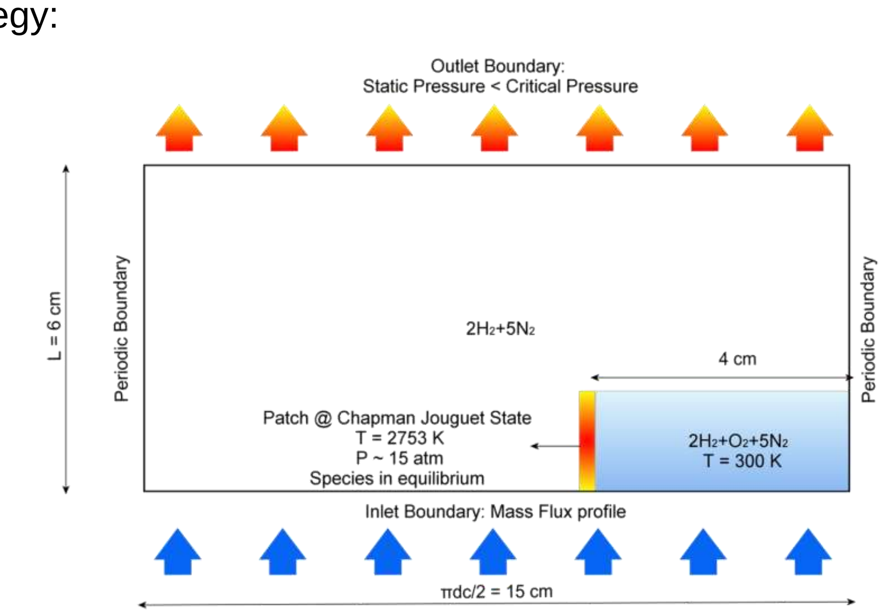
$$\rho u S = \rho_* u_* S_*,$$

$$\left(\gamma/(\gamma-1)\right)\left(p/\rho\right) + u^2/2 = u_{max}^2/2$$

Inlet boundary condition variation with chamber pressure

Implementation of inlet B.C. performed through user defined function (UDF).

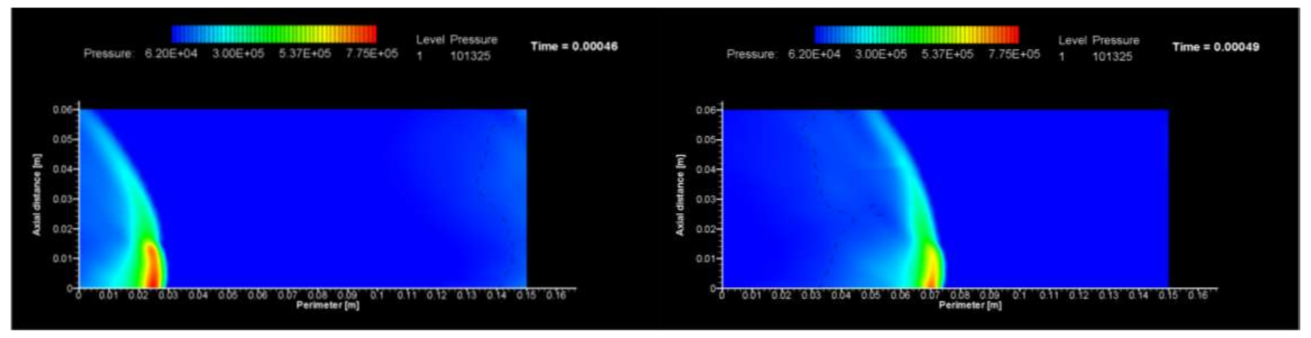
- Chemical reactions for H_2-O_2-N_2 mixture modeled using chemical mechanism with 14 species and 43 reactions [3] including NOx chemistry.
- Solution Strategy:



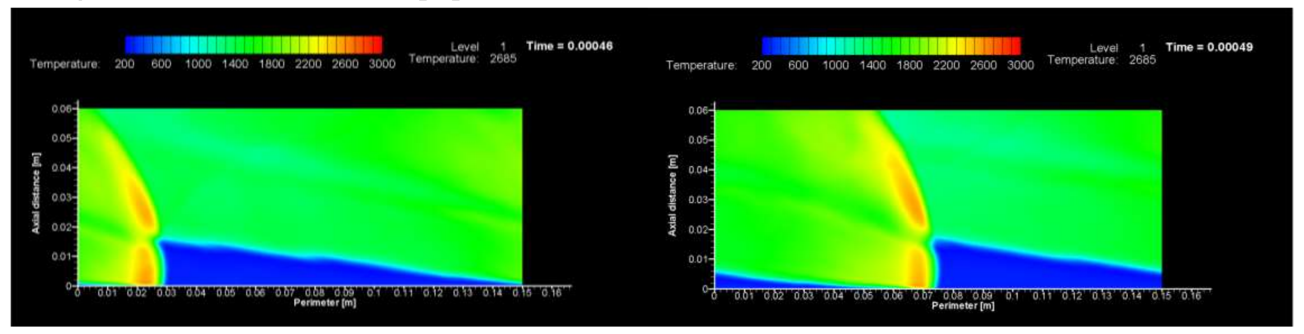
Initiation process and domain dimensions

Results

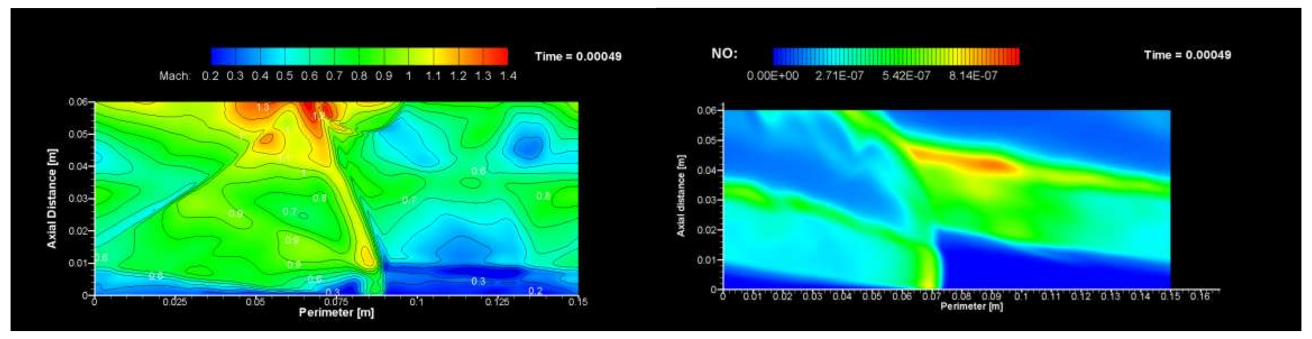
- Transient behavior is observed up to 0.4 ms.
- Pressure distribution for at periodic operation [Pa].



- Temperature distribution [K]



- Mach number.
- NO mass fraction



Conclusions

- Transient simulations of RDC are performed using commercial solver ANSYS Fluent to the extent of our knowledge, for the first time.
- Tailored sub models are implemented to emulate RDC injection system using FLUENT UDFs.
- Periodic solution achieved for hydrogen oxygen mixture.
- Qualitative comparison with experimental data shows that general aspects of the detonation phenomena are appropriately captured.

Future Work

- Quantitative comparison of outlet and chamber pressure, and wall temperatures between simulations and experiments.
- Simulation of coal syn-gas operation.
- Characterization of outlet condition and its implications on the design of turbine stage.
- Development of detonation simulation capability for in house CFD code.

Acknowledgements

- This research project entitled Simulation and Validation for Innovative Energy Concepts (S&V-IEC) WVU Combustion Modeling is being carried out in support of DOE's National Energy and Technology Laboratory under the RES contract 1000023/134

References

1. Zdhan S.A.,Bykovskii F.A. and Bykovskii F.A., *" Mathematical modeling of a rotating detonation wave in a hydrogen oxygen mixture"*, Comb. Exp. & Shock Waves 43 (2007)
2. Bykovskii F.A., Zdhan S.A, *"Realization and modeling of continuous spin detonation", Comb. Exp. & Shock Waves 43 (2007)*
3. Li, J., Zhao, Z., Kazakov, A., and Dryer, F.L. "An Updated Comprehensive Kinetic Model for H2 Combustion", Tech. Meeting of the ESSC Combustion Institute(2003)

NETL-RUA Regional University Alliance · U.S. DEPARTMENT OF ENERGY · NETL · Carnegie Mellon · PENNSTATE 1855 · University of Pittsburgh · VirginiaTech · WestVirginiaUniversity · URS

NATIONAL ENERGY TECHNOLOGY LABORATORY

Albany, OR • Fairbanks, AK • Morgantown, WV • Pittsburgh, PA • Sugar Land, TX