Computational Fluid Dynamics Simulations of a High-Efficiency Free-Piston Linear Alternator Using HPC

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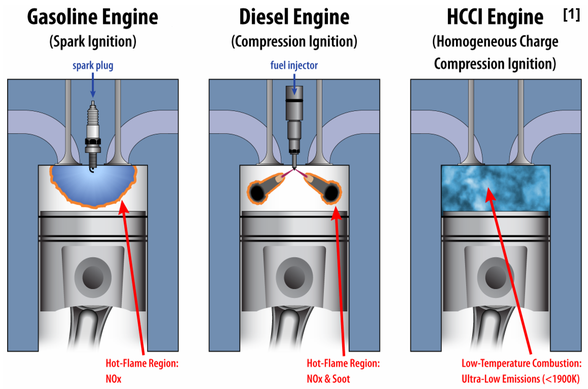
Motivation

- Free-Piston Linear Alternators (FPLAs) are an attractive alternative for stationary and mobile power generation.
- 2-stroke piston motion controlled by forces balance. Variable compression ratio (VCR) can be achieved. Higher efficiency at part-load and fuel flexibility can be realized.
- Linear piston motion with no side loading. Reduced frictional losses.
- Potential for lean Homogeneous Charge Compression Ignition (HCCI) combustion with thermal efficiency benefits and reduced NO_x, PM emissions.

Challenges

- Sophisticated piston motion control required
- Adverse gas exchange process
- High inefficiencies due to small engine size

Objective: Explore the potential of FPLA with HCCI combustion to achieve 40% electrical efficiency, 1 kWe power output and ultra-low NO_x and UHC emissions.



Research Methods

- Use a system level model to predict piston motion.
- Couple it with Converge CFD to model combustion process.
- Combine Reynolds-Averaged Navier-Stokes (RANS), multi-zone SAGE combustion model, Han Turbulent heat transfer model, and AramcoMech 2.0 chemical kinetics mechanism
- Utilize openmpi for parallel code execution
- Utilize adaptive mesh refinement (AMR) and fixed embedding for balancing accuracy and computational cost.
- Apply METIS load balancing to optimize parallel scalability.

Navier-Stokes Conservation Equations:

– Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j\right] = 0$$

– Conservation of momentum:

$$\rho\frac{Du_i}{Dt} = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}\left[2\mu e_{ij} - \frac{2}{3}\mu\left(\nabla\cdot\mathbf{u}\right)\delta_{ij}\right]$$

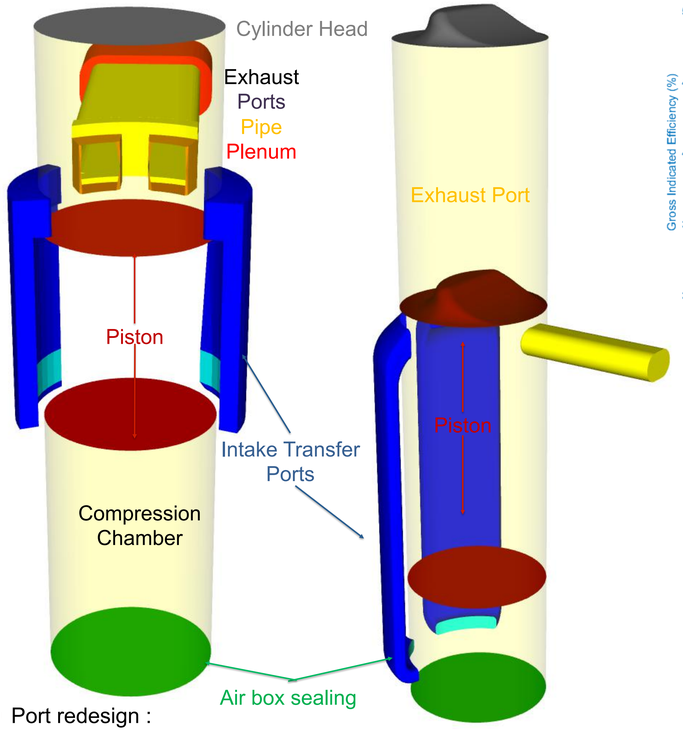
– Conservation of energy:

$$\frac{\partial \rho E}{\partial t} + \left(\rho u_\alpha E\right)_{,\alpha} = \left(u_\alpha \tau_{\alpha\beta}\right)_{,\beta} + \left(kT_{,\alpha}\right)_{,\alpha} + \rho u_\alpha f_\alpha^b + \rho q$$

Species conservation equations:

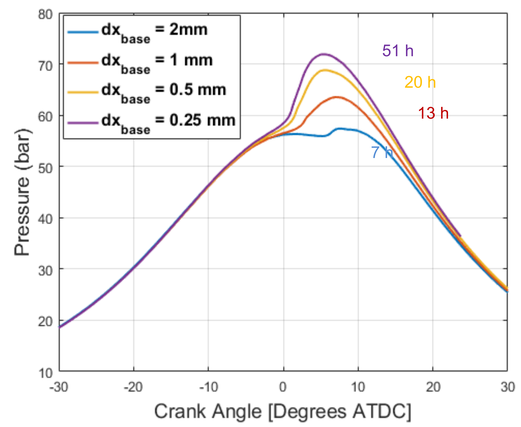
$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \rho_m u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial Y_m}{\partial x_j}\right) + S_m$$

Initial Engine Design

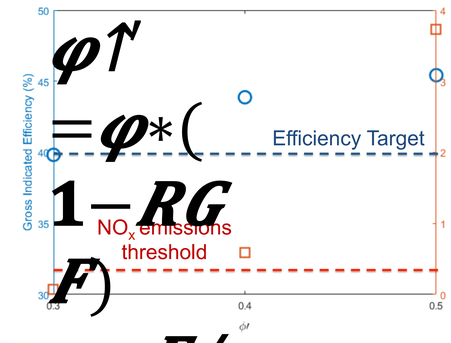


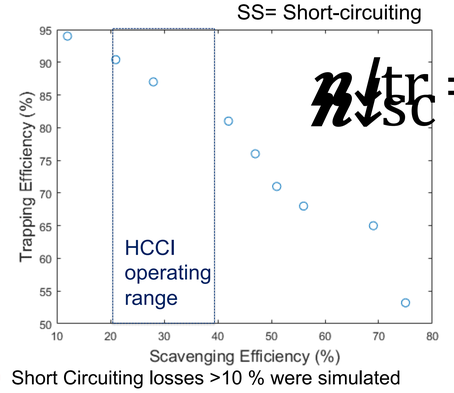
Redesigned Engine

- Port redesign :
  - Elimination of right angles (reduced pressure drop)
  - Reduction of port effective area
    - Reduction of gas exchange duration and fresh mixture flow to the exhaust
- Increased Stroke to bore ratio:
  - Lower heat transfer losses
  - Increased Compression ratio

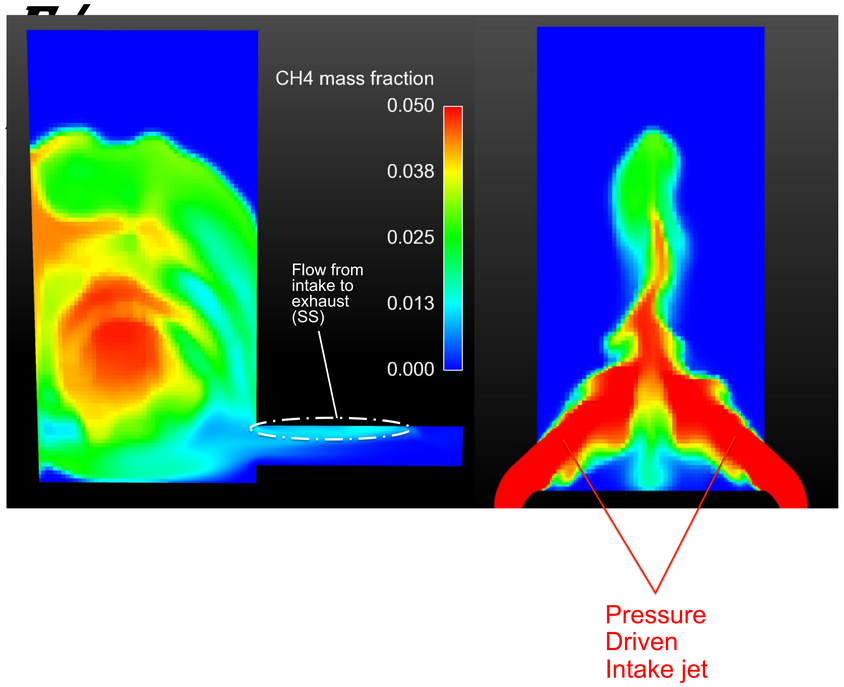


- Grid Convergence is an essential feature of CFD simulations.
- Criteria of grid convergence depend on combustion regime
- P_{max} and its timing were considered for HCCI combustion (5% tolerance)
- A base Cartesian grid of 0.5 mm was chosen
- AMR was utilized to capture temperature and species gradients
- Runtime reduction of ~60% without significant accuracy losses





- Operation at Φ' = 0.3 is chosen to comply with emissions regulations
- Short Circuiting losses >10 % were simulated
- Reduced efficiency high emissions
- Transfer port relocation will be considered to reduce trapping inefficiency
- Piston redesign to block the direct flow will be investigated



Conclusions

- Engine was re-designed to reach high efficiency
- Grid convergence was achieved for acceptable combustion runtimes
- Φ' = 0.3 was chosen to comply with NO_x regulations
- Gas exchange investigation indicated increased short-circuiting
- Piston re-design is being considered to shift gas exchange to higher trapping efficiency regions

References

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