**Applied Sciences (CEAS)**

**College of Engineering and Applied Sciences (CEAS)**

**Department of Mechanical Engineering**

**Objective**
- Explore the potential of FPLA with HCCI combustion to achieve 40% electrical efficiency. 1 kWh power output and ultra-low NO, PM and UHC emissions.

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

**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, PM 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 openmp 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: \[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \]
- Conservation of momentum: \[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial \left( \frac{\partial (\rho u_i u_j)}{\partial x_j} \right)}{\partial x_i} = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \]
- Conservation of energy: \[ \frac{\partial (\rho E)}{\partial t} + \frac{\partial}{\partial x_i} (\rho E u_i) = \frac{\partial}{\partial x_i} \left( \tau_{ij} u_j \right) - \frac{\partial P}{\partial x_i} \]

**Species conservation equations:**
- Species conservation equations depend on combustion regime
- No chemical reactions

**Initial Engine Design**
- Cylinder Head
- Exhaust Ports
- Plenum
- Piston
- Intake Transfer Ports
- Compressor Chamber
- Air box sealing

**Redesigned Engine**
- Piston 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**
- Grid Convergence is an essential feature of CFD simulations.
- Criteria of grid convergence depend on combustion regime
- Peak 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

**Conclusions**
- Engine was re-designed to reach high efficiency
- Grid convergence was achieved for acceptable combustion runtimes
- \( \Phi = 0.3 \) was chosen to comply with NOx regulations
- Gas exchange investigation indicated increased short-circuiting
- Piston re-design is being considered to shift gas exchange to higher trapping efficiency regions

**References**