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Department of Mechanical Engineering

Computational Fluid Dynamics Simulation of the gas Exchange Process of a Free Piston Engine Using High Performance Computing

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Motivation and Challenges

- Motivation
  - Free-Piston Linear Alternators (FPLAs); Attractive for stationary power generation.
  - 2-stroke piston motion, variable compression ratio, high part-load efficiency, fuel flexibility.
  - Linear piston motion - reduced friction losses.
  - Suitable for lean Homogeneous Charge Compression Ignition (HCCI): high thermal efficiency, low NO_x and PM emissions.
- Challenges:
  - Gas exchange in 2-stroke engines – High trapping losses – low combustion efficiency, high UHC emissions
  - Advanced piston motion control strategy

Research Methods

- Develop 3D CFD model of the entire engine in CONVERGE CFD [1].
- Use RANS to solve Navier-Stokes equation, RNG k-ε turbulence model [2], and modified law of the wall by Amsden et al. [3]

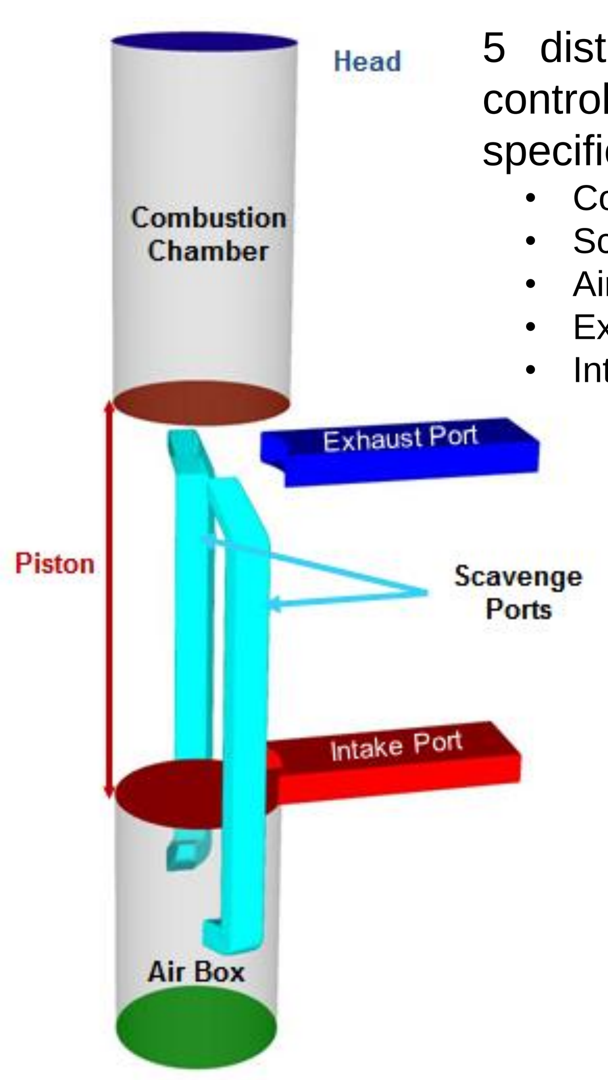
$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_j}{\partial x_j}=0$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial \sigma_{ij}}{\partial x_j}+S_i$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial u_j \rho \varepsilon}{\partial x_j}=$$

$$-P\frac{\partial u_j}{\partial x_j}+\sigma_{ij}\frac{\partial u_i}{\partial x_j}+\frac{\partial}{\partial x_j}\left(K_t\frac{\partial T}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(\rho D\sum_m h_m\frac{\partial Y_m}{\partial x_j}\right)+S$$

- Use SAGE combustion model [4] , a skeletal chemical kinetics mechanism [5], and a multi-zone model [6].
- Use adaptive mesh refinement (AMR) and variable time-step.
- Use METIS for load balancing [7].



5 distinct regions for flow control and initial conditions specification:

- Combustion chamber
- Scavenge ports
- Airbox
- Exhaust Port
- Intake Port

Figure 1: Free piston engine model

Gas Exchange Efficiency Definitions

- Scavenging efficiency: $n_{sc}=\frac{m_{tr,fresh}}{m_{tr,total}}$
- Trapping efficiency: $n_{tr}=\frac{m_{tr,fresh}}{m_{SP-cylinder}}$
- Effective equivalence ratio: $\varphi'=\varphi*(1-RGF)$
- Goal for natural gas HCCI: φ´=0.25 – 0.35, n_{sc} = 25-35%, $n_{trapping}$ > 98 % [7]

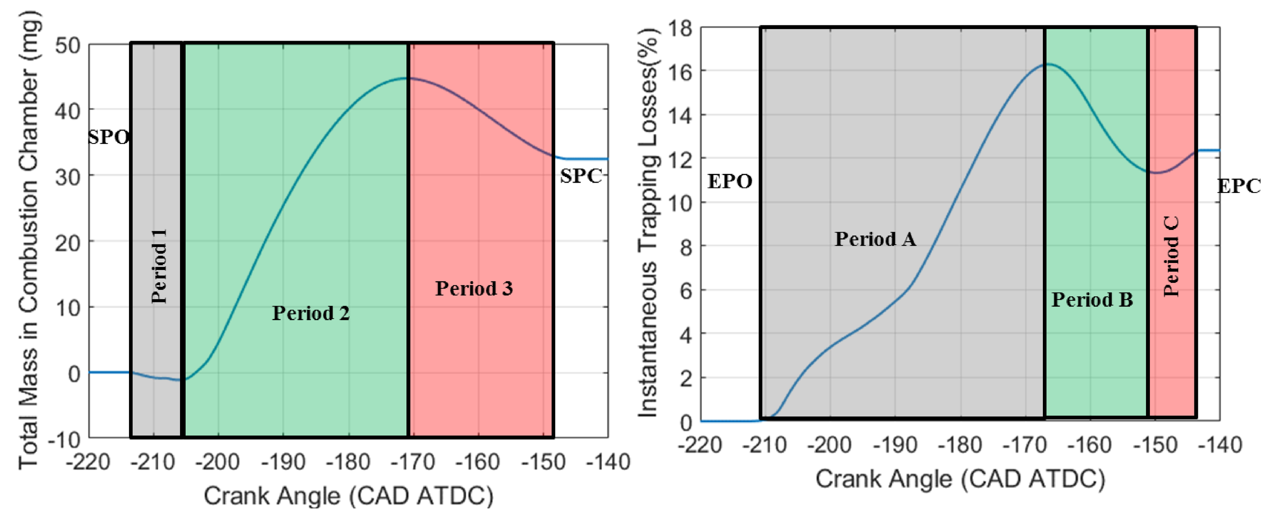


Figure 2: Fresh charge flow (left) and instantaneous trapping losses (right) as a function of CAD

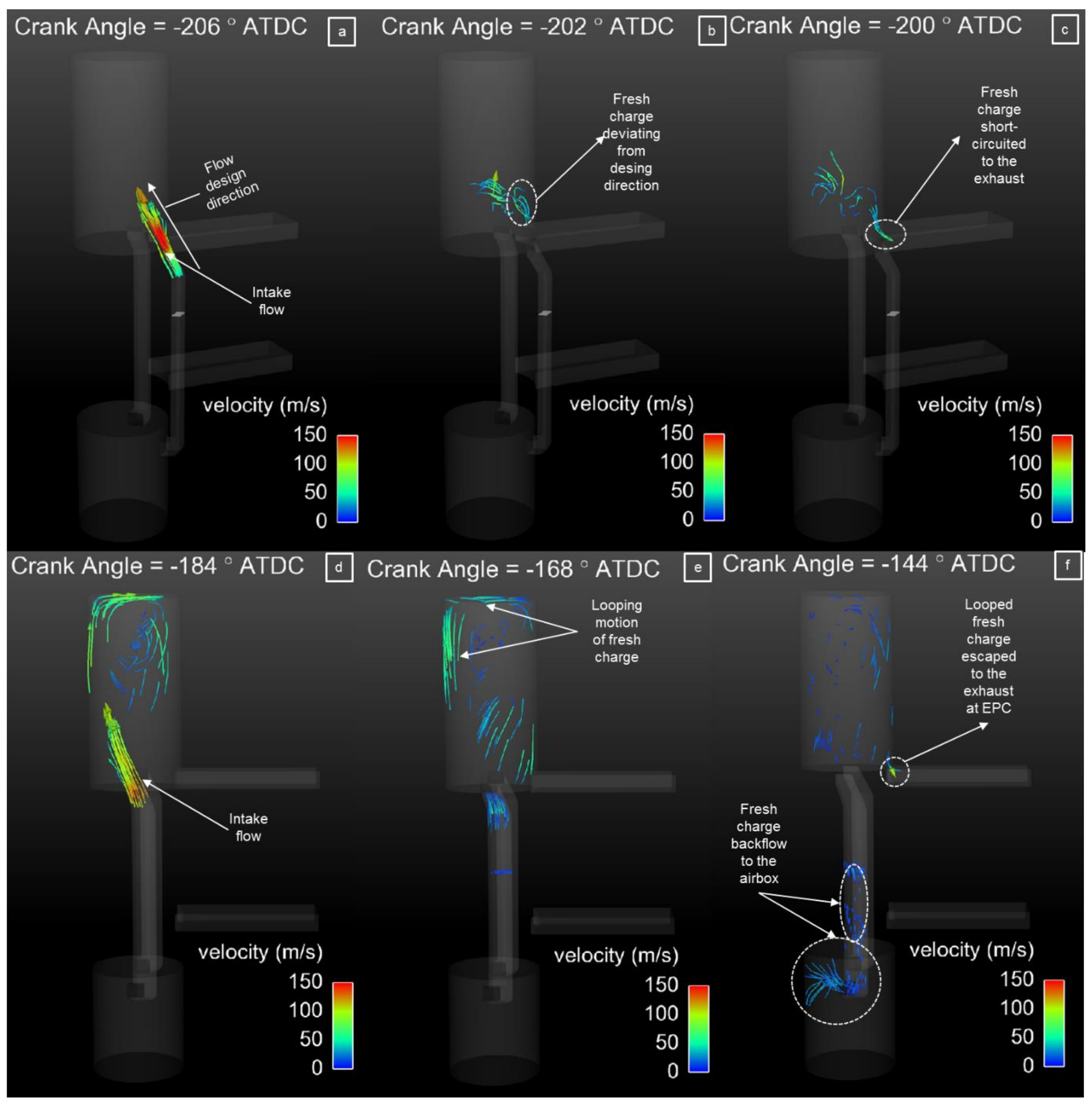


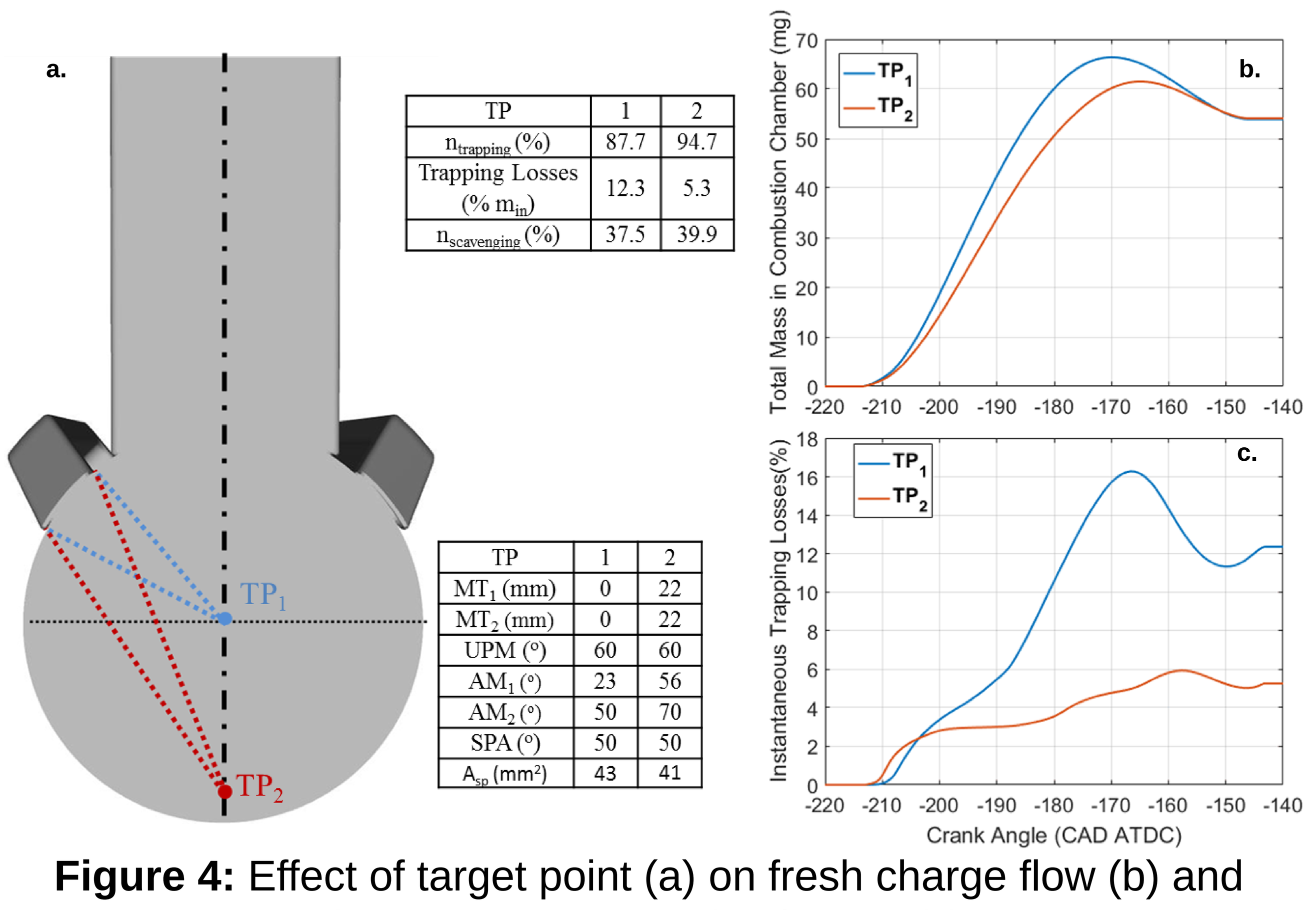
Figure 3: Pathlines of direct entrainment (a-c) and loop (d-f) trapping losses.

Analysis of Scavenging Process

- 2 regions of fresh charge backflow to the combustion chamber (figure 2 left):
  - Reduced scavenging efficiency, air box design was modified to eliminate backflow.
- 2 distinct regions of trapping losses were recognized:
  - Figure 2 Right Period A: **Direct Entrainment losses;** fresh charge entering the combustion chamber with low momentum entrained in the exhaust flow (figure 3(a-c)).
  - Figure 2 Right Period C: **Loop losses;** fresh charge looped around the combustion chamber entrained in the exhaust close to exhaust port closing (figure 3 (d-f)).
- Low trapping efficiency – n_{tr} = 87%

Goal: Improve Trapping Efficiency

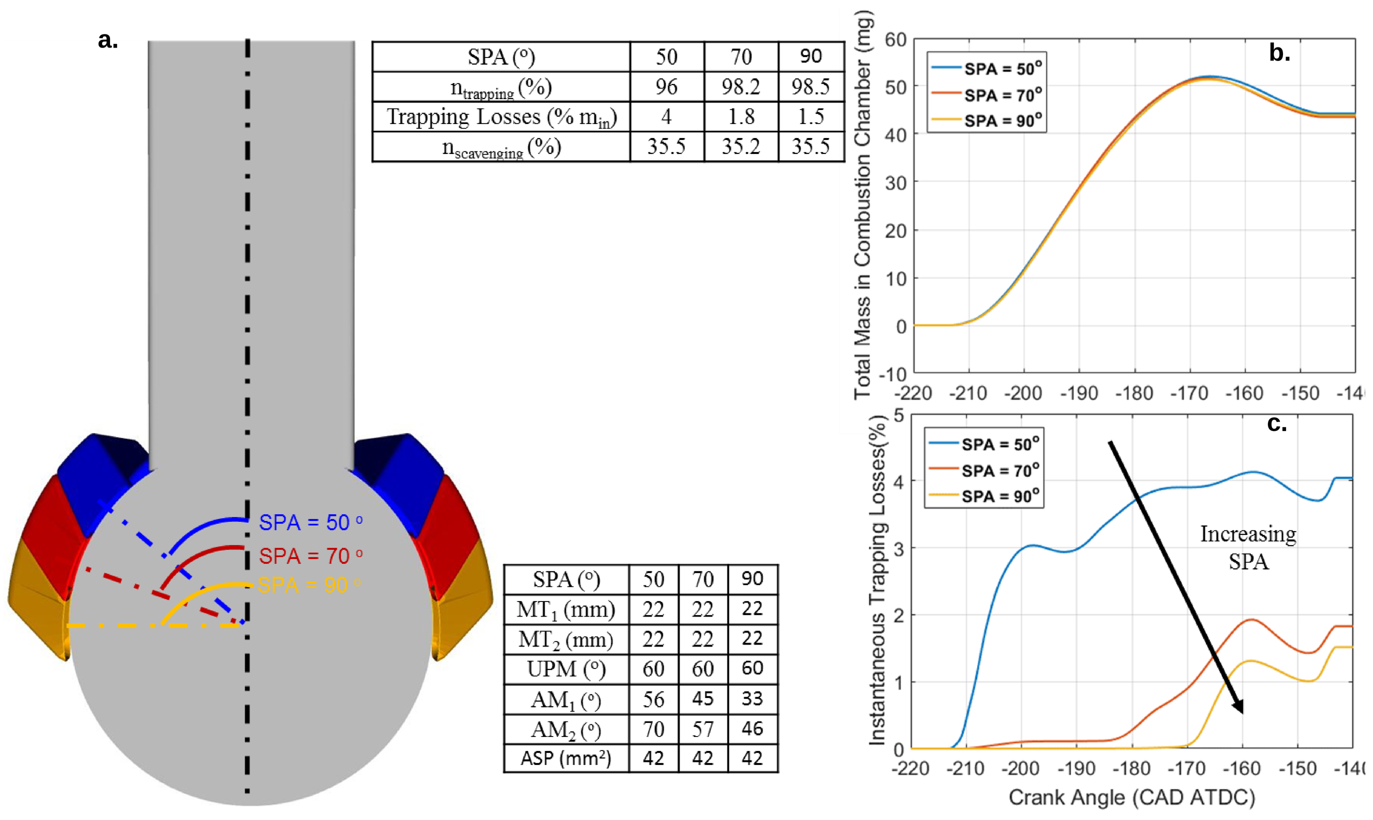
- Targeting the scavenge ports to the liner reduced direct entrainment losses (figure 4).
- Increasing angle between scavenge and exhaust port eliminated direct entrainment losses (figure 5).
- n_{tr} = 98.5 % was achieved for n_{sc} = 35.5 %.
- Multicycle operation: HCCI combustion with 38% gross indicated efficiency.



TP	1	2
$n_{trapping}$ (%)	87.7	94.7
Trapping Losses (% m_{in})	12.3	5.3
$n_{scavenging}$ (%)	37.5	39.9

TP	1	2
MT_1 (mm)	0	22
MT_2 (mm)	0	22
UPM (°)	60	60
AM_1 (°)	23	56
AM_2 (°)	50	70
SPA (°)	50	50
A_{sp} (mm^2)	43	41

Figure 4: Effect of target point (a) on fresh charge flow (b) and instantaneous trapping losses (c)



SPA (°)	50	70	90
$n_{trapping}$ (%)	96	98.2	98.5
Trapping Losses (% m_{in})	4	1.8	1.5
$n_{scavenging}$ (%)	35.5	35.2	35.5

SPA (°)	50	70	90
MT_1 (mm)	22	22	22
MT_2 (mm)	22	22	22
UPM (°)	60	60	60
AM_1 (°)	56	45	33
AM_2 (°)	70	57	46
ASP (mm^2)	42	42	42

Figure 5: Effect of scavenge port angle (a) on fresh charge flow (b) and instantaneous trapping losses (c)

Conclusions

- Proper design of the gas exchange process is critical in FPLAs
- 2 different mechanisms of trapping losses were recognized:
  - Direct Entrainment losses
  - Loop losses
- Targeting the scavenge port to the back wall of the liner and increasing the scavenge port angle increased trapping efficiency
- n_{tr} = 98.5 % for the target n_{sc} without poppet valves can be achieved
- 38% gross indicated efficiency was simulated

References: 1. Richards et al. *CONVERGE (v2. 2.0), Convergent Science.* Inc., Madison, WI, 2014, 2. Han, Z. and R.D. Reitz, *Turbulence modeling of internal combustion engines using RNG κ-ε models.* Combustion science and technology, 1995. **106**(4-6): p. 267-295, 3. Amsden, A., *KIVA3V. A Block-Structured KIVA Program for Engines with Vertical or Canted Valves*. 1997, 4. Senecal, P., et al., *Multi-dimensional modeling of direct-injection diesel spray liquid length and flame lift-off length using CFD and parallel detailed chemistry*. 2003, SAE Technical Paper, 5. Hockett, A., G. Hampson, and A.J. Marchese, *Development and Validation of a Reduced Chemical Kinetic Mechanism for Computational Fluid Dynamics Simulations of Natural Gas/Diesel Dual-Fuel Engines.* Energy & Fuels, 2016. **30**(3): p. 2414-24276. Babajimopoulos, A., et al., *A fully coupled computational fluid dynamics and multi-zone model with detailed chemical kinetics for the simulation of premixed charge compression ignition engines.* International journal of engine research, 2005. **6**(5): p. 497-512, 7. Karypis et al. METIS -- Unstructured Graph Partitioning and Sparse Matrix Ordering System, Version 2.0 (1995),

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