Power & Mobility (P&M)

GVSETS GROUND VEHICLE SYSTEMS ENGINEERING & TECHNOLOGY SYMPOSIUM & ADVANCED PLANNING BRIEFING FOR INDUSTRY

NDIA Michigan

A Modeling Methodology for the Analysis of Abradable Powder Piston Skirt Coatings

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Acknowledgement

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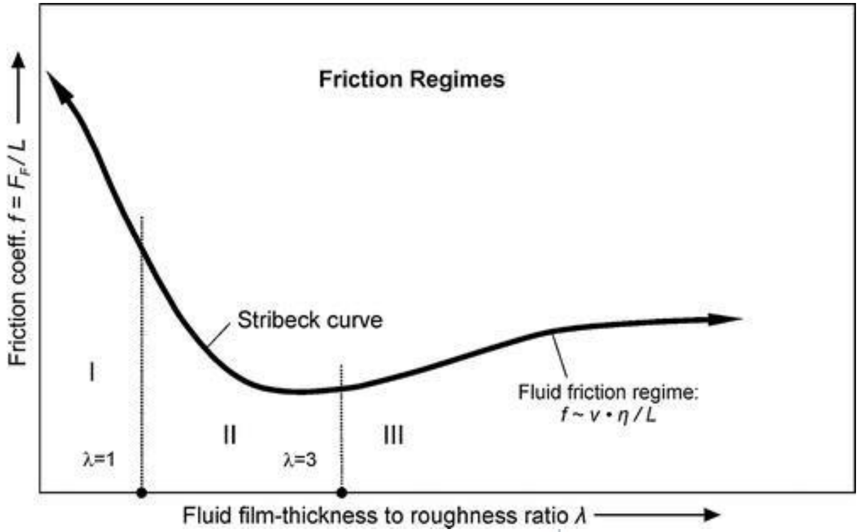
Overview

Introduction	• Background on abradable powder coatings (APC)
Modeling Overview and Configuration	• Piston Dynamics Modeling • Surface Texture, Friction, and Wear Modeling
Simulation Results and Discussion	• Piston Dynamics • Ring Wear
Optimization Methodology and Results	• Optimized Vs. Original Profile • Comparison with experimental FMEP
Conclusion and Future Work	• Future Modeling Efforts • Experimental Validation

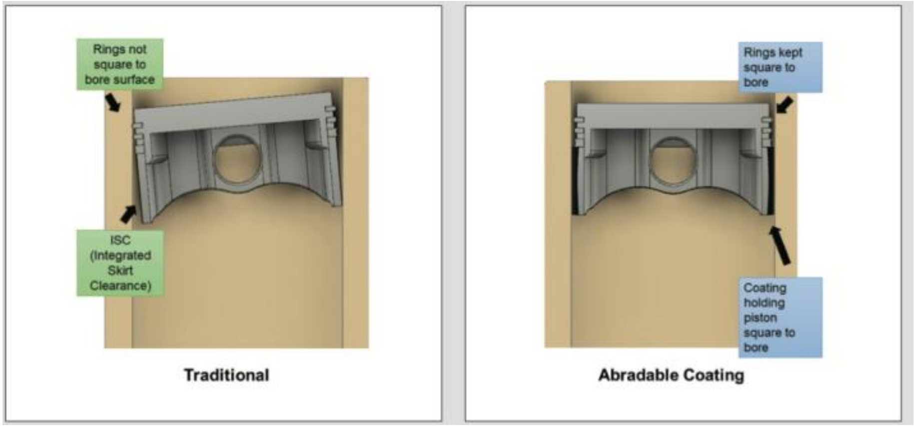
Abradable Powder Coatings (APC)

- A mechanism of clearance control between mating components.
- Reduces excess piston-to-liner volume introduced by manufacturing tolerances and variations in thermal/mechanical loading.
  - The volume between the skirt and cylinder liner is referred to as *integrated skirt clearance* (ISC).
- Coating is applied "thick" and abrades during operation.
  - Abrasion of the coating yields a unique optimum piston skirt geometry that minimizes boundary friction.
  - Surface texture and oil retention properties are improved through the abrasion process as well.



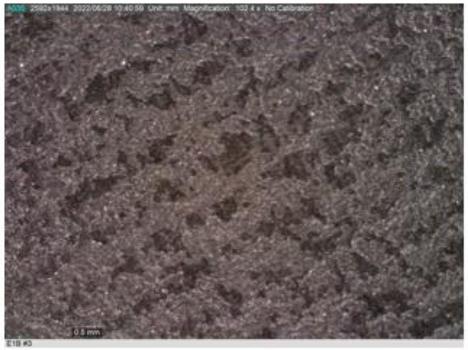
Abradable Powder Coatings (APC)

- Excess clearance (ISC) between the skirt and liner results in undesirable secondary (transverse) piston motion, noise, and vibration.
- Reducing the ISC (clearance volume) at the skirt-to-liner interface results in less secondary motion and improved engine durability.
  - Also reduces the relative motion between the piston and rings, improving ring durability and likely ring sealing capabilities.
- The coatings are soft as applied and can be applied over a wide range of thicknesses (15 – 250 microns).
- During operation, the high points on the surface abrade and leave an array of oil-retaining valleys. The improved oil retention further minimizes boundary contact between the piston and cylinder liner.



Prior to Break – In

After Break – In



Summary of Study

- Two piston models generated:
  - One with the post-run stock coated geometry, and one with the post-run APC piston geometry.
- The pistons had been installed within two separate Cummins R2.8 L turbo diesel engines, both of which were subject to several hours of runtime.
- A measurement methodology has been developed to obtain pre- and post-run piston measurements.
- The effect of the APC piston geometry on piston secondary motion and ring wear is investigated.
- A skirt profile optimization methodology has been developed to investigate the geometric features of a piston skirt that lead to reduced frictional losses.
- Terminology:
  - APC: Abradable powder coated
  - ISC: Integrated skirt clearance
  - Boundary Contact: The direct interaction of surfaces without the separation of a lubricating film.

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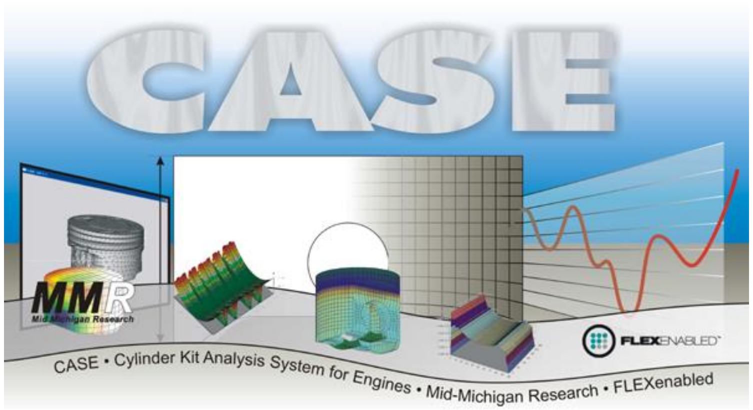
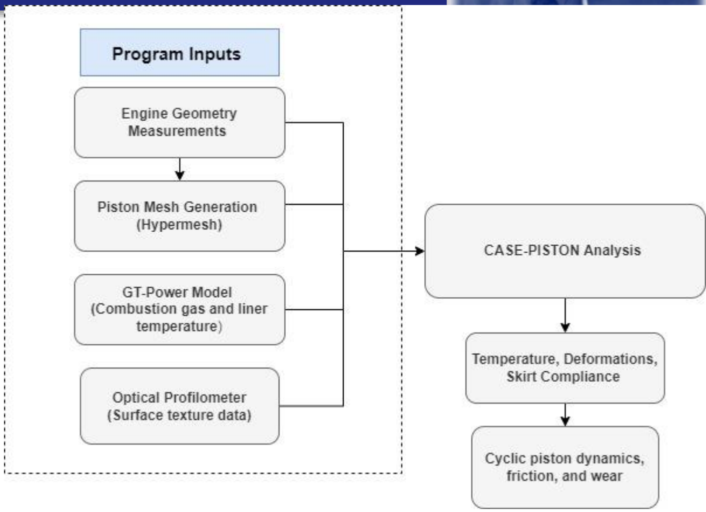
Numerical Modeling of the Cylinder Kit

- Utilized the Cylinder-Kit Analysis System for Engines (CASE) by Mid-Michigan Research.
- CASE is a software package that predicts:
  - Piston: Thermal and mechanical deformations (including elastohydrodynamic), boundary and hydrodynamic frictional losses, axial and lateral piston dynamics, piston skirt wear.
  - Ring: Boundary and hydrodynamic frictional losses, ring dynamics (including ring collapse and uniform ring twist), gas flow dynamics, oil vaporization, ring face and groove side wear.
- Piston lateral dynamics constitute a highly nonlinear problem that is solved for iteratively considering the transverse forces acting on the piston due to:
  - Combustion gas pressure, connecting rod orientation, boundary forces between the piston and cylinder liner, and hydrodynamic forces developed at the piston skirt-to-liner interface.



Model Inputs and Workflow

- Geometric inputs obtained via direct measurement of engine components.
  - CAD model generated in Siemens NX and then meshed in Altair Hypermesh.
- Combustion gas pressure obtained via experimental pressure transducer measurements.
  - Average of 250 cycles obtained at 0.1 crank angle degree increments.
- GT – Power model was generated and calibrated using experimental data and turbocharger maps. This model was then used to estimate combustion gas and liner temperatures.
- Surface texture inputs for piston obtained via optical profilometry (Michigan Metrology). Bore surface texture inputs obtained via stylus profilometry and a literature review [1-2].
- Piston thermal boundary condition estimates obtained via literature review [3-5].



Parameter	Value
Engine Speed	2000 RPM
Bore Diameter	94.25 mm (At Operating Temp.)
Stock Piston Diameter	93.901 mm (Cold)
APC Piston Diameter	93.957 mm (Cold)
Stock Piston Ovality	-0.3505 mm
APC Piston Ovality	-0.4267 mm
Stroke	100 mm
Compression Ratio	16.9

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Modeling Thermal Distortions

- Thermal expansion significantly alters the geometry and clearances at the skirt-to-liner interface.
- Maximum expansion on the piston skirt top is approximately 190 microns.

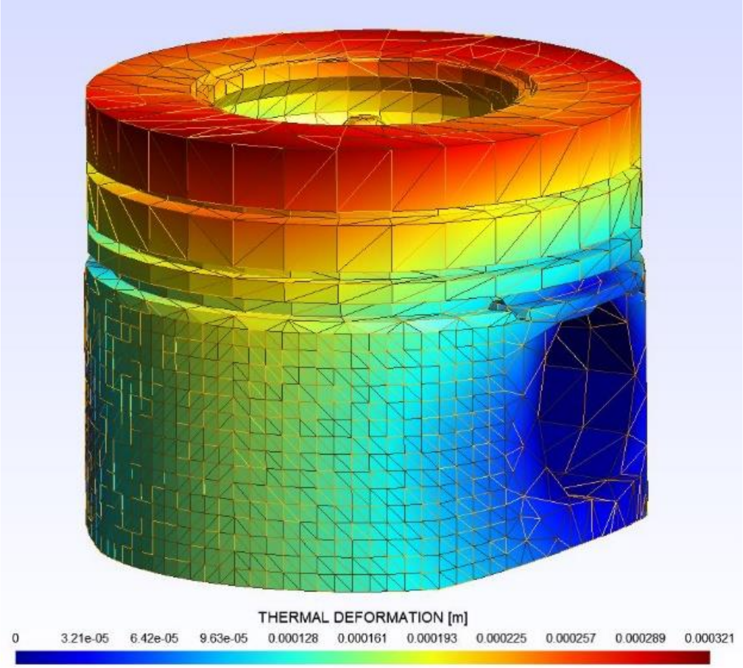

Figure: Predicted Piston Thermal Deformation

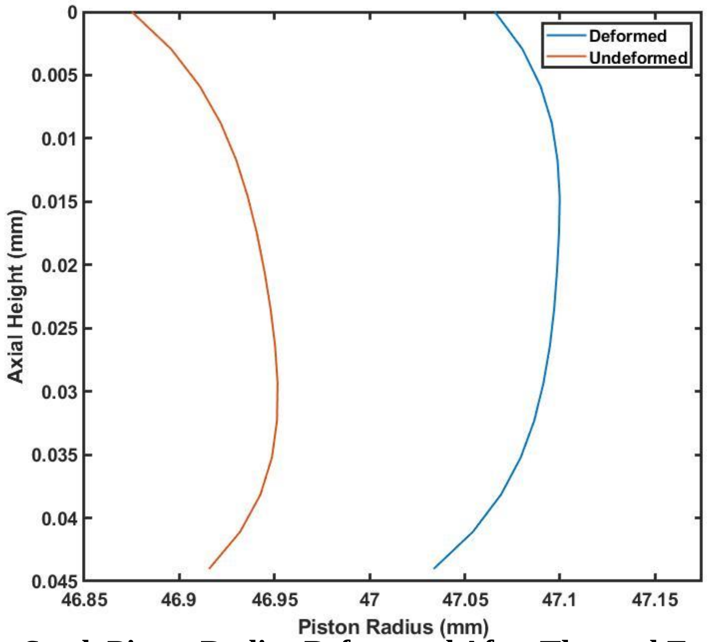

Figure: Stock Piston Radius Before and After Thermal Expansion

Worn APC Skirt Vs. Worn Stock Skirt

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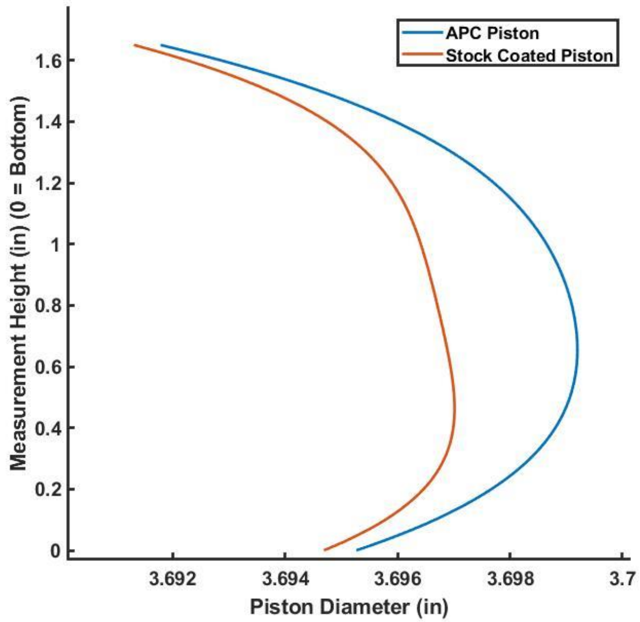
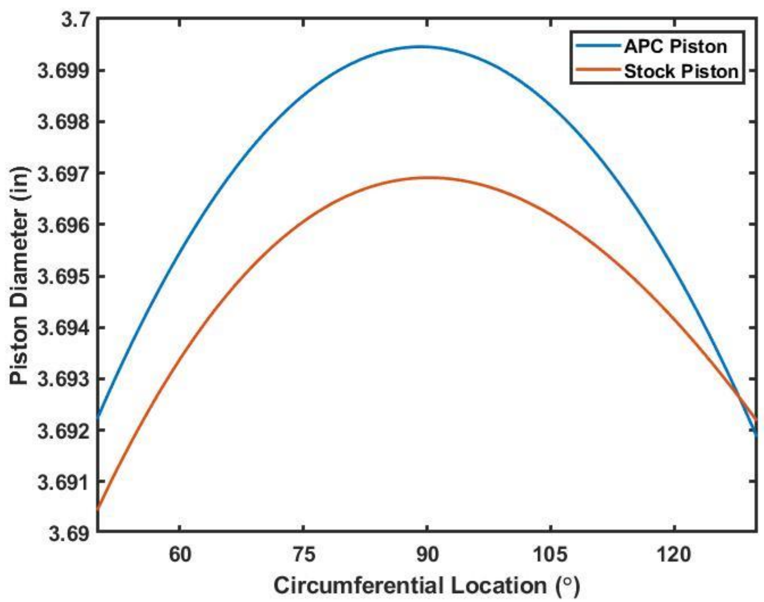
- Axial piston trace taken along skirt center. Circumferential trace taken at 0.632” from skirt bottom, at the gauge point.
- APC piston coating eliminates a significant amount of ISC.
- The Axial trace and circumferential trace are superimposed to determine the clearance around the skirt.

Piston	ISC (mm^3)
Stock	588.741
APC	482.627

An 18% Reduction

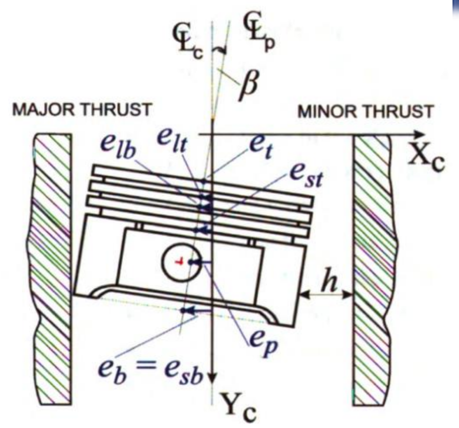
*Clearances above 0.02 inches were assumed to be off the skirt and were therefore filtered out of the ISC calculation

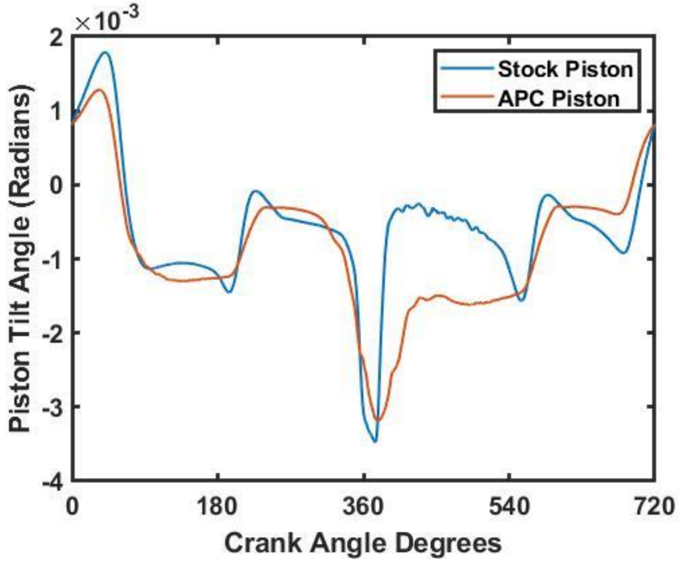


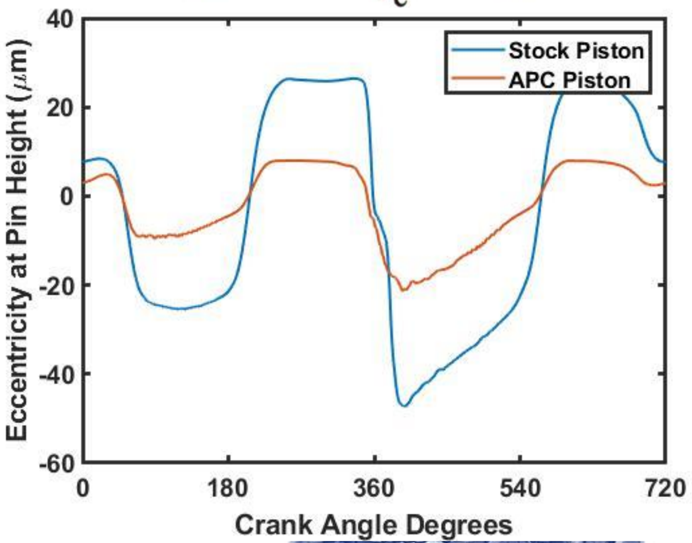


Piston Dynamics Modeling Results

- *Piston eccentricities* = transverse position in the cylinder bore at several axial locations along the piston centerline.
- In general, the eccentricity at the pin height and the piston tilt angle are sufficient to characterize the secondary motion of the piston.
- The APC piston experiences a significant reduction in secondary motion and piston tilt.







Ring Groove Side Wear Modeling

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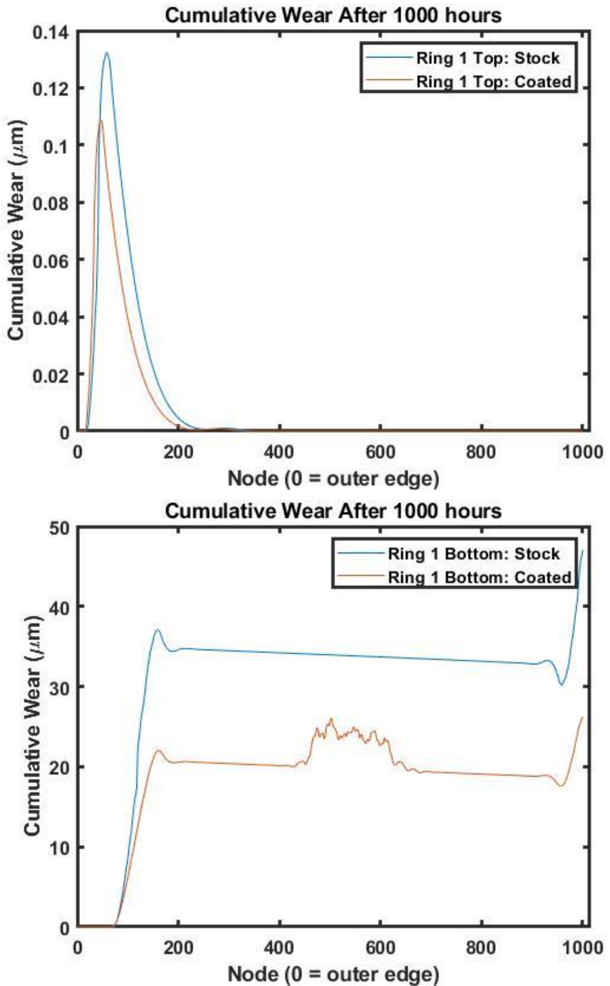
- Wear is proportional to the relative motion between the ring and groove.
- Archard's model used to estimate wear:
  - $\psi = k(\frac{W_a L}{H})$
    - ψ = worn volume
    - k = wear coefficient
    - W_a = asperity contact load
    - L = relative sliding distance
    - H = surface hardness
- Piston secondary motion is a significant contributor to ring/groove relative motion, greatly influencing ring wear.
- The reduced secondary motion of the APC piston is predicted to yield a significant reduction in ring wear.



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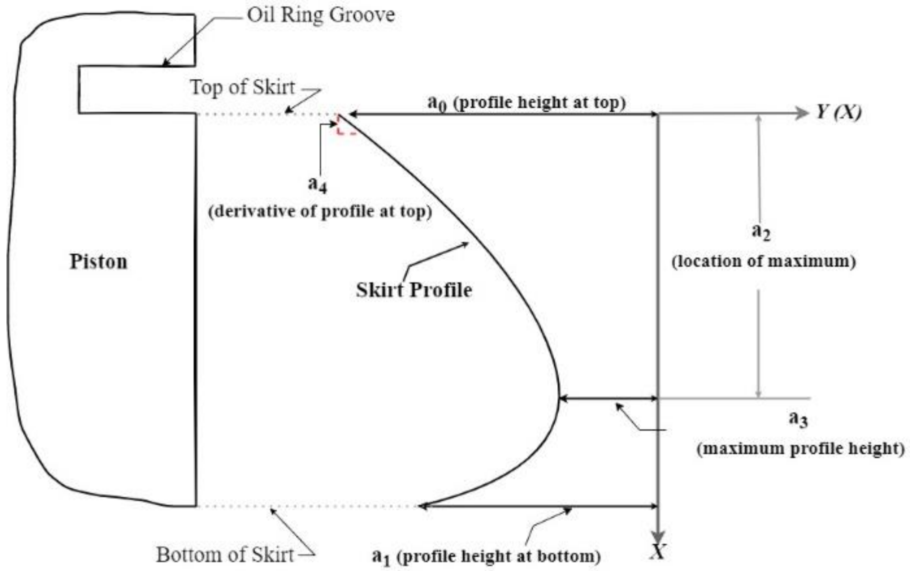
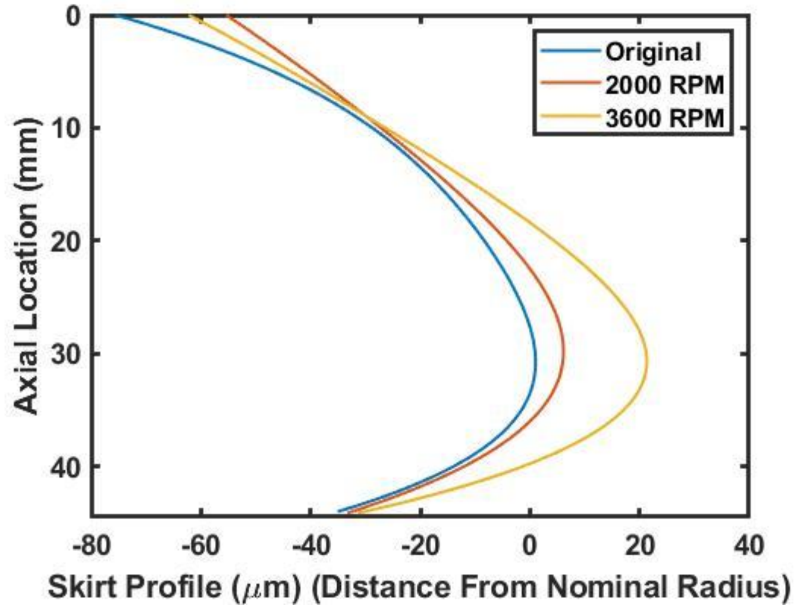
Definition of Optimization Problem

- Hypothesis: APC piston skirt profile will wear to minimize boundary contact between the skirt and cylinder liner.
- Objective: Minimize the average cyclic power loss over one engine cycle.
  - This is the product of piston velocity and frictional forces (both shear friction and contact friction).
- The Skirt profile is defined by a fourth-order polynomial which is calculated from 5 parametric values [a_0 $through$ a_4].
- Constraint: Optimized skirt radius must be larger than the stock skirt radius, as the coating adds material to the piston skirt.



Optimization Results and Breakdown

- It can be estimated that 10% to 25% of engine frictional losses occur at the skirt-to-liner interface [14].
  - average of 17.5%
- FMEP = NMEP - BMEP
- Experimental FMEP at 2000 RPM $= 2.25\ Bar\ =\ 3.52\frac{HP}{Cylinder} \times 0.175 \approx 460\ W$
- Measured FMEP at 3600 RPM $= 2.75\ bar\ \rightarrow \approx 1000\ W$
- Measured FMEP values in close agreement with model prediction.
- An estimated 0.77% gain in peak power and BSFC.



RPM	Original	Optimized	% Reduction
2000	468.89 W	417.96 W	10.86 %
3600	1132.4 W	909.05 W	19.72 %

Conclusion and Future Work

- Worn APC piston exhibits a significantly smaller ISC than the worn stock piston.
  - This yields a significant reduction in piston secondary motion. The reduction in secondary motion yields a significant reduction in ring groove side wear. This is expected to improve ring durability.
  - Experimental engine tests are underway to compare a stock engine to an engine with APC pistons.
- The optimization study suggests that the addition of material to the piston skirt can reduce friction by geometric changes.
- Moving Forward:
  - Improve the model inputs and relax assumptions including:
    - Constant thermal boundary conditions
    - Uniform bore diameter
    - "Fully flooded" skirt assumption
  - Analyze experimental engine data from two engines: one with APC pistons, and the other with a stock configuration.
  - Update model inputs with data from the more recent experimental engine runs.

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Optimization Results and Breakdown

- Optimized profiles yield a large decrease in boundary friction at the expense of a small increase in hydrodynamic friction.
  - A larger region of the skirt is supported by oil film as opposed to surface asperities, yielding the increase in hydrodynamic shear friction.
- Future optimization studies will include the piston ovality, which characterizes the skirt geometry around the piston circumference.
- Engine speed and load were varied, although thermal boundary conditions and bore diameter were held constant.
  - Future efforts will include the relaxation of this assumption and additional optimization studies.

CONFIGURATION	HYDRODYNAMIC	BOUNDARY
2000 RPM ORIGINAL	104.83 W	364.06 W
2000 RPM OPTIMIZED	105.46 W	312.50 W
3600 RPM ORIGINAL	364.06 W	759.92 W
3600 RPM OPTIMIZED	366.20 W	542.88 W