Massachusetts Institute of Technology

Low Engine Friction Technology for Advanced Natural Gas Reciprocating Engines

Advanced University Reciprocating Engine Program (AUREP)

Annual Review Meeting

July 12, 2005

Argonne, IL

Victor W. Wong, Principal Investigator, MIT

(B. Willson, R. Stanglmaier, Partner PI's – CSU)

Ronald Fiskum, Program Sponsor, DOE/EERE

William Cary Smith , Contract Manager, DOE/NETL

COOPERATIVE AGREEMENT DE-FC26-02NT41339

Presentation Topics

- **Overview (12 minutes)**
  - Goals and significance
  - Summary: where we stood; where we are, going
  - Experiments and measurements
- **Piston Design Results: (11 minutes)**
- **Lubricant Effects on Ring-Pack Friction (9 minutes)**
- **Piston Material and Surface Results: (8 minutes)**
- **Recap (5 minutes)**

- **TOTAL (45 minutes)**
- **Q & A (10 minutes)**

PROJECT OBJECTIVES

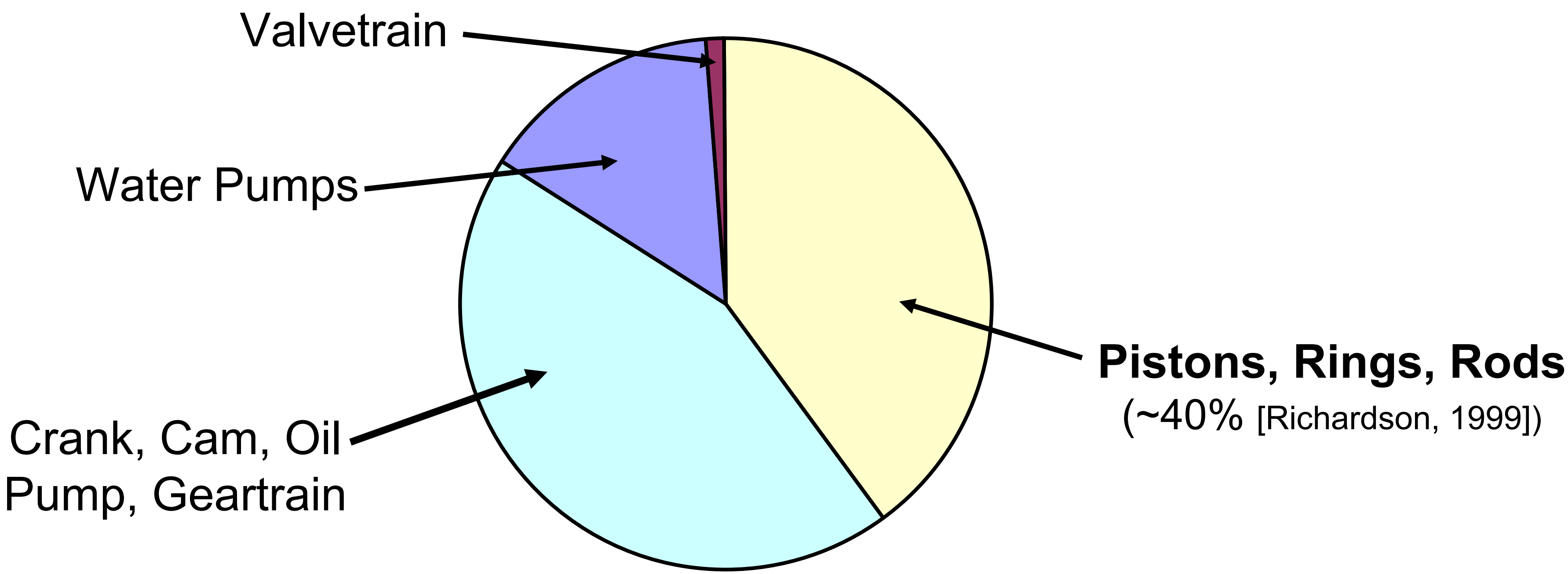
- To reduce parasitic losses of Advanced Natural Gas Reciprocating Engines by reducing piston/ring assembly friction, without introducing major adverse effects

- Target:

  - Initial 30% reduction in piston and ring pack friction
  - Subsequent 50% friction reduction in power-cylinder friction
  - 2% engine efficiency improvement

Mechanical Loss Comparison

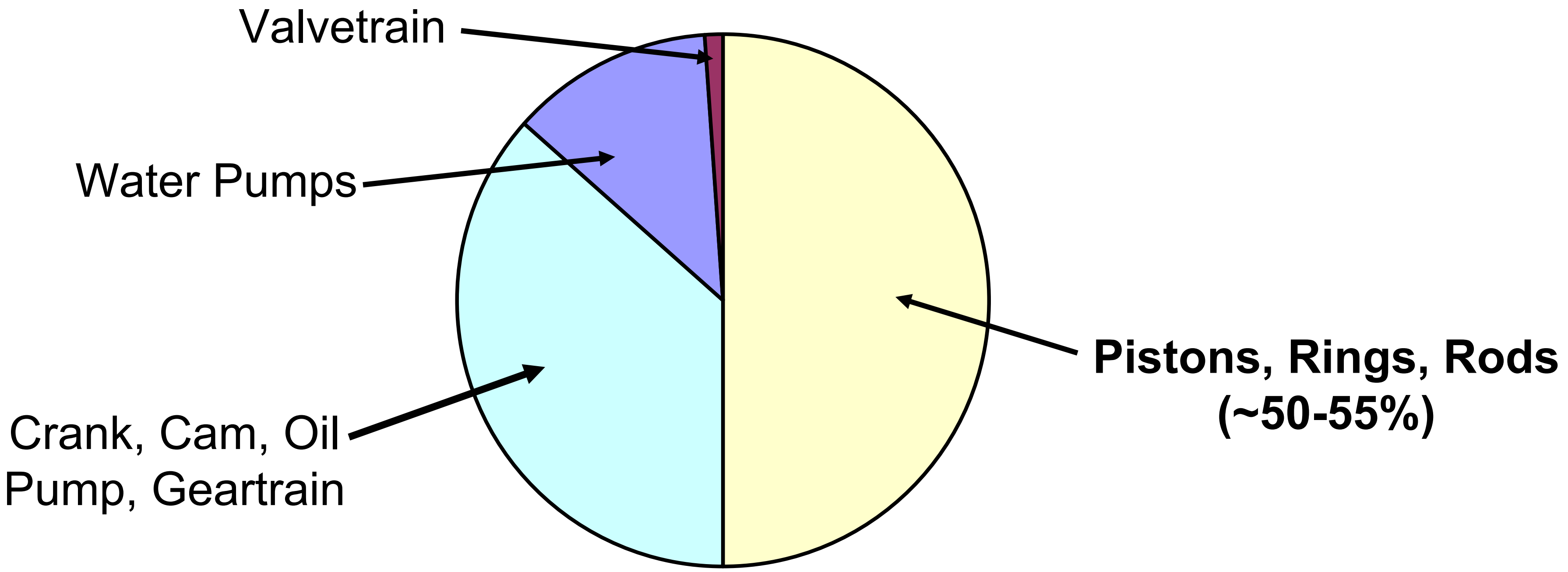
(Motoring)



Motoring Tear-Down Test: Waukesha F18GL Engine
1800 RPM (2002)

Mechanical Loss Comparison

(Firing)



Projected Firing Component Losses from Power Cylinder

[+25% at mid-load. Mufti, 2004]

TECHNICAL APPROACH

- **Bridge fundamental research in engine component tribology with engine application**
- **Develop low-friction piston/ring-pack/engine system strategies by modeling & engine validation**
  - System analysis and evaluation
  - Design and prototyping candidate components or materials
  - Full-scale engine demonstration
- Initial System: Ring-Pack

☞ **Overall system: Piston, Liner, Material, Engine, Lubricants (Current)**

Relevance to ARES Objectives

- Power cylinder friction accounts for about half of all mechanical losses
- Goal is to reduce half of power-cylinder friction, (or 25% of all mechanical losses)

⇨ 2% increase in brake thermal efficiency towards 50% target
(5% fuel economy improvement from current level)

Criteria	Baseline Engine Status	ARES Target
Efficiency	37%	50%
NO_x Emissions	1-2 g/hp-hr	0.1 g/hp-hr
Cost	$ 0.05-0.06 /kWh	10% Reduction

PROJECT MILESTONE PLAN

DoE Form 4600.3

(Low Engine Friction Technology for Advanced Natural Gas Reciprocating Engines)

Milestone Plan Period: October 1, 2004 – September 30, 2006

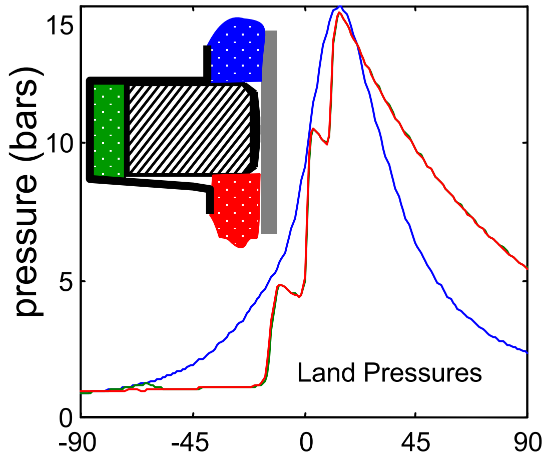
#	MAJOR TASKS	CY2004			CY2005												CY2006								
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
3	**Design & Performance Analysis**																								
3.1	(a) Piston analyses for improved piston friction reduction																								
3.2	(b) Perform parametric and system analyses to include effects of material, surface characteristics such as roughness, wear trends, and lubricant interactions.																								
3.3	(c) Recommend low-friction design options for ring/piston, material, and lubricant systems. Procure prototype components for testing																								
4	**Demonstrate Optimal Design**																								
4.1	Establish Baseline Tests (Done)																								
4.2	Validate effects of individual component design parameter changes to include piston, material, & lubricants																								
4.3	Demonstrate complete low-friction engine system with aggregate																								
5	**Analyze Test Results of Additional System Parameters (Piston, Material, & Lube); Iterate and Improve Designs**																								
6	**Manage Reporting & Education**																								
6.1	prepare periodic reviews and reports																								
6.1.1	- Monthly team telephone conferences	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6.1.2	- Deliver annual reports																								
6.1.3	- Deliver final report																								

* Monthly activities
△ Major Milestones

Research Program Structure

Modeling

Oil film thickness, friction, ring dynamics, gas flow, piston motion, design options



Experiments

Engine performance, friction cylinder pressures, inter-ring land pressures, oil consumption, emissions.

Engine Manufacturer(s)/ Suppliers

Technical Support/Input

Major Tasks

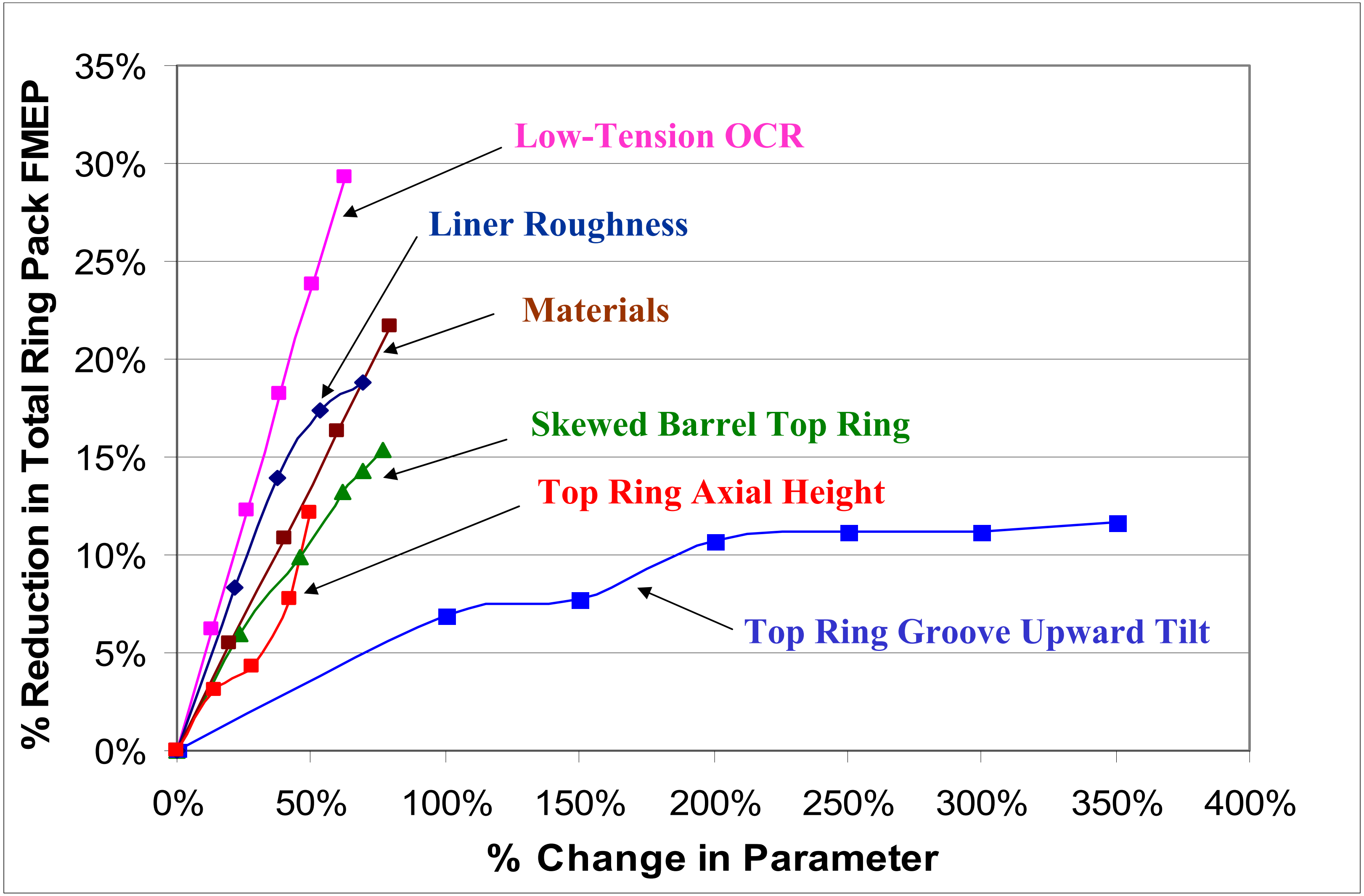
- Expand analyses for improved piston friction: Parametric study on shape, rigidity, secondary motion effects, coatings
- Perform System Analyses to include effects of mechanical design, material, surface features, lubricants, and engine as a system
- Recommend and design components and system
- Complete ring-pack studies: ring/liner surface characteristics and lubricant effects; additional testing
- Demonstrate low-friction power-cylinder components and system on full-scale engine at CSU
- Analyze test results and iterate designs for optimized system

Waukesha VGF18GL

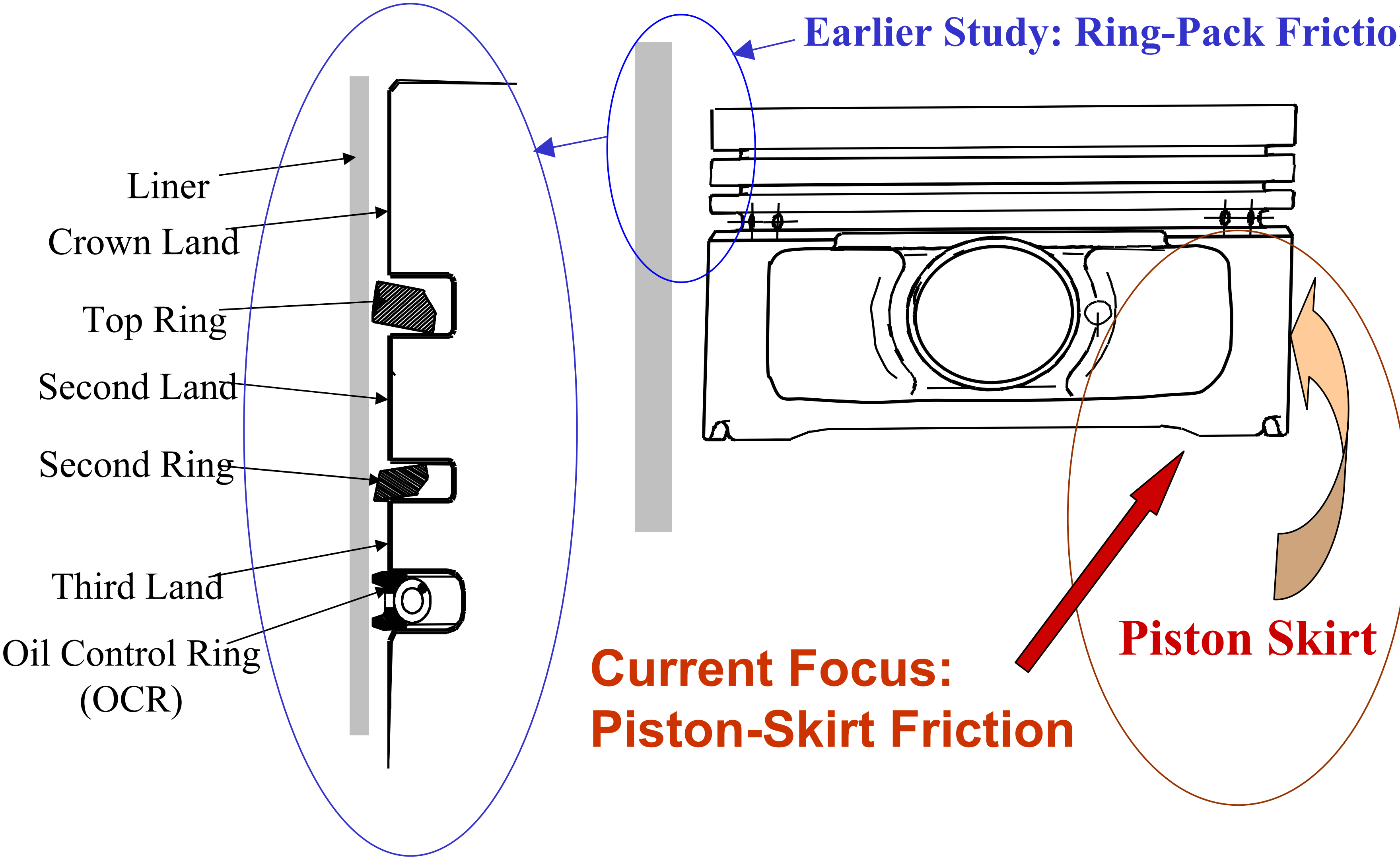
Synopsis of Where We Stood: Prior Accomplishments

- Developed/adapted computer simulations for piston and ring-pack friction applicable to ANGRE engines.
- Reduced-friction ring-pack designs developed, with overall friction reduction potential of 35%.
- Top ring and oil control ring identified as major friction sources. Scraper ring strategy improves oil consumption
- Tests on full-scale Waukesha engine at CSU measured friction reduction of 30% with low-friction OCR design
- Piston design, material and lubricant identified as areas to further optimize system for low-friction and improved efficiency

Friction Reduction Potential of Designs



Analyses: Piston and Ring-Pack System



Current Accomplishments

- Developed surface-finish analyses, which showed that surfaces that are smoother, more plateau honed, and with cross-hatch patterns more perpendicular to the cylinder axis can reduce ring-pack friction by 15%
- Detailed piston-skirt friction analysis showed that a flatter piston-skirt profile offers potential friction improvement of 15-25% from current designs.
- Identified and quantified other parameters that affect piston friction, such as the skirt stiffness, waviness pattern and oil supply to the piston skirt, all of which can affect piston friction by 30-40%
- Worked and continue to work with a major lubricant supplier in optimizing lubricants for ARES efficiency

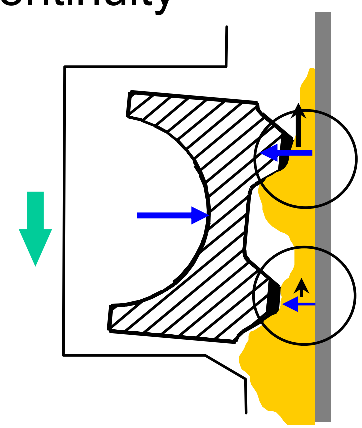
Current Accomplishments

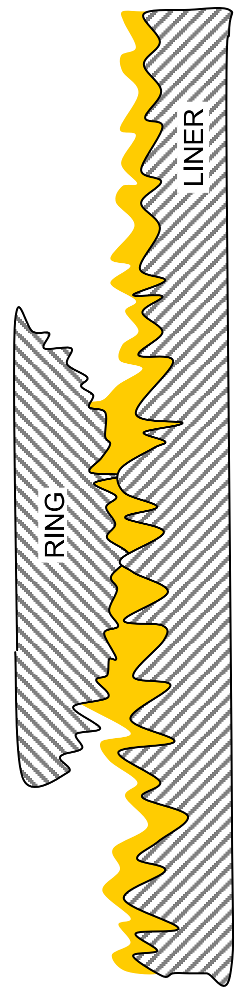
- Lubricant models show that less viscous oils are better for hydrodynamic friction, up to a point where boundary friction becomes dominant. Results show 10% additional friction improvement beyond all other approaches.
- Confirmed piston-friction reduction potential is comparable to ring-pack friction reduction.
- System analysis and optimization, considering various combinations of parameters, are continuing
- Full-Scale ARES engine testing and demonstration continues at CSU. Diagnostics significantly improved.
- Developed and will continue periodic technical exchange & interactions with engine manufacturers, Purdue & MIT

Analyses

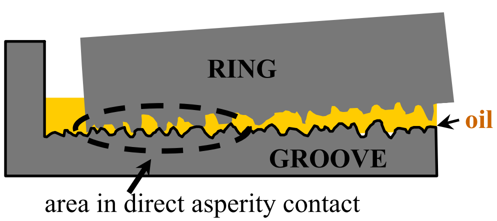
Friction and Lubrication

Mixed Lubrication
Three Lubrication Modes
Outlet Conditions
Flow Continuity

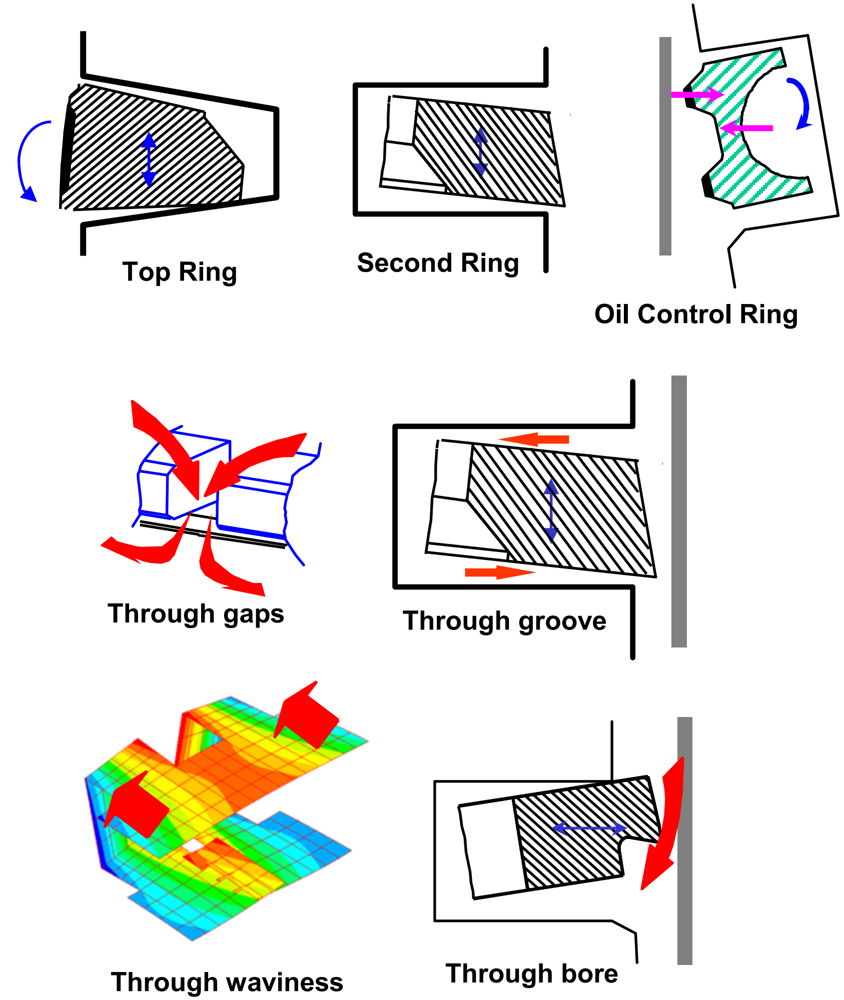




Asperity Contact



Ring Dynamics and Gas Flow

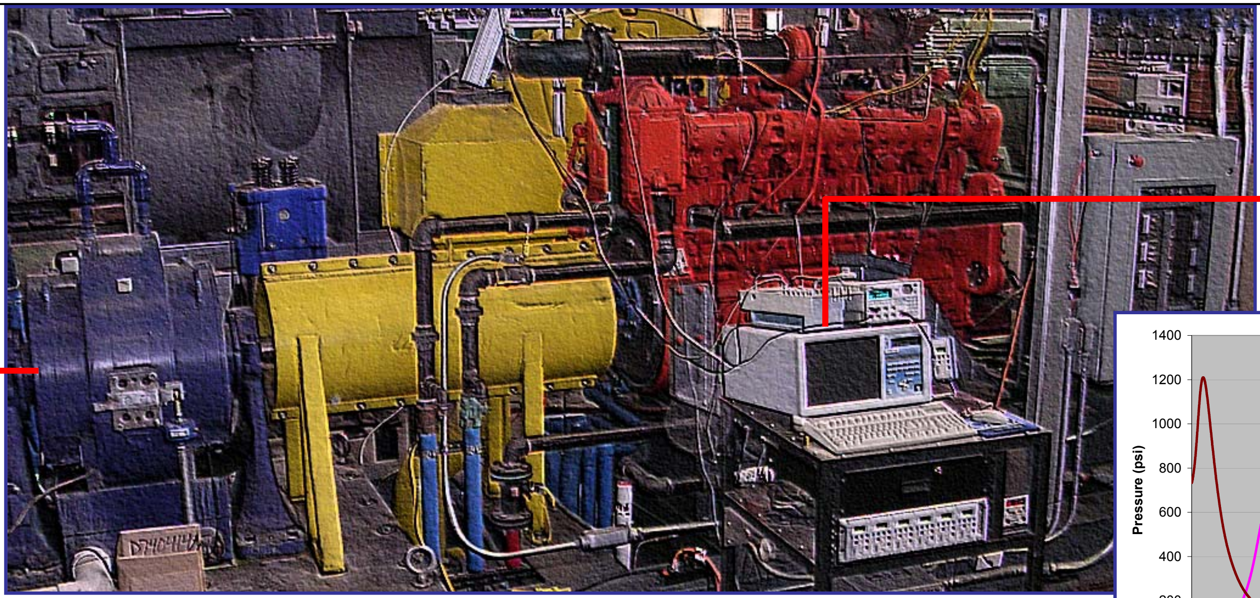


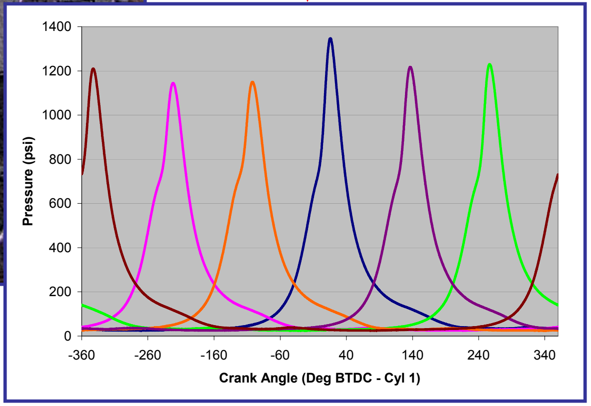
EXPERIMENTS

Waukesha VGF Engine Test Cell

18 liters 6 cylinders, 1800 RPM, 200 psi BMEP

FMEP Measurement





Speed
Torque

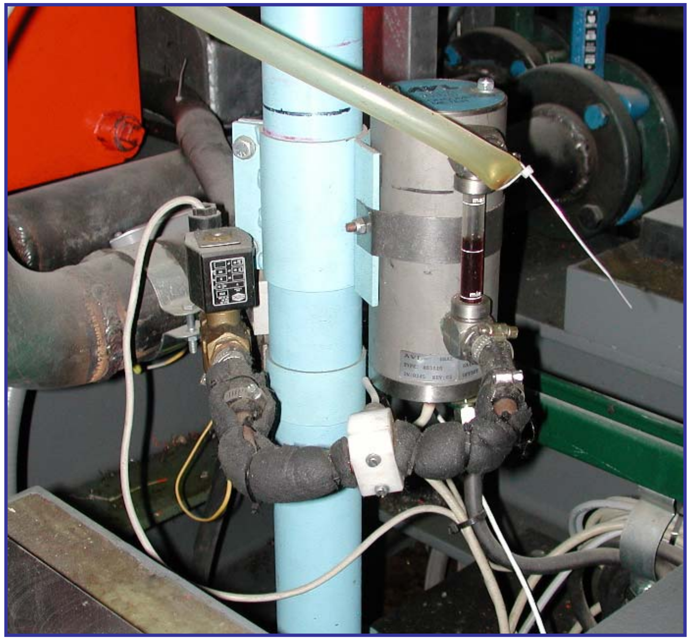
Cyl. Pressures
Crank Angle

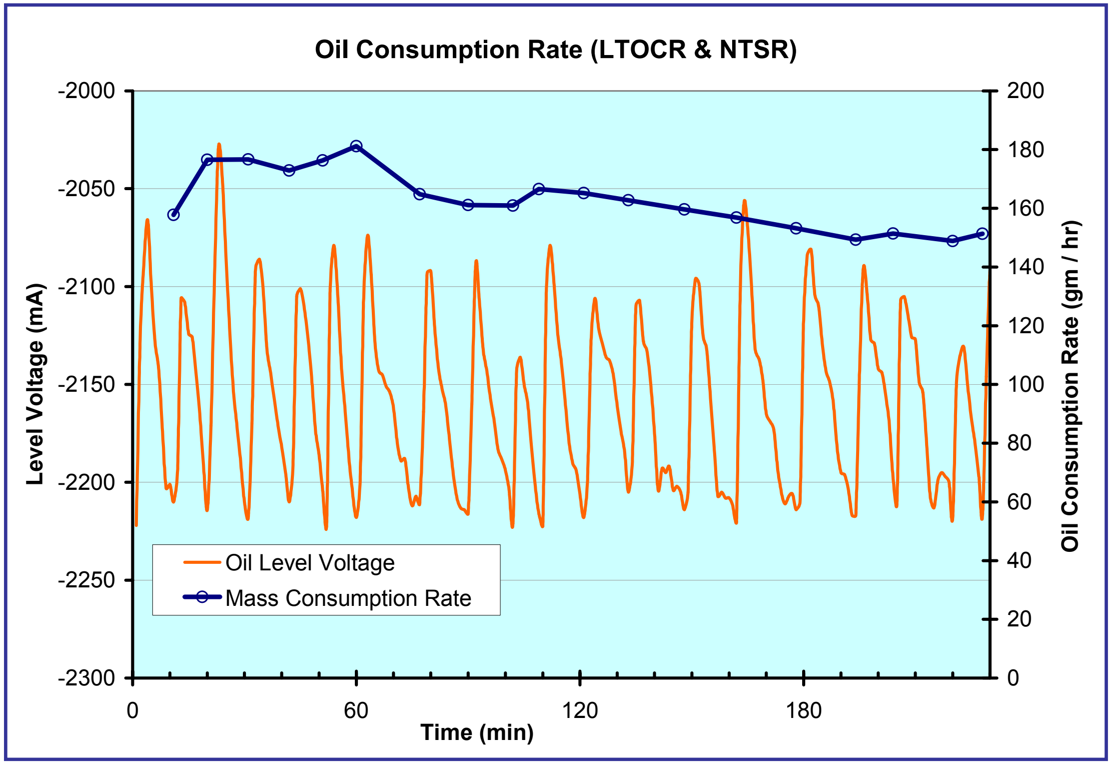
FMEP = IMEP - BMEP

- Conceptually, it is simple to measure FMEP…
  – As long as IMEP and BMEP can be measured accurately

Oil Consumption Measurement

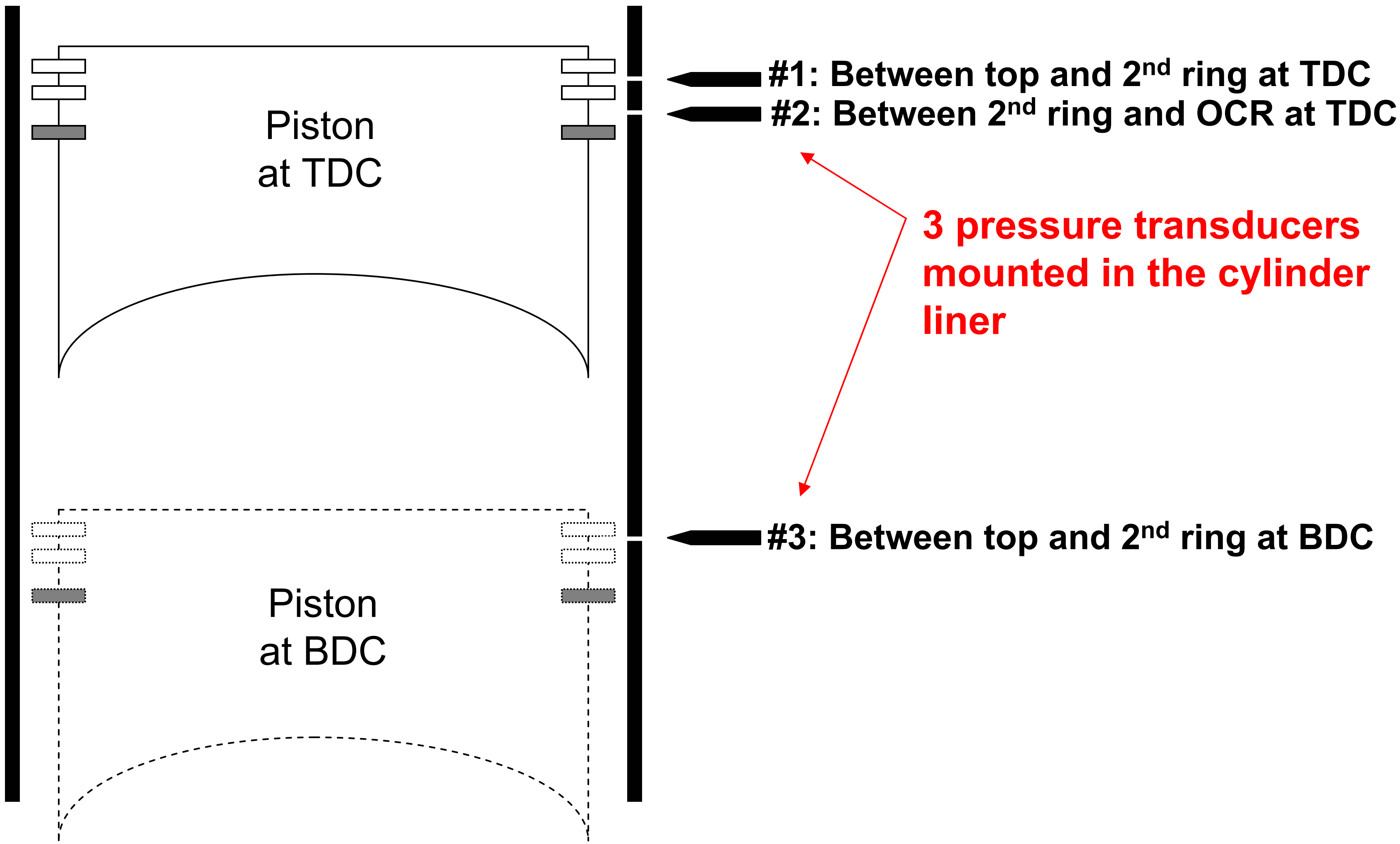
- AVL 403S automatic oil consumption meter
  - Provides continuous monitoring of oil addition to maintain a constant level in the sump





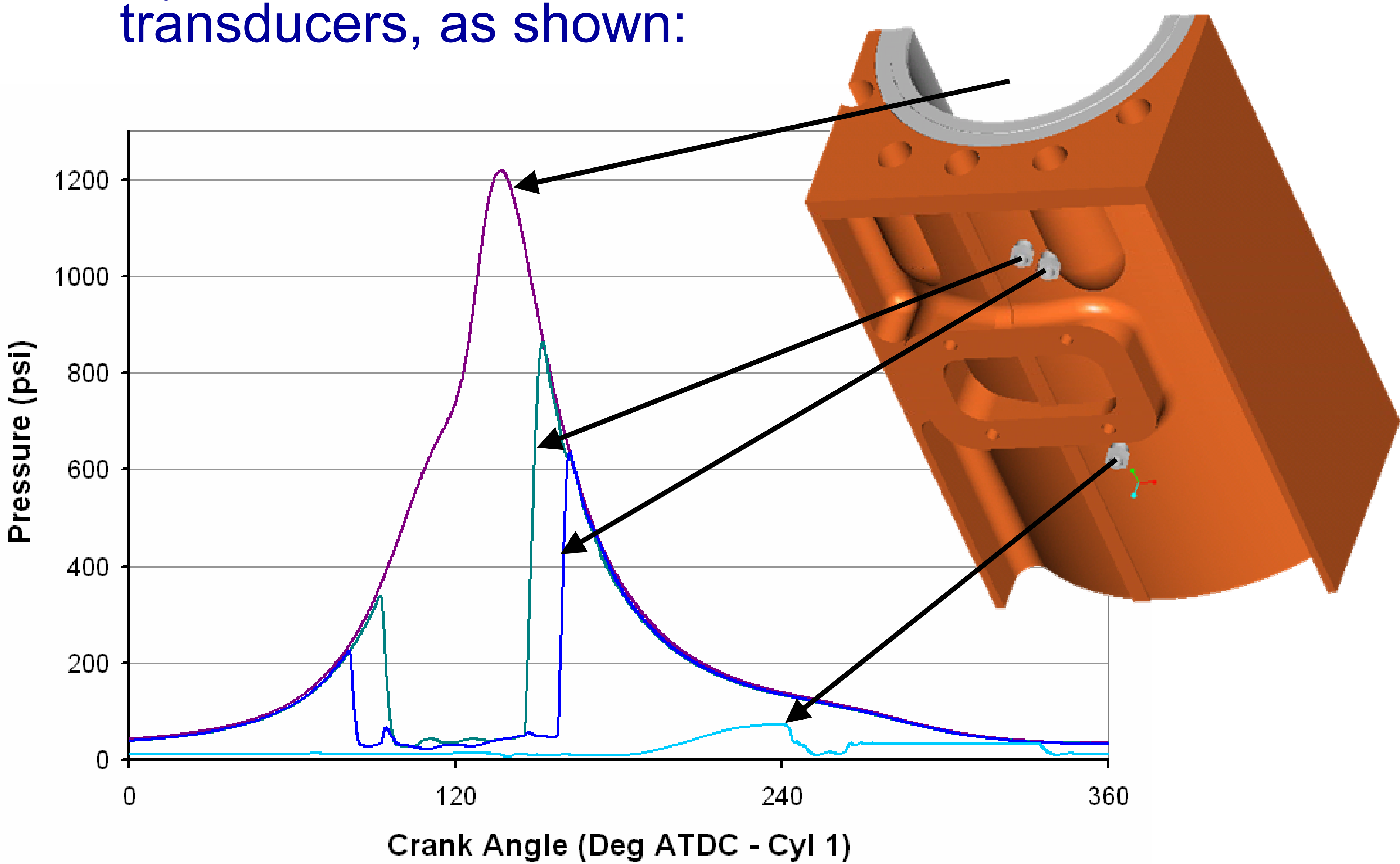
- Oil consumption measurement stabilizes over a few hours of operation

Piston-Ring Pressure Measurement by Inter-Ring Pressure Diagnostics



Pressure Measurement

- Cylinder 5 is instrumented with 4 pressure transducers, as shown:

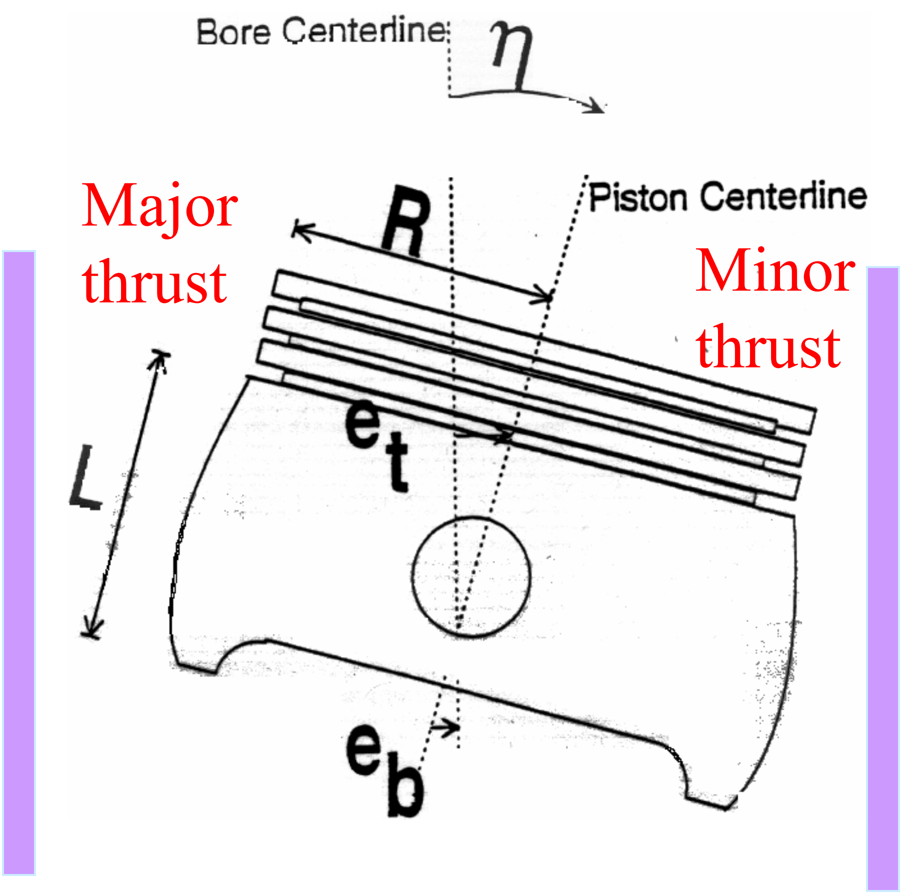


PISTON DESIGN RESULTS

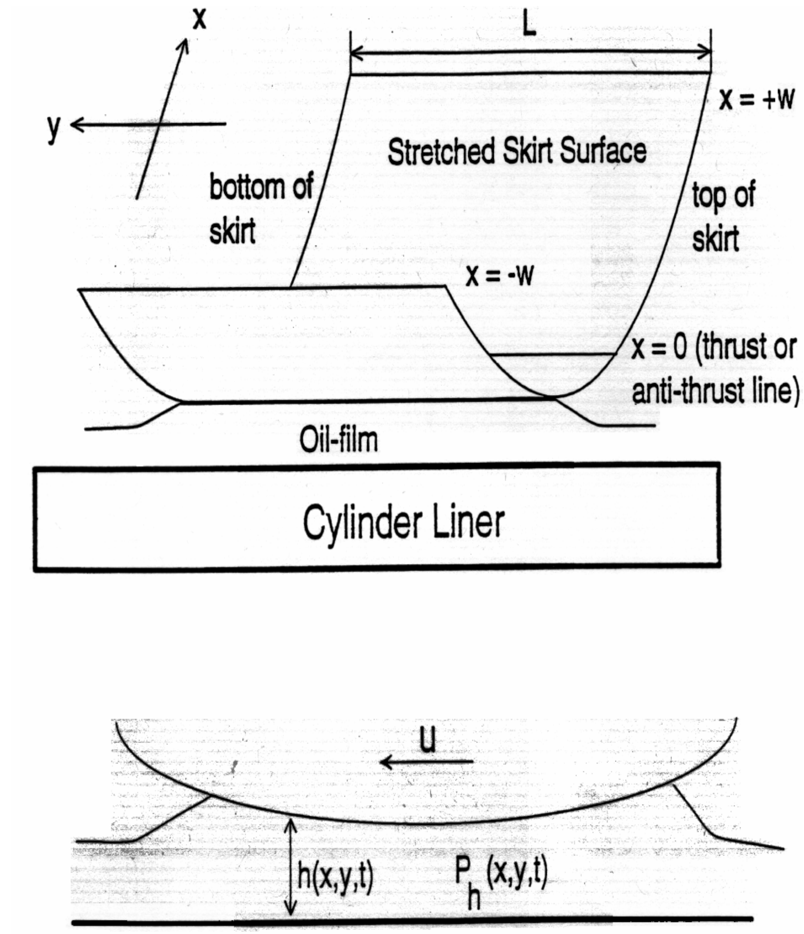
For

Low Friction

Piston-Skirt and Cylinder-Liner Interactions

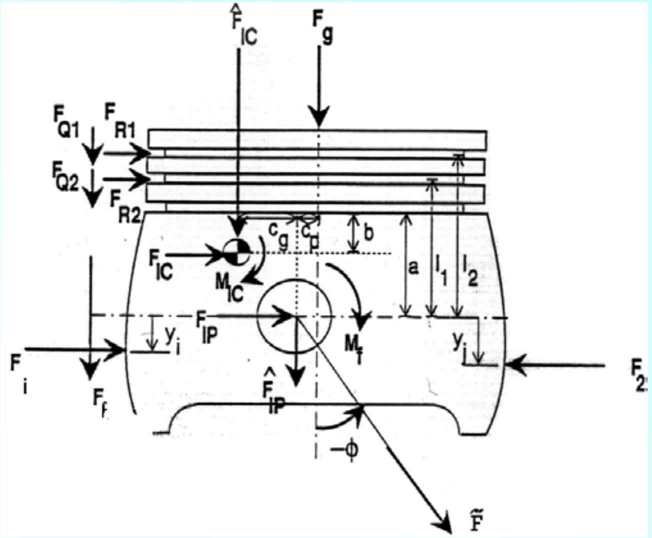


Piston tilts - side impact (secondary motion)



Two-Dimensional Oil-Film Between Skirt and Liner Surfaces

Piston Dynamics



Engine Design Parameters:

Basic engine parameters

Ring-pack parameters

Piston-skirt parameters

Skirt Lubrication: Unsteady Modified Reynolds Equation

- With flow factors for skirt surface waviness and roughness

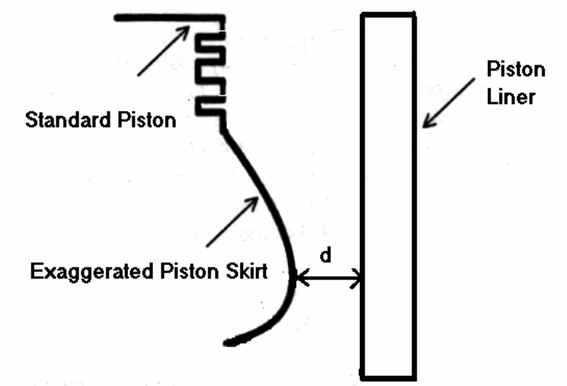
$$\frac{\partial}{\partial x}\left(\Phi_x h^3 \frac{\partial p_h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Phi_y h^3 \frac{\partial p_h}{\partial y}\right)=$$

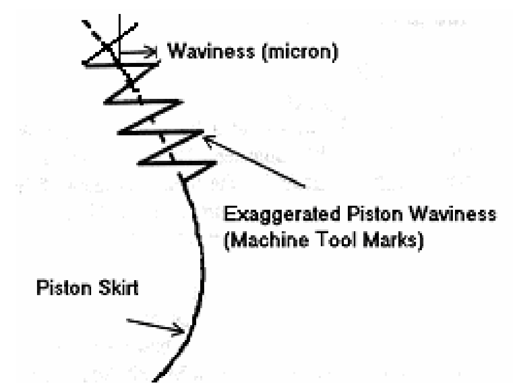
$$-6\mu U\left(\frac{\partial h}{\partial y}+\Omega\frac{\partial \Phi_s}{\partial y}\right)+12\mu\frac{\partial h}{\partial t}$$

Approach to Piston Friction Study

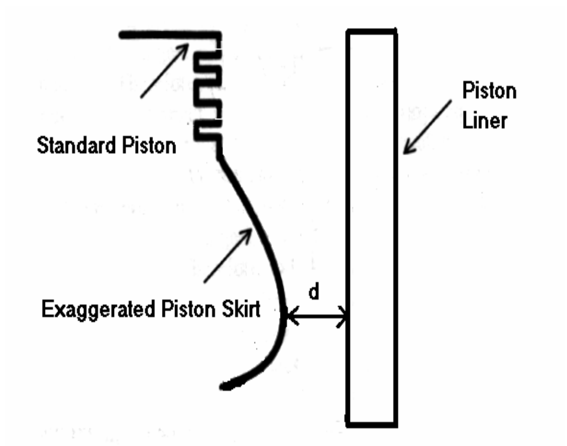
- **Effects of varying piston design parameters of an ARES engine were investigated using modeling tools**

- **The following piston design parameters were considered:**
  - **Piston skirt-to-liner clearance**
  - **Initial oil film thickness between skirt and liner**
  - **Piston-skirt profile**
  - **Surface characteristics: waviness**
  - **Skirt material stiffness**
  - **Lubricant Viscosity**

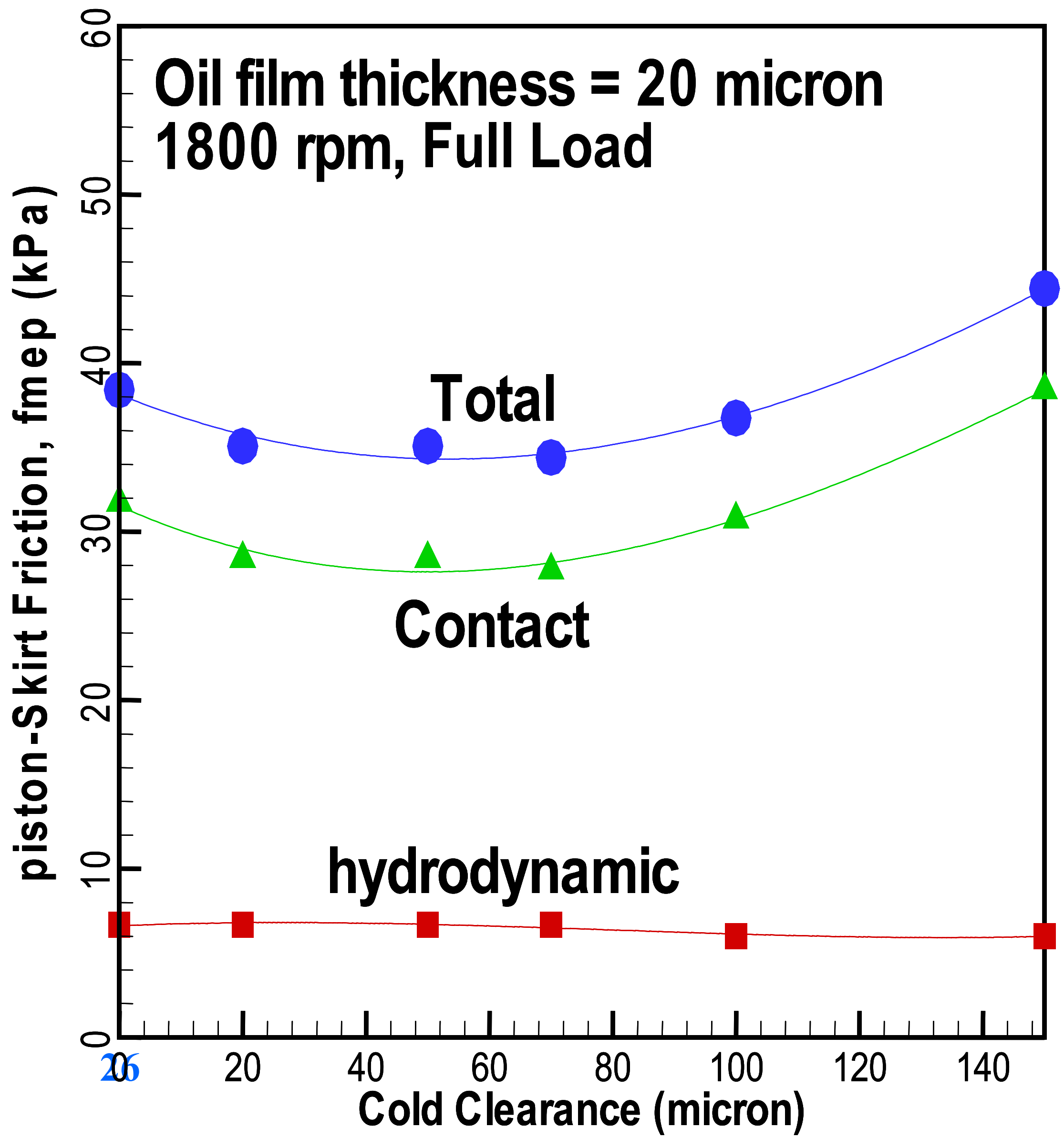




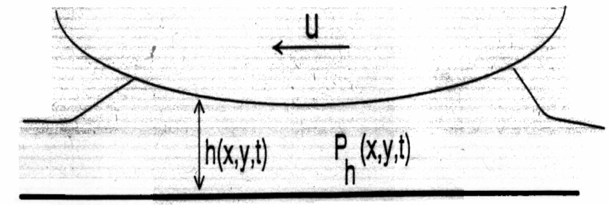
Effect of piston-liner clearance

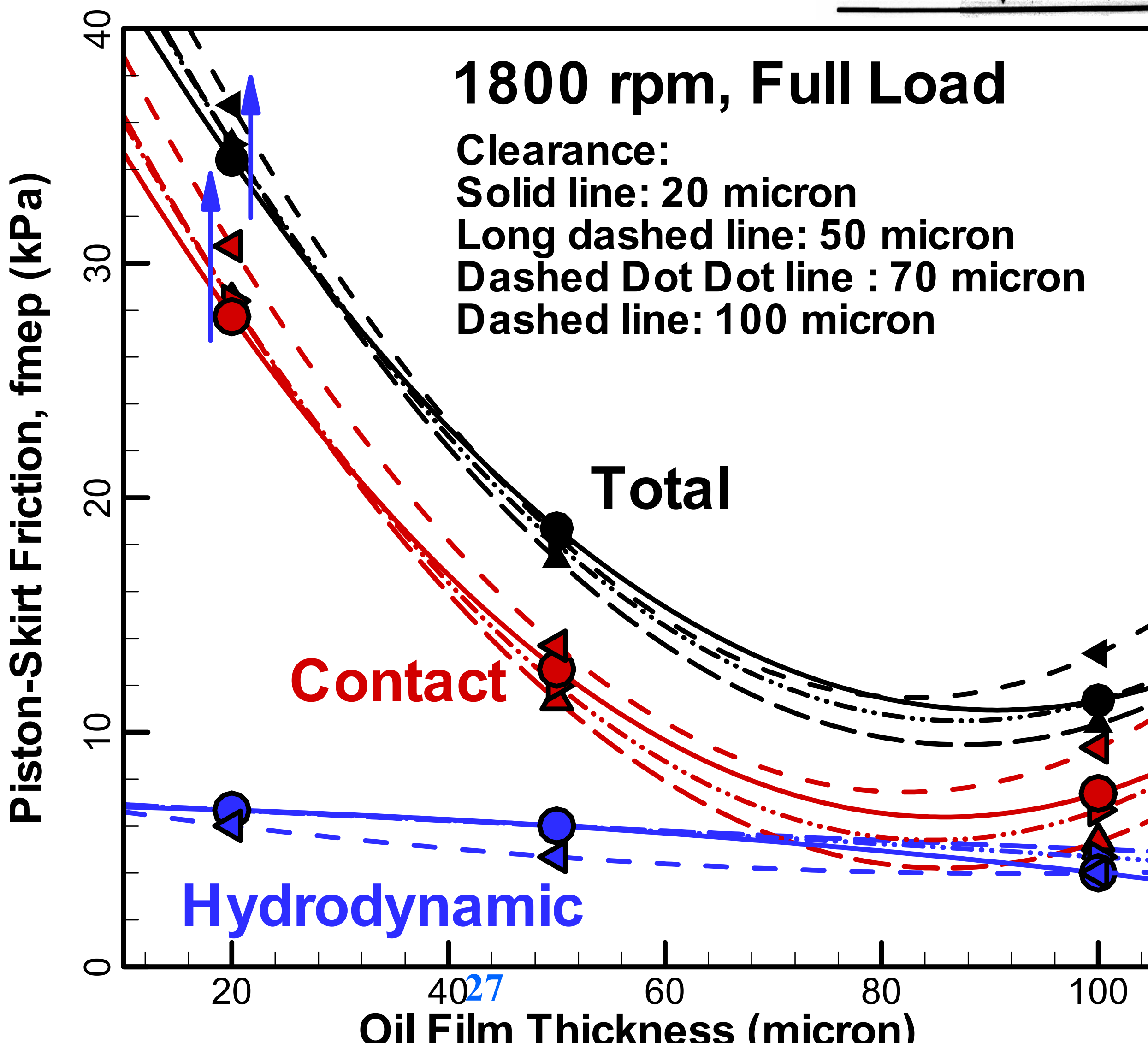


- **Perceptible but small effect on friction**

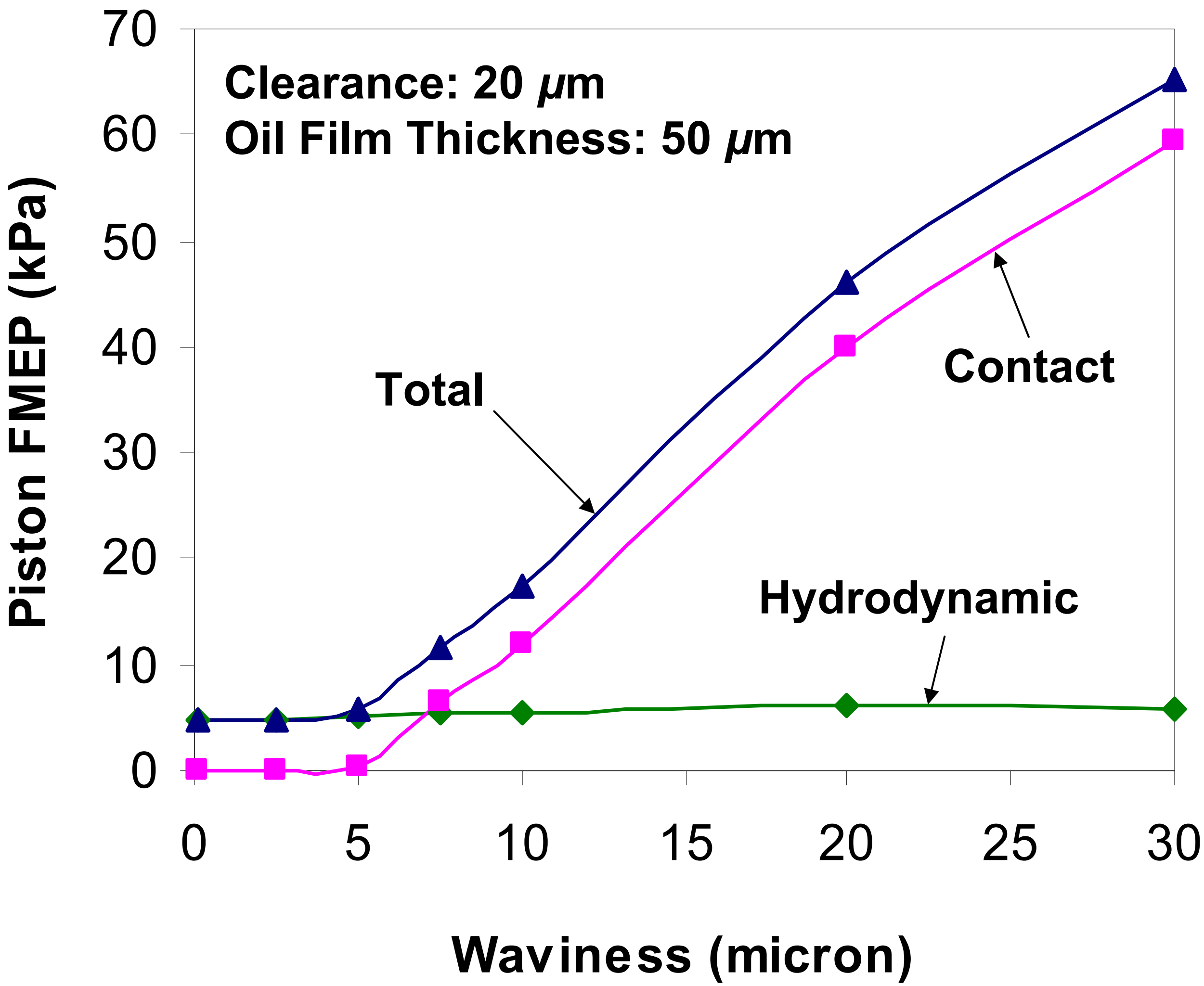


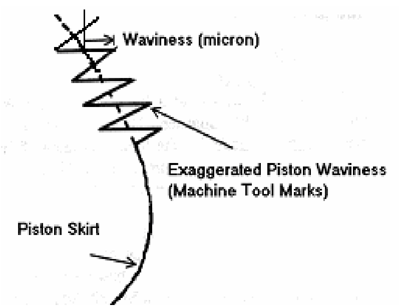
Effects of oil film thickness





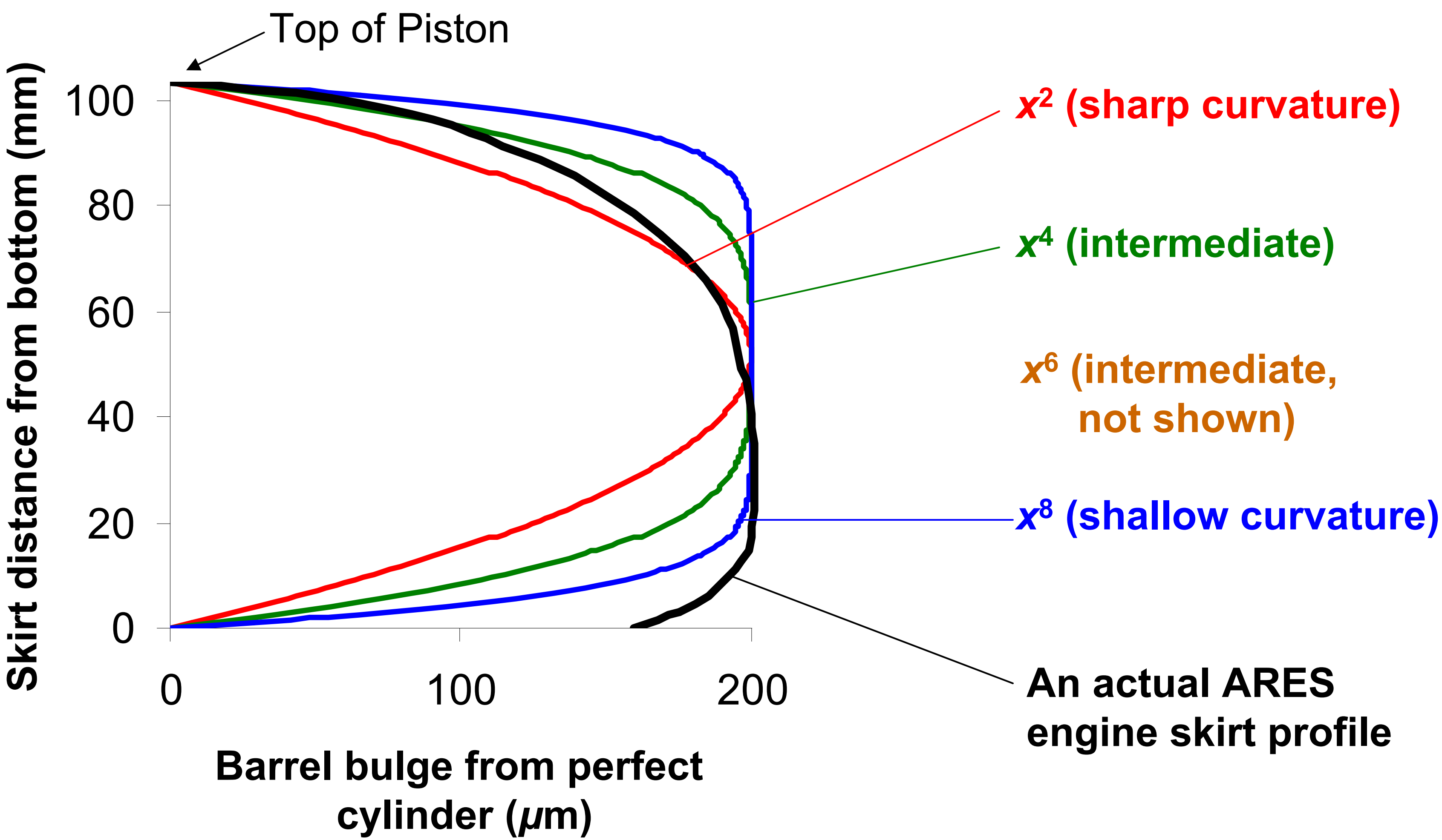
Effects of Skirt Waviness on Piston Friction





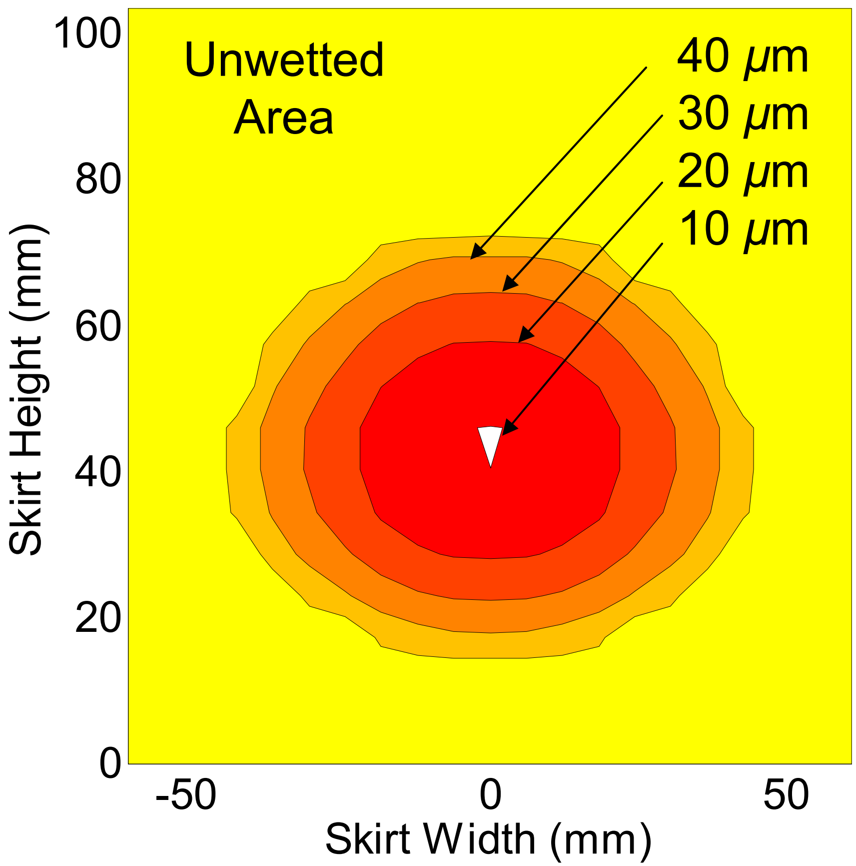
Skirt Waviness

Piston Profile Shapes (Curvature)

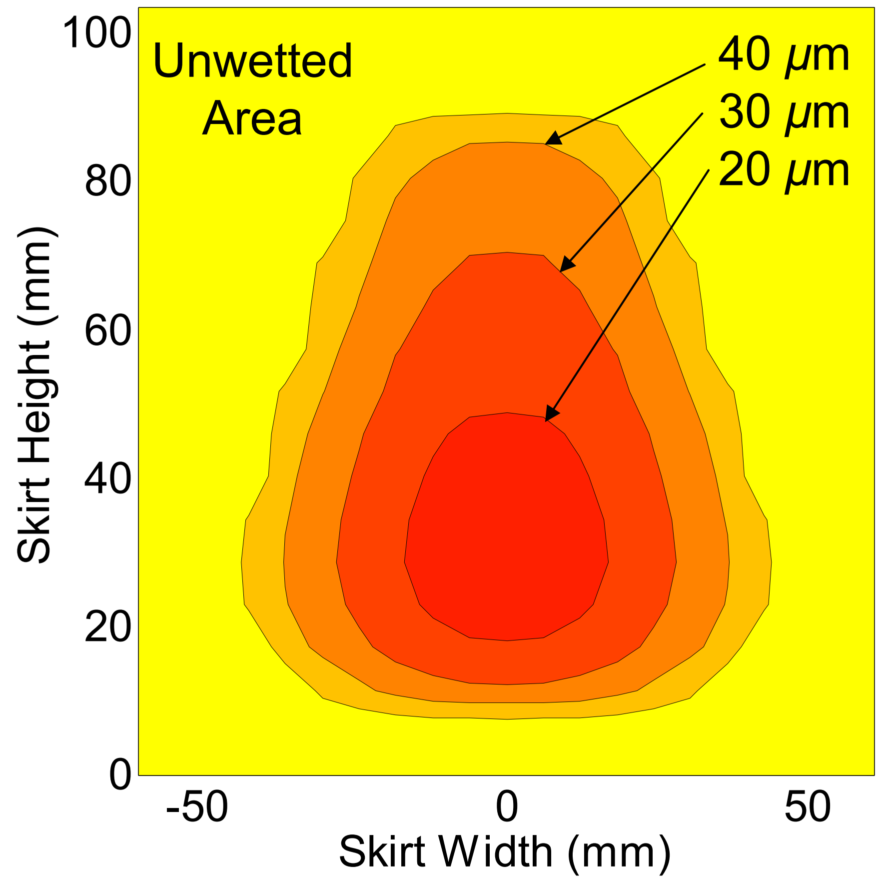


Wetted Area & Penetration Depth vs. Curvature

(Crank angle = 40° ATDC during expansion stroke)



x^2 (sharp-curvature) profile

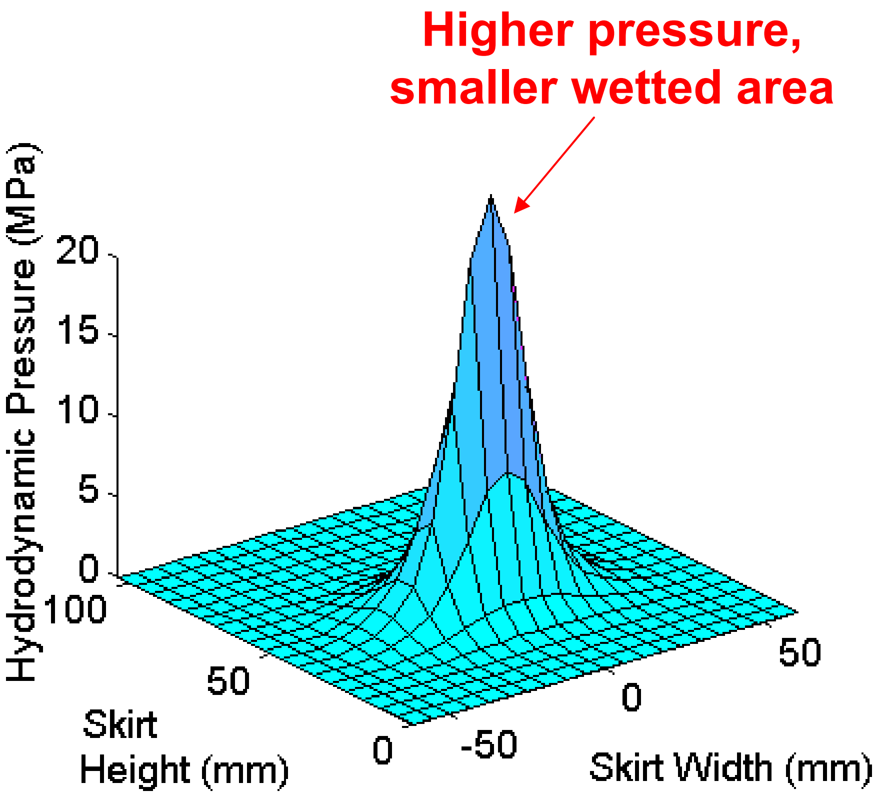


x^8 (shallow-curvature) profile

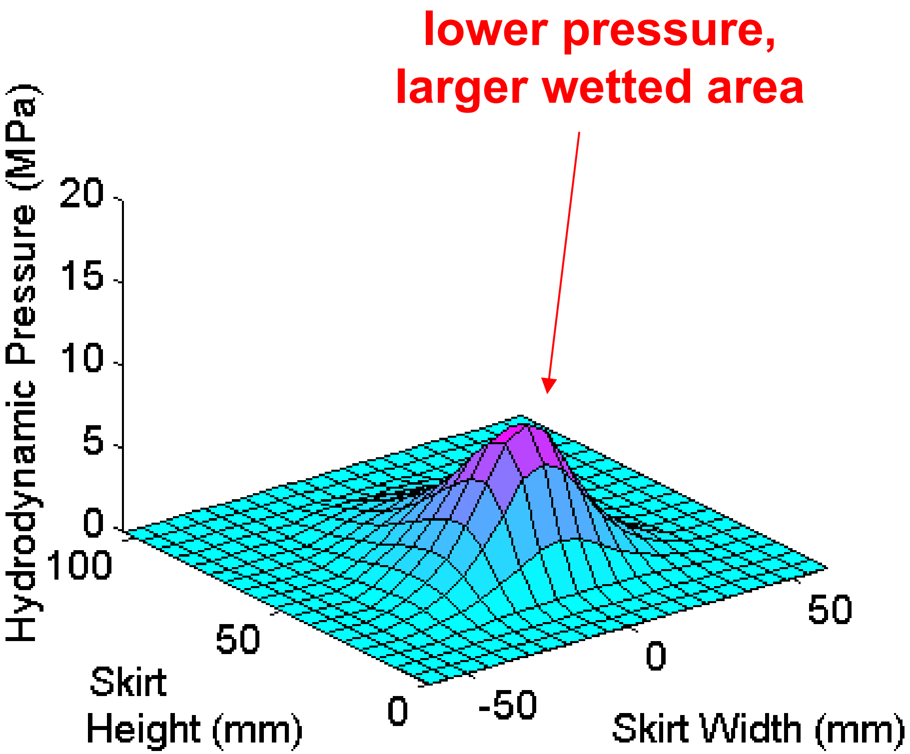
Flatter (shallow-curvature) profile has larger wetted area and shallower penetration depth

Pressure Distribution vs. Piston Curvature

(Crank angle = 40° ATDC during expansion stroke)

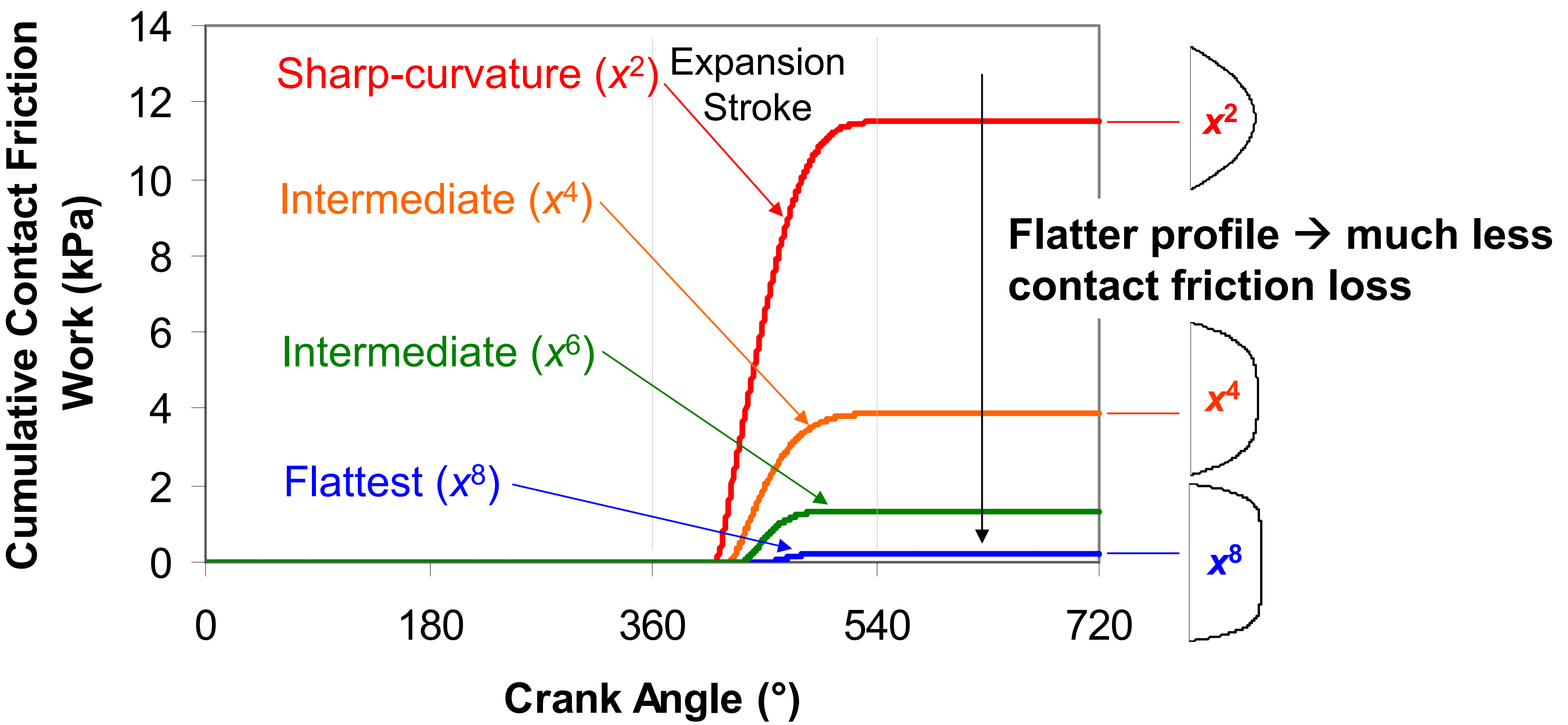


x^2 profile
(sharp curvature)



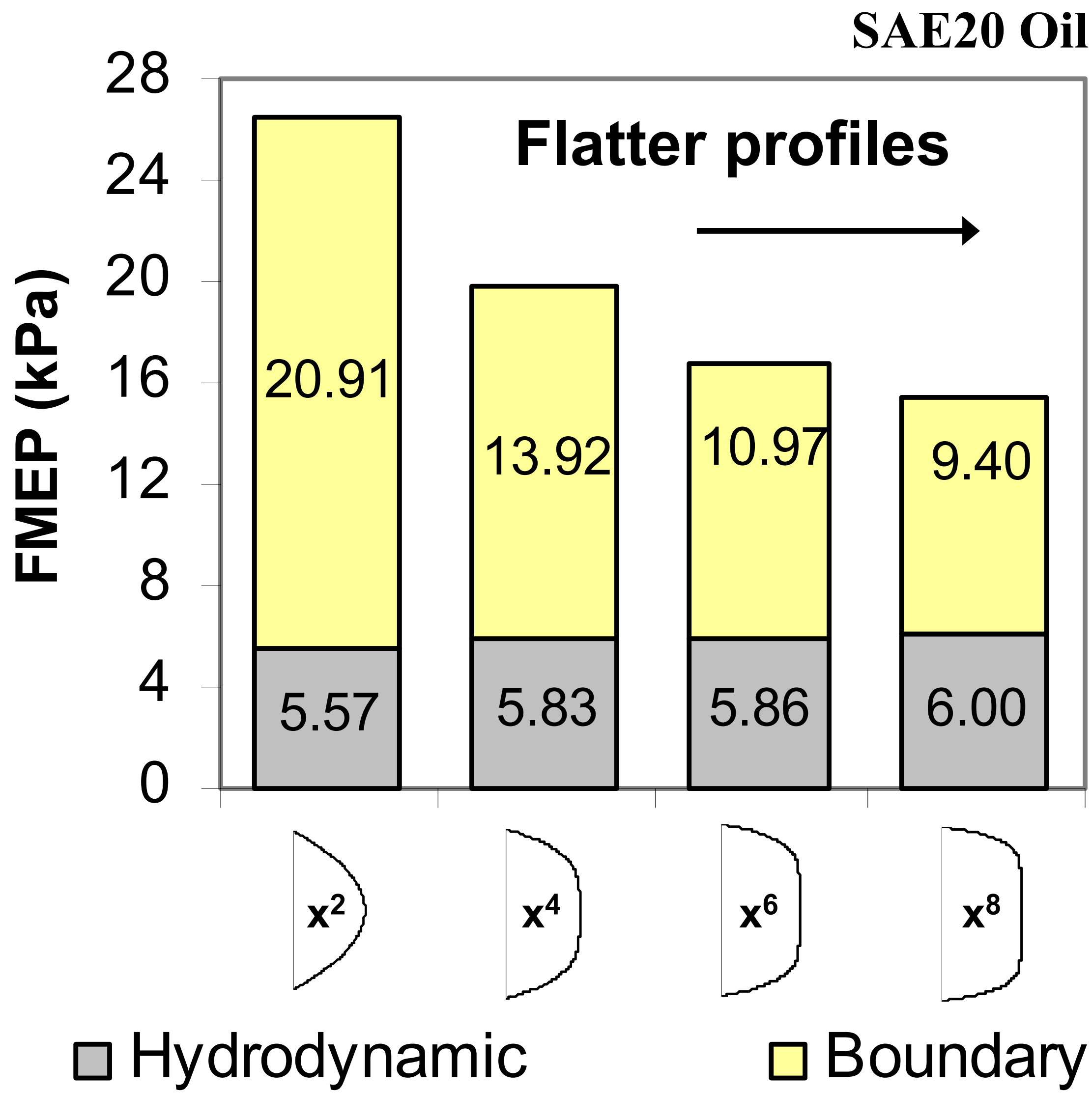
x^8 profile
(shallow curvature)

Cumulative Boundary Friction Work vs. Crank Angle (Thrust Side)

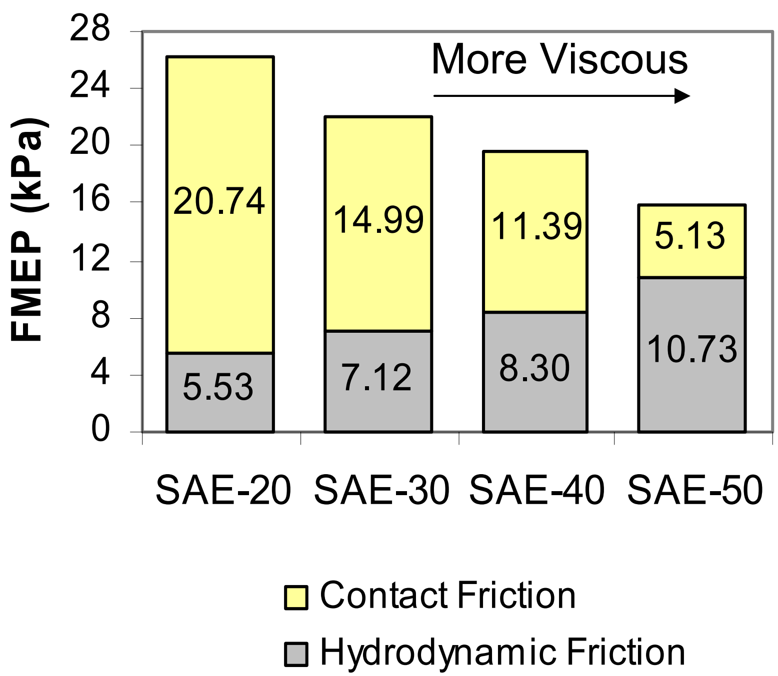


Effect of Piston-Skirt Profile on Piston Friction

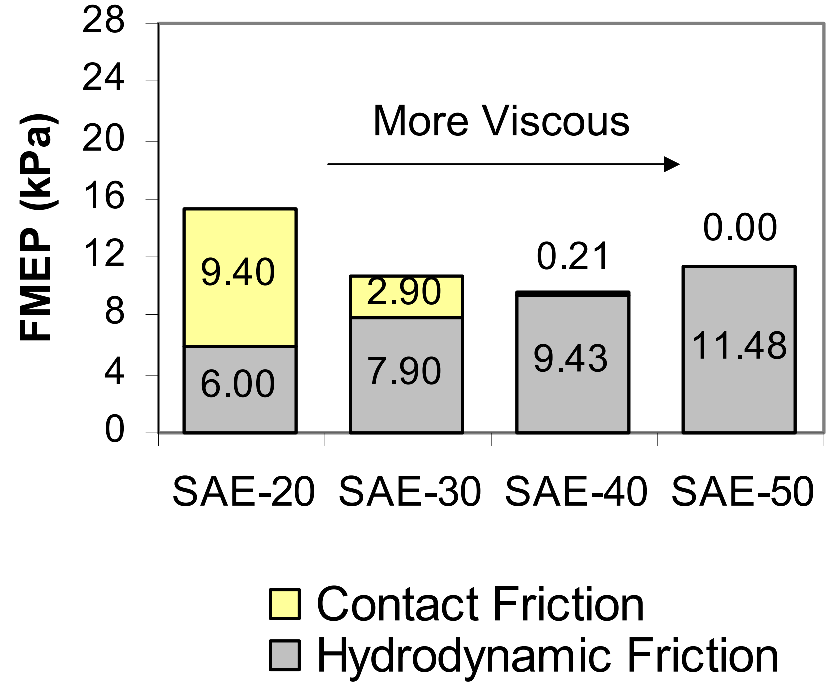
- Flatter profiles result in lower boundary contact and total friction
- Hydrodynamic friction changes only marginally



Effects of Oil Viscosity on Piston-Skirt Friction



Sharply-Curved Piston-Skirt Profile

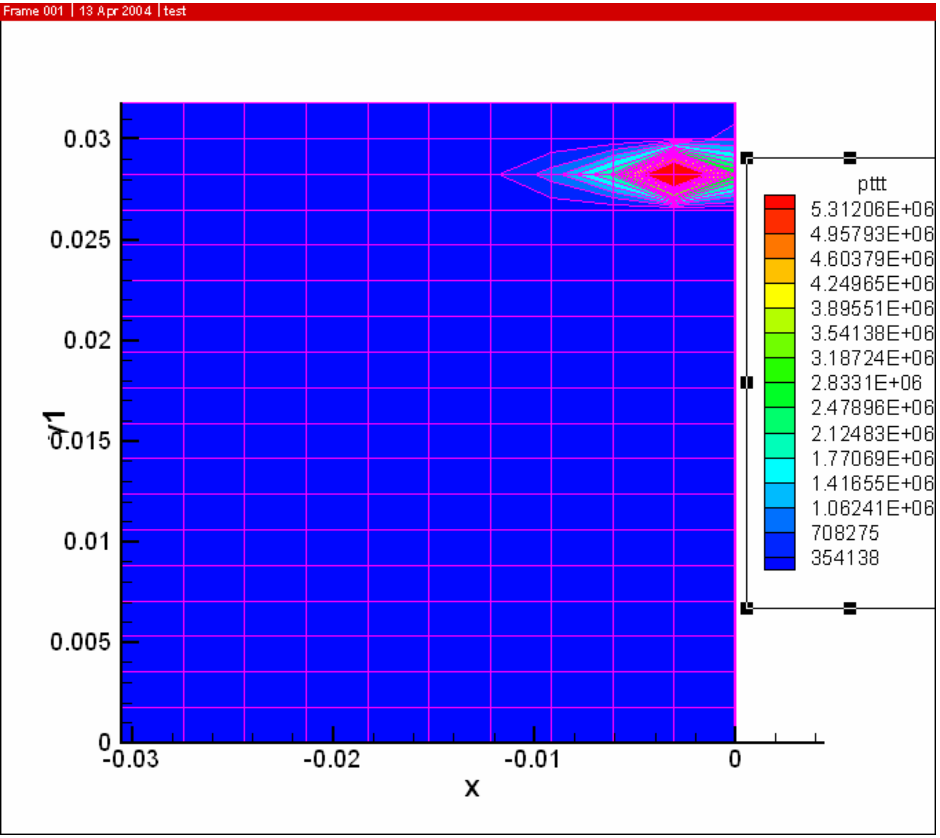


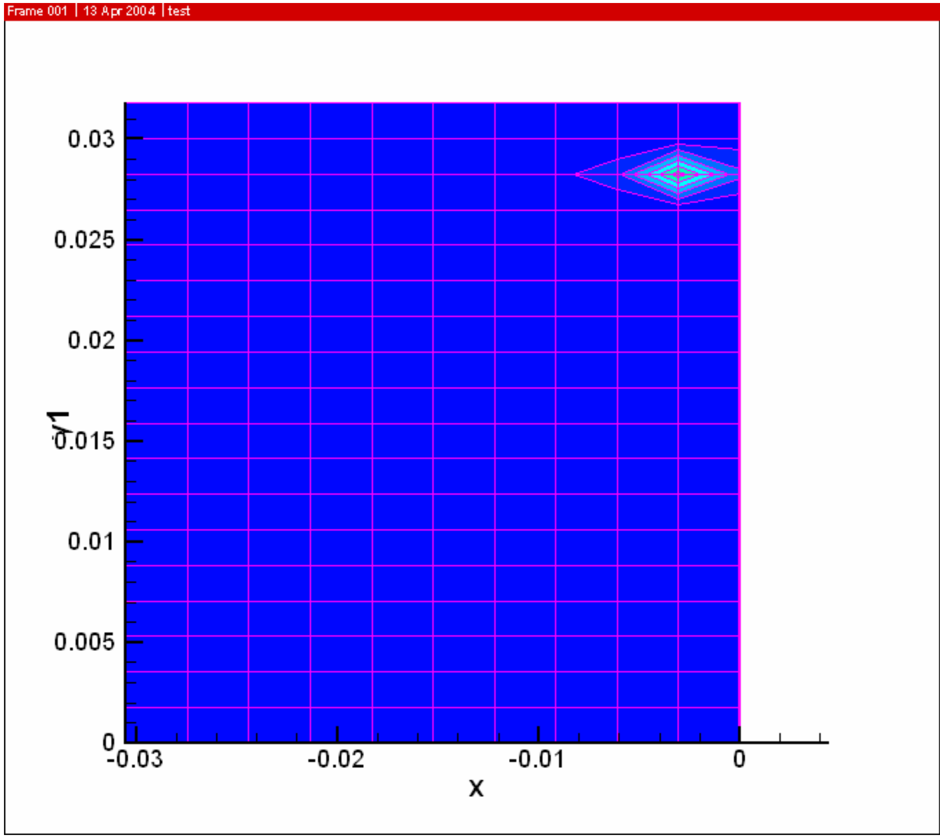
Very Flat Piston-Skirt Profile

- **Lower viscosity oils result in higher piston-skirt boundary and total friction. There appears to be an optimum viscosity for given mechanical design.**

Pressure Distribution on the Thrust Side

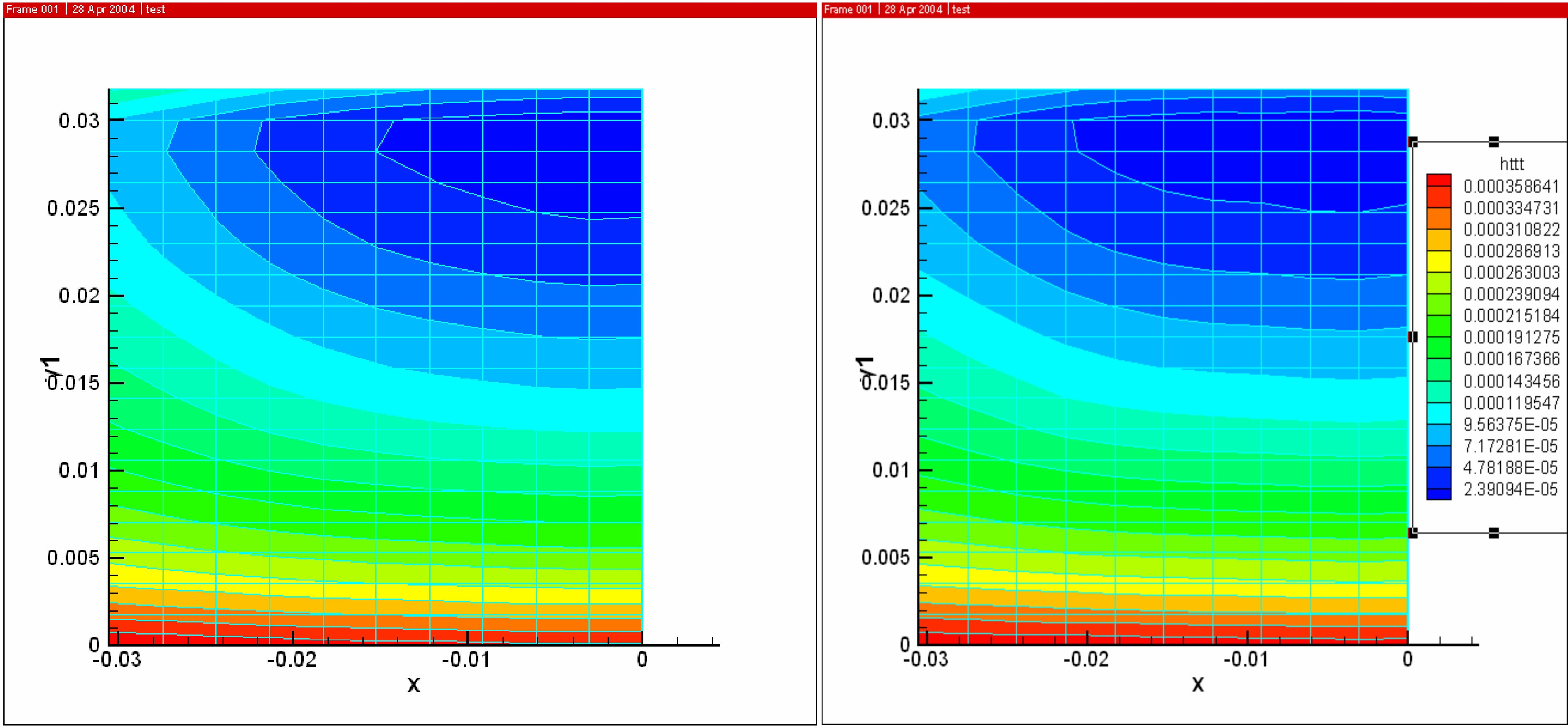
Reference Skirt 5 Times Flexible



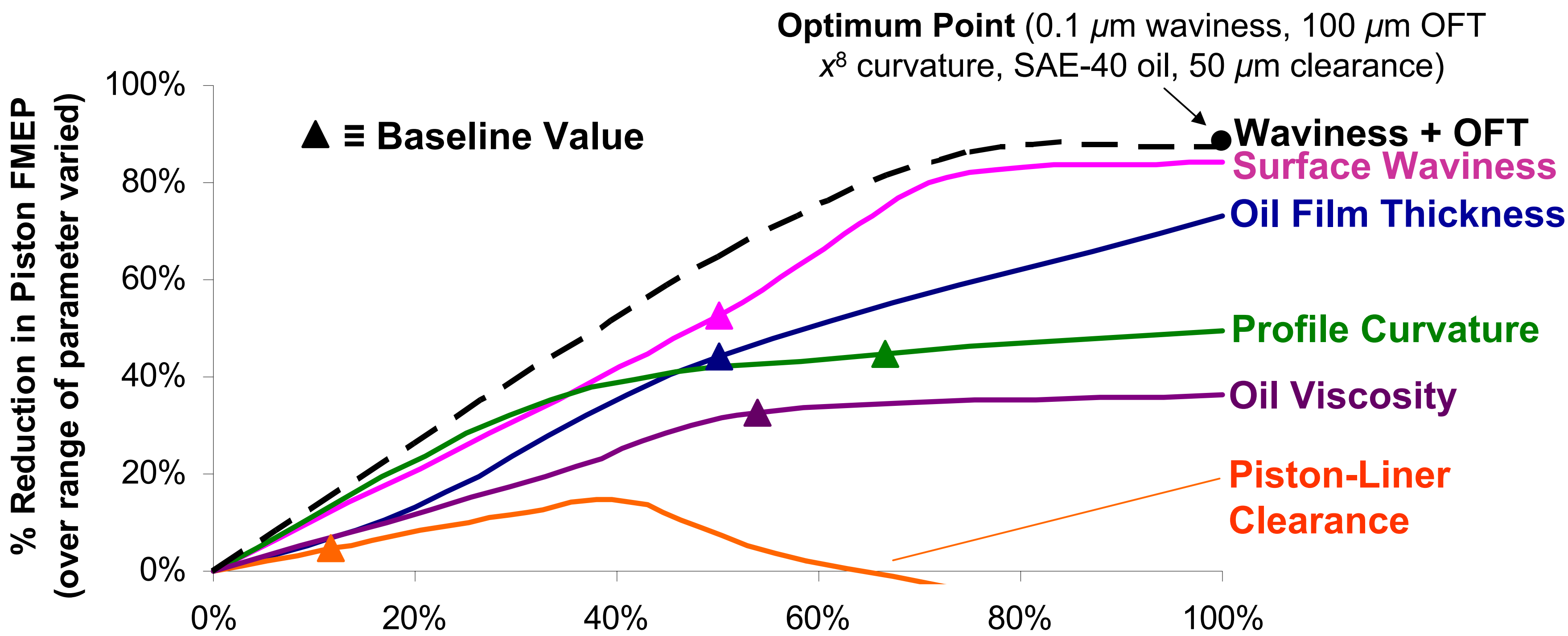


Distance between Skirt and Liner from 360 to 600 ATDC

Reference Skirt / 5 Times Flexible



Friction Reduction Potential of Design Changes



End of Range (0%)	% Change in Parameter	End of Range (100%)
20 μm	Surface Waviness	0.1 μm
0 μm	Oil Film Thickness	100 μm
x^2	Profile Curvature	Flattest (x^8)
0 μm	Piston-Liner Clearance	150 μm
8.1 cSt	Oil Viscosity (100° C)	20.4 cSt

Summary of Piston Friction Study

- Clearance between piston and liner shows a perceptible but mild effect on skirt friction

- Reduced skirt waviness and increased oil supply to skirt tend to reduce piston friction significantly

- A flatter piston-skirt profile (at given oil film thickness) decreases the tendency of solid-solid contact and thus reduces total piston-skirt friction

- A less viscous oil reduces hydrodynamic friction but tends to enhance boundary contact. Optimum viscosity for given mechanical design desirable

- A more flexible (less rigid) skirt reduces friction in a similar manner to a flatter skirt profile

LUBRICANT EFFECTS

on

RING-PACK FRICTION

Ring-Pack Friction Reduction

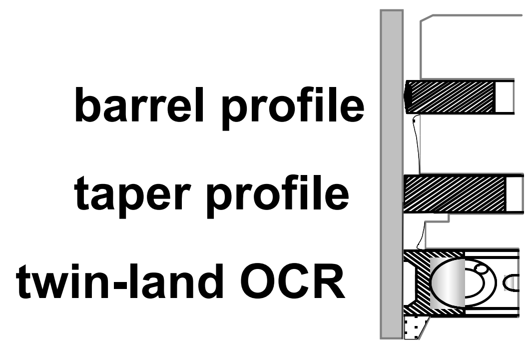
Ring-Pack Design Parameters:

- OCR tension
- Ring profiles
- Barrel skewness (top ring)
- Ring surface roughness

Ring-Pack Parameters:

Roughness:

Top Ring 0.3 μ
Oil Ring: 0.1 μ
Liner: 0.2 μ

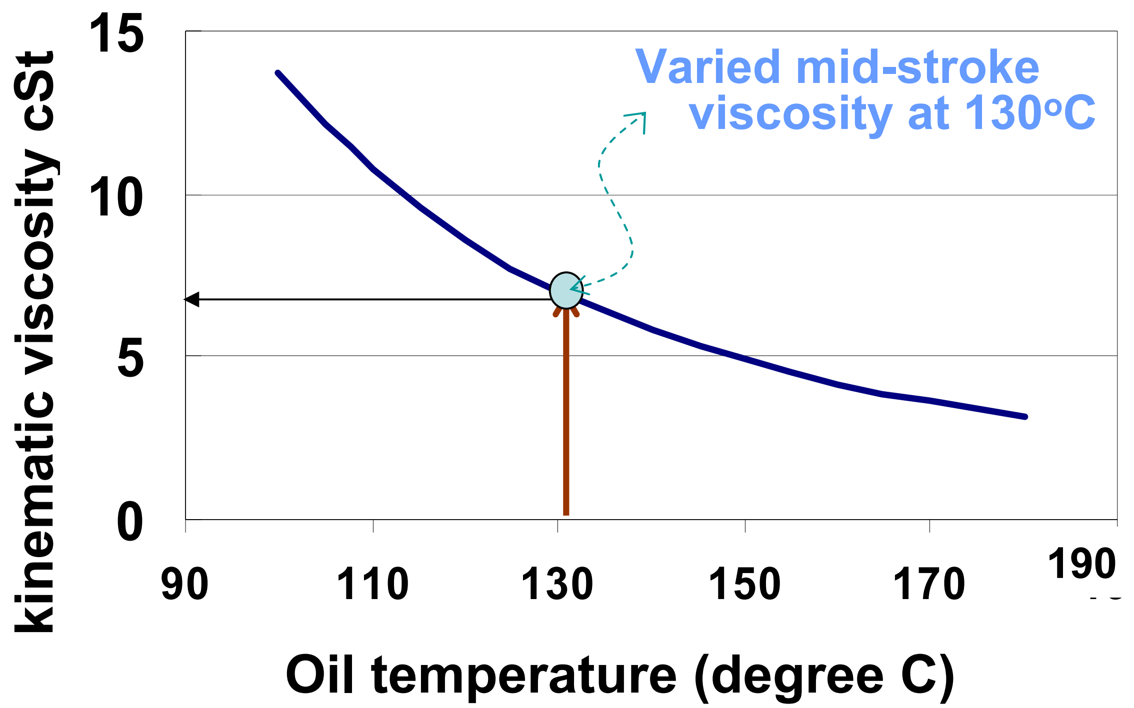


Lubricant parameters:

- Oil viscosity
- Boundary friction modification
- Temperature dependence of viscosity
- Shear dependence of viscosity

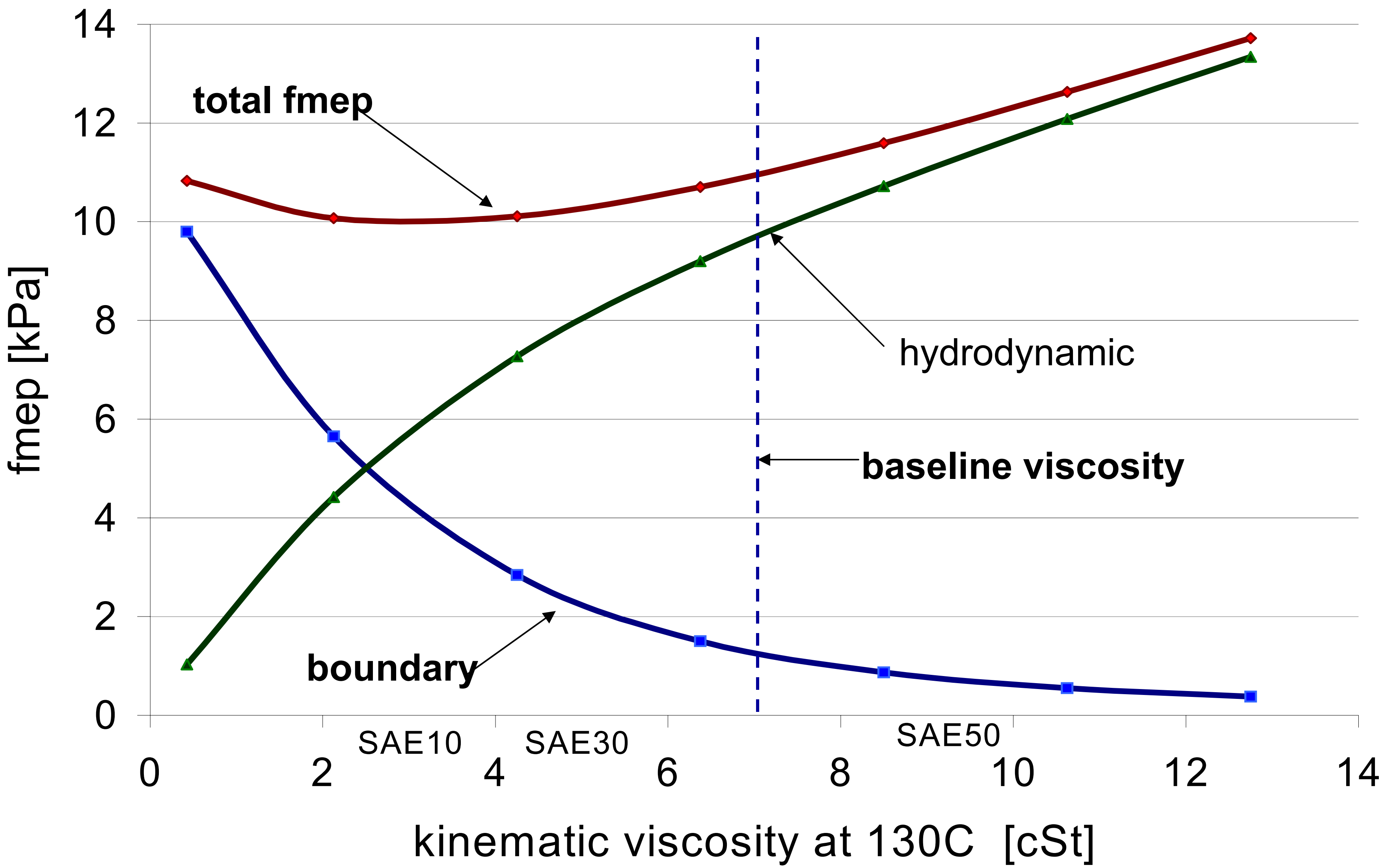
Lubricant parameters studied:

Varied viscosity (at 130°C)



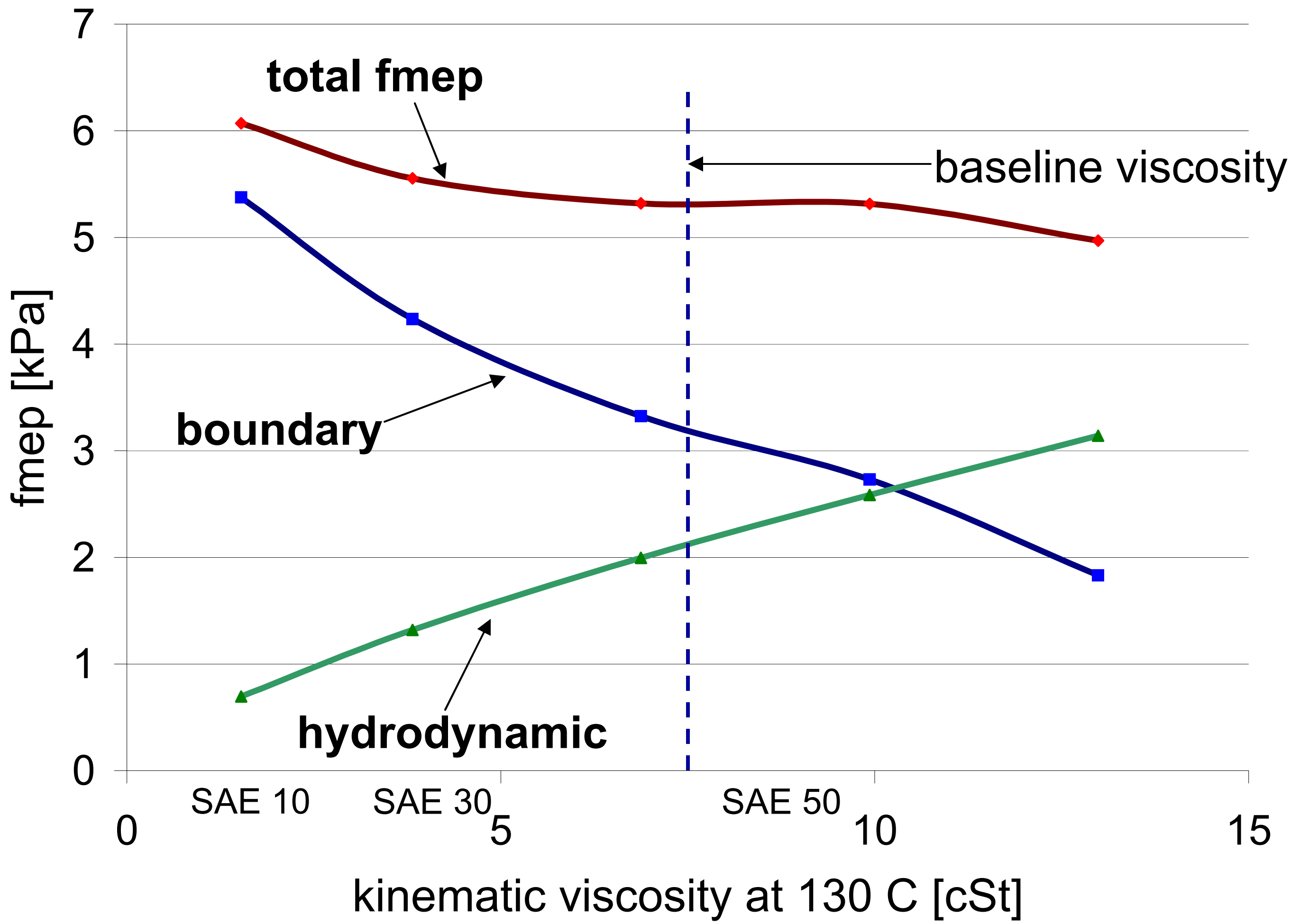
- Viscosity temperature dependence (gradient)
- Viscosity shear-rate dependence

Effects of lubricant viscosity on oil-control ring friction



Note tradeoff of boundary friction versus hydrodynamic friction
Total friction shows a minimum with viscosity

Effects of lubricant viscosity on top-ring friction

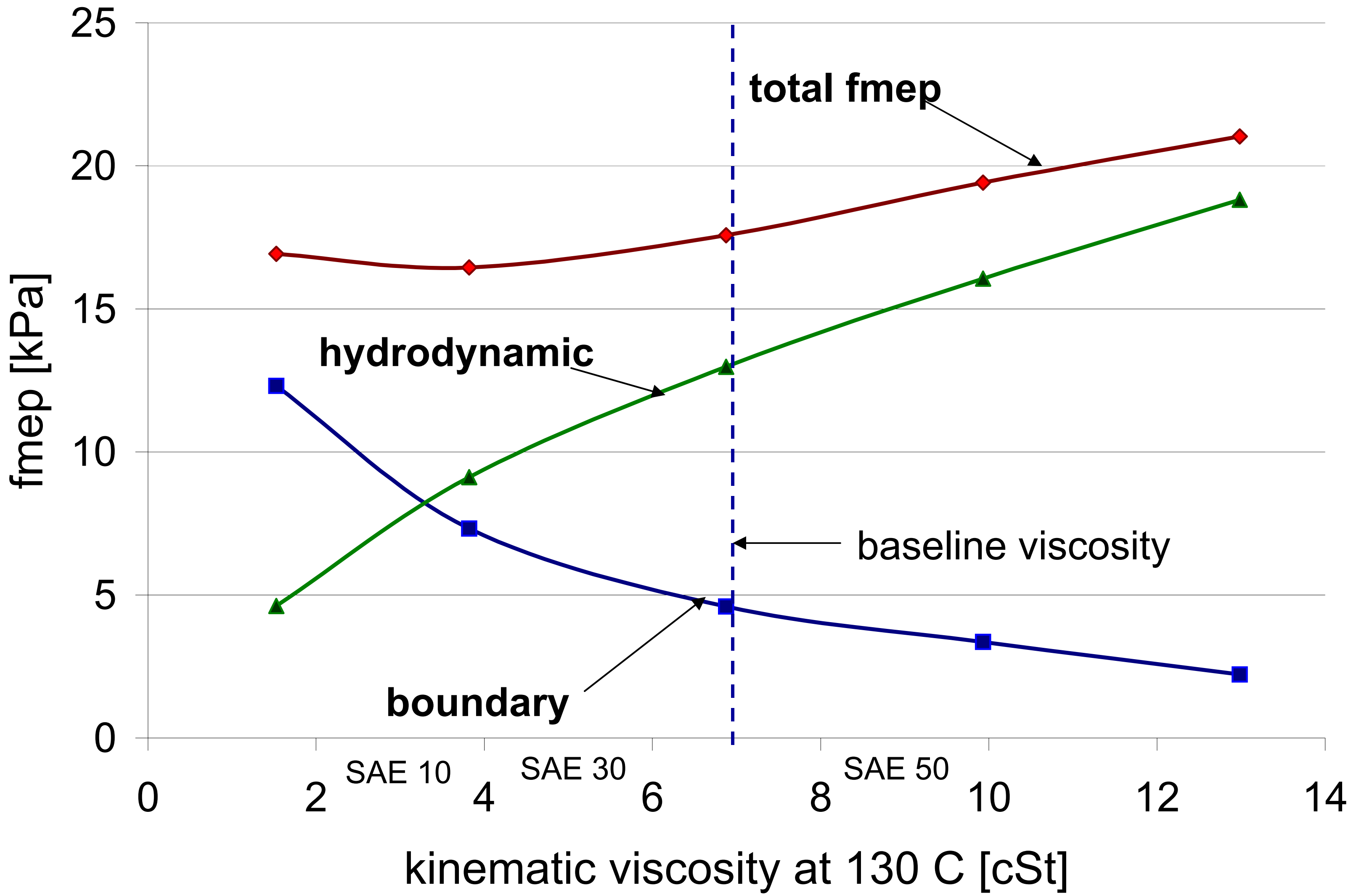


As viscosity increases: hydrodynamic friction increases

boundary friction can increase or decrease

overall friction may show a minimum, depending on conditions

Effects of lubricant viscosity on total Ring-Pack friction

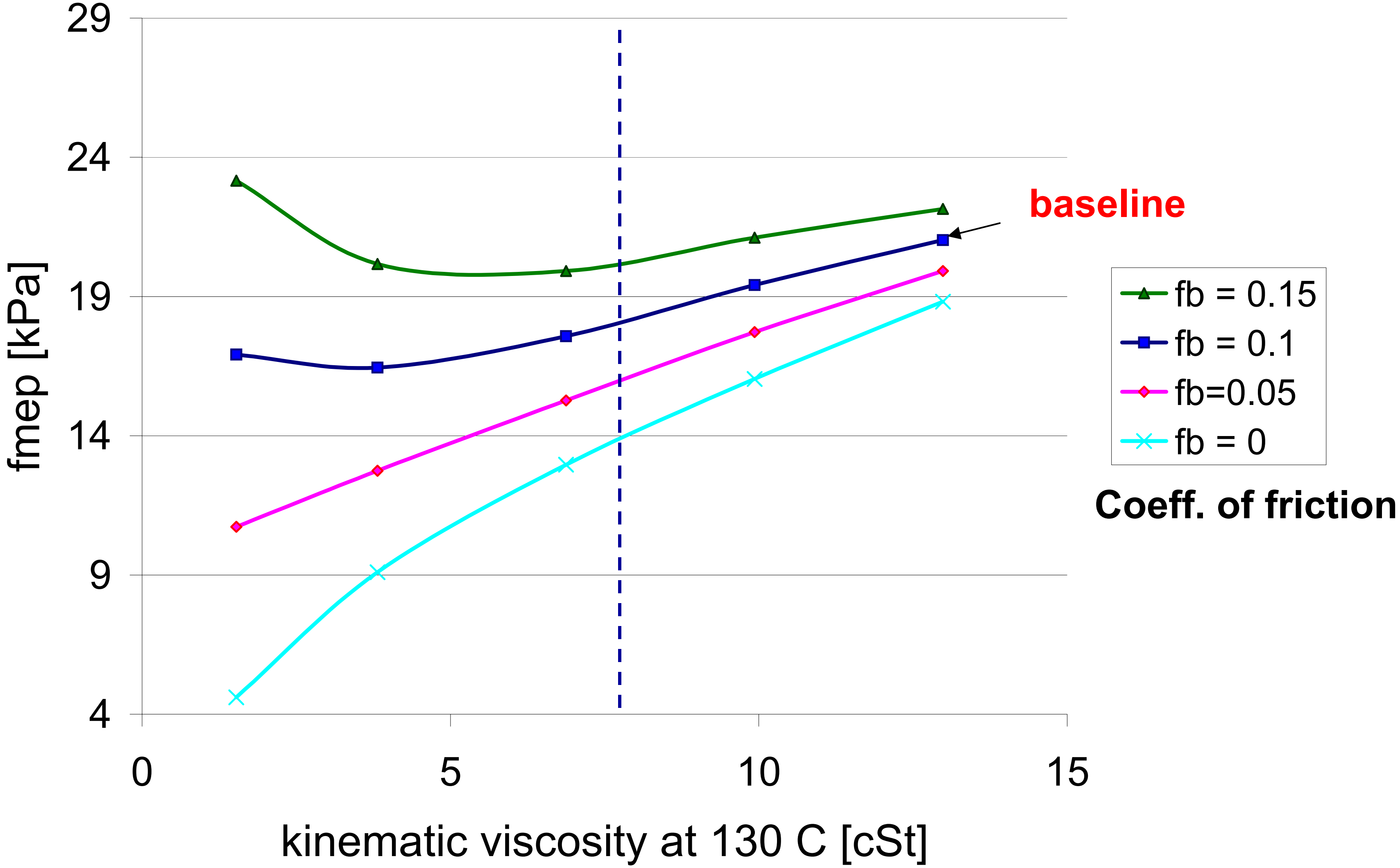


As viscosity increases: boundary contact decreases

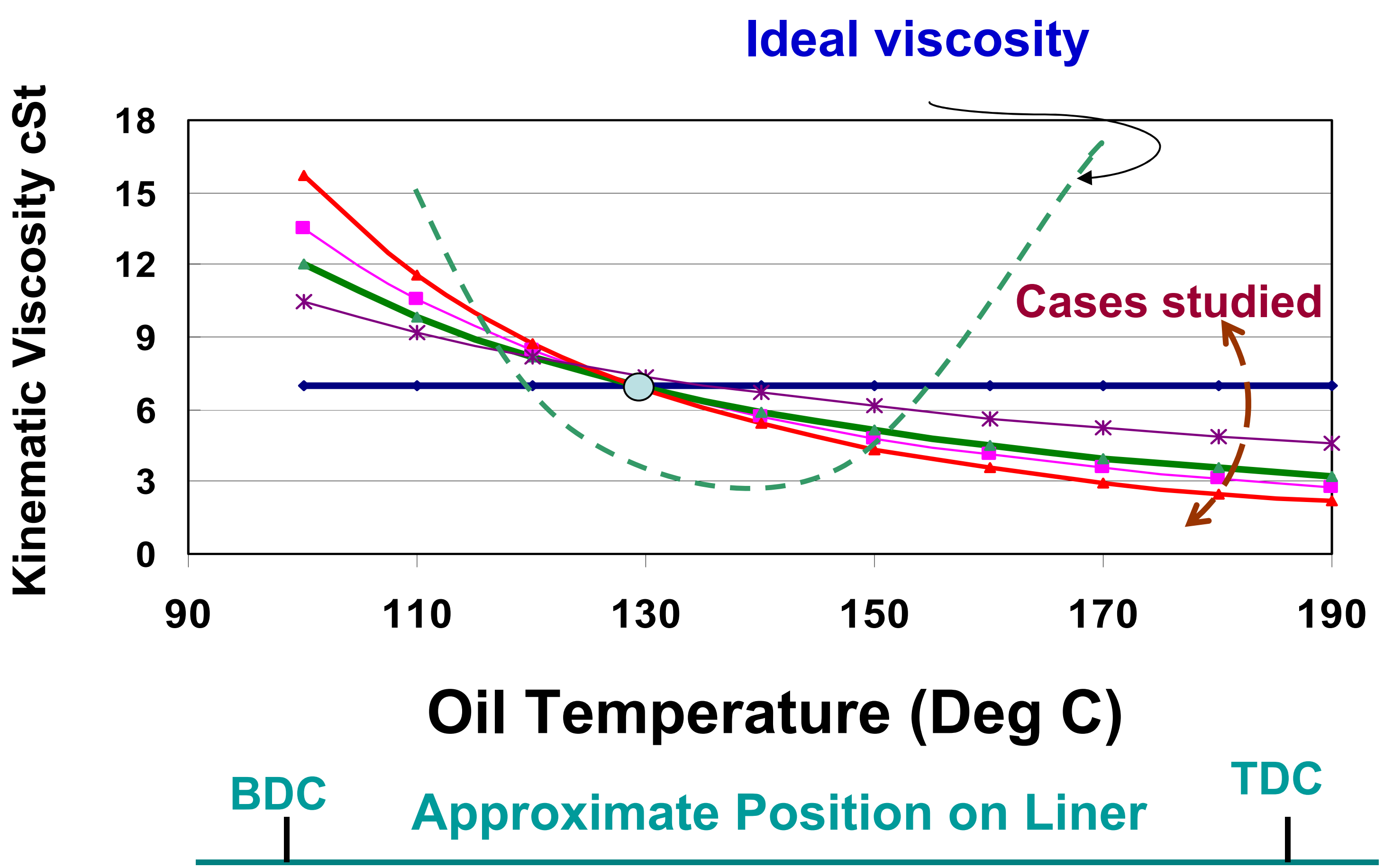
hydrodynamic friction increases

total friction may show a minimum with viscosity

Ring pack friction decreases with boundary friction coefficient

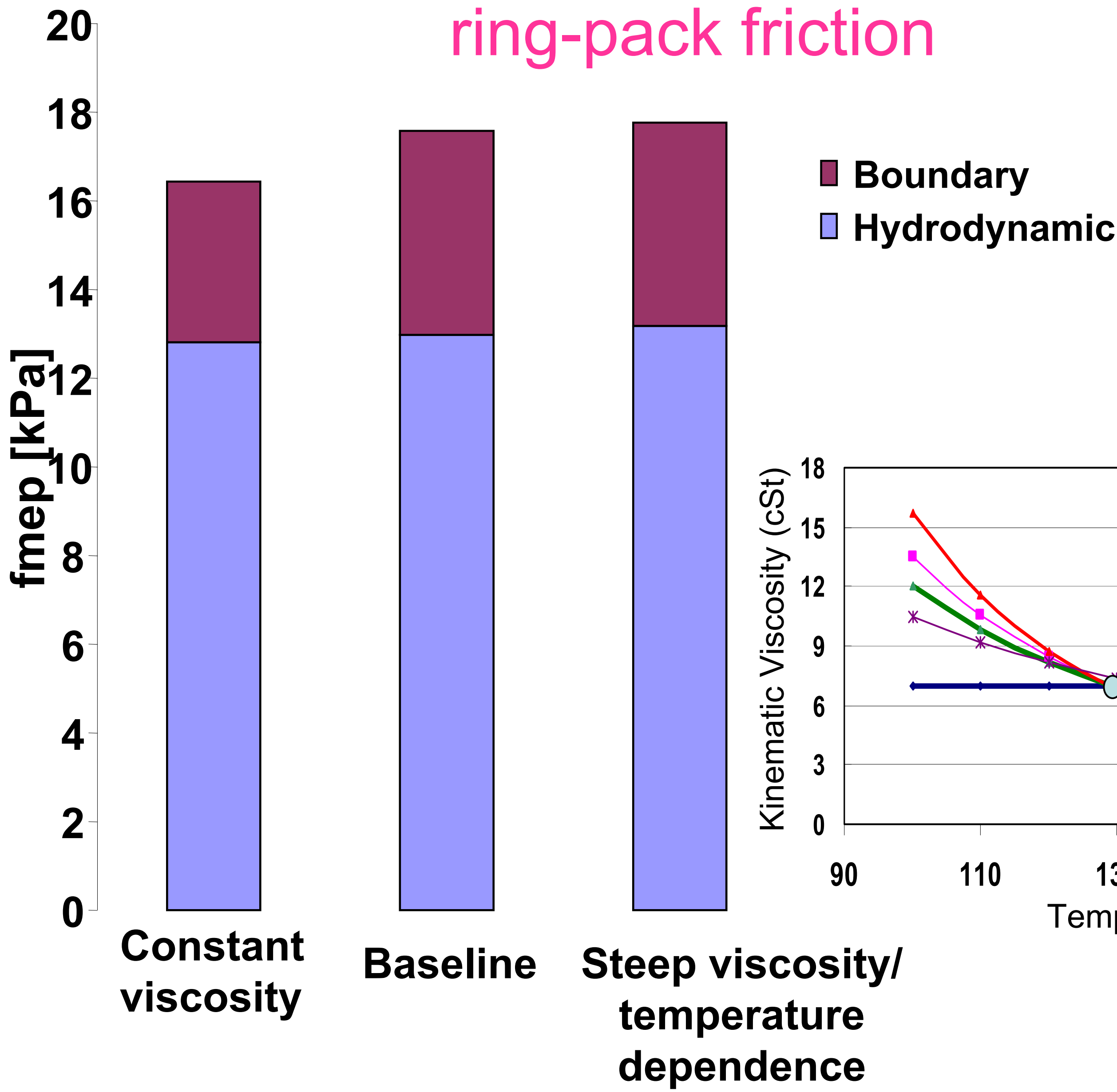


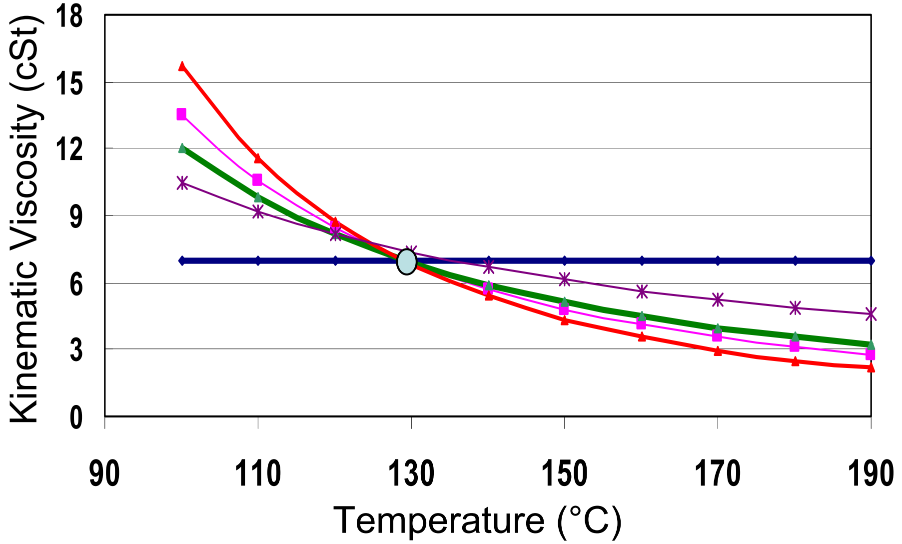
Effects of temperature sensitivity of viscosity (By changing slope of viscosity-temperature curve)



- Ideal viscosity should be low at mid-stroke and high at end strokes: either via lubricant design or component thermal management

Effect of temperature dependence of viscosity on ring-pack friction





Viscosity: shear rate dependence

- Cross equation:

$$\nu = \nu_0 \cdot \frac{1 + \frac{\nu_\infty}{\nu_0}\left(\frac{\gamma}{\beta}\right)^m}{1 + \left(\frac{\gamma}{\beta}\right)^m} \quad , \quad \beta = 10^{(c_1 + c_2 T)}$$

ν_0 = kinematic viscosity at zero strain rate

ν_∞ = kinematic viscosity at infinite strain rate

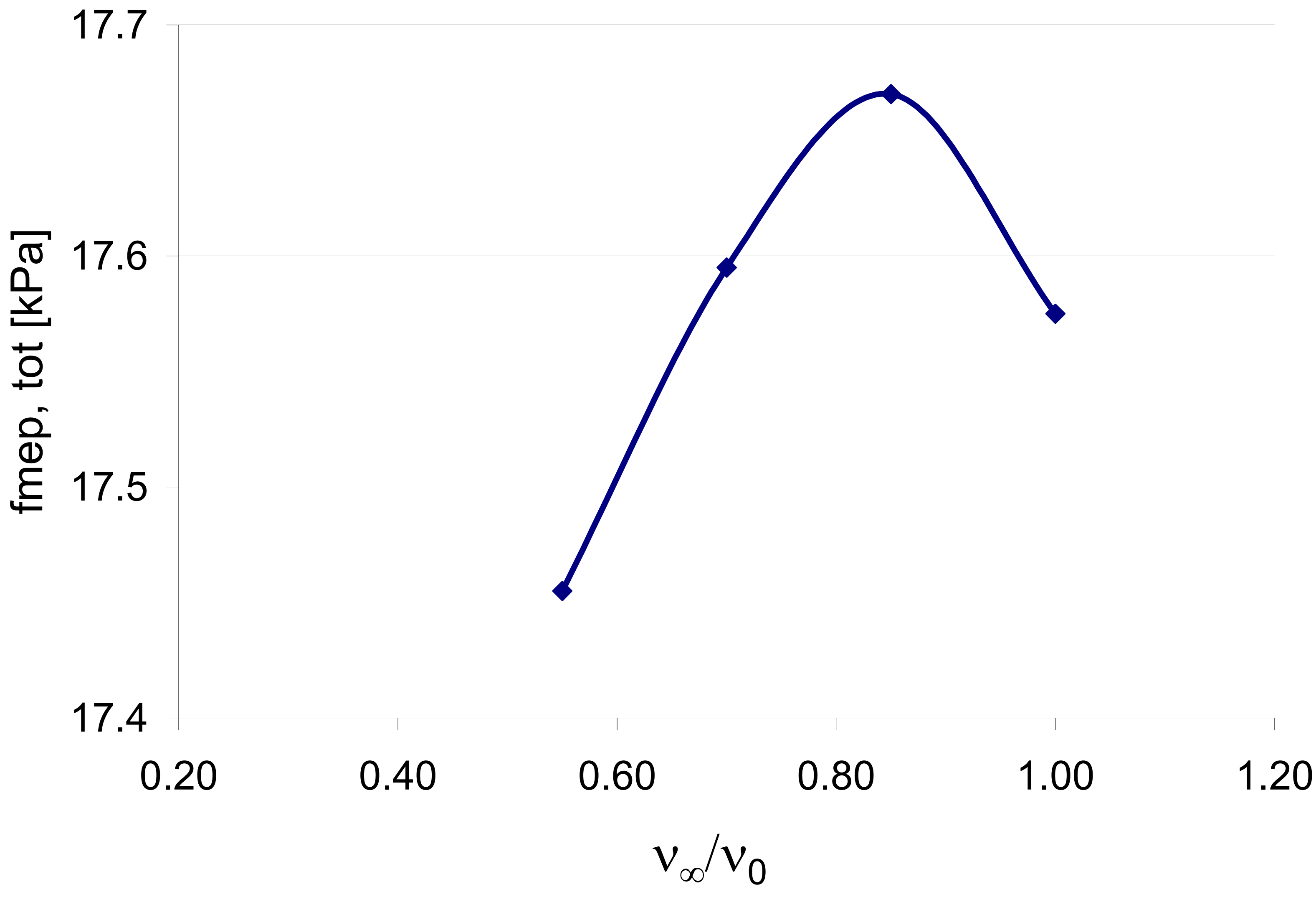
γ = lubricant shear rate

β = critical shear rate

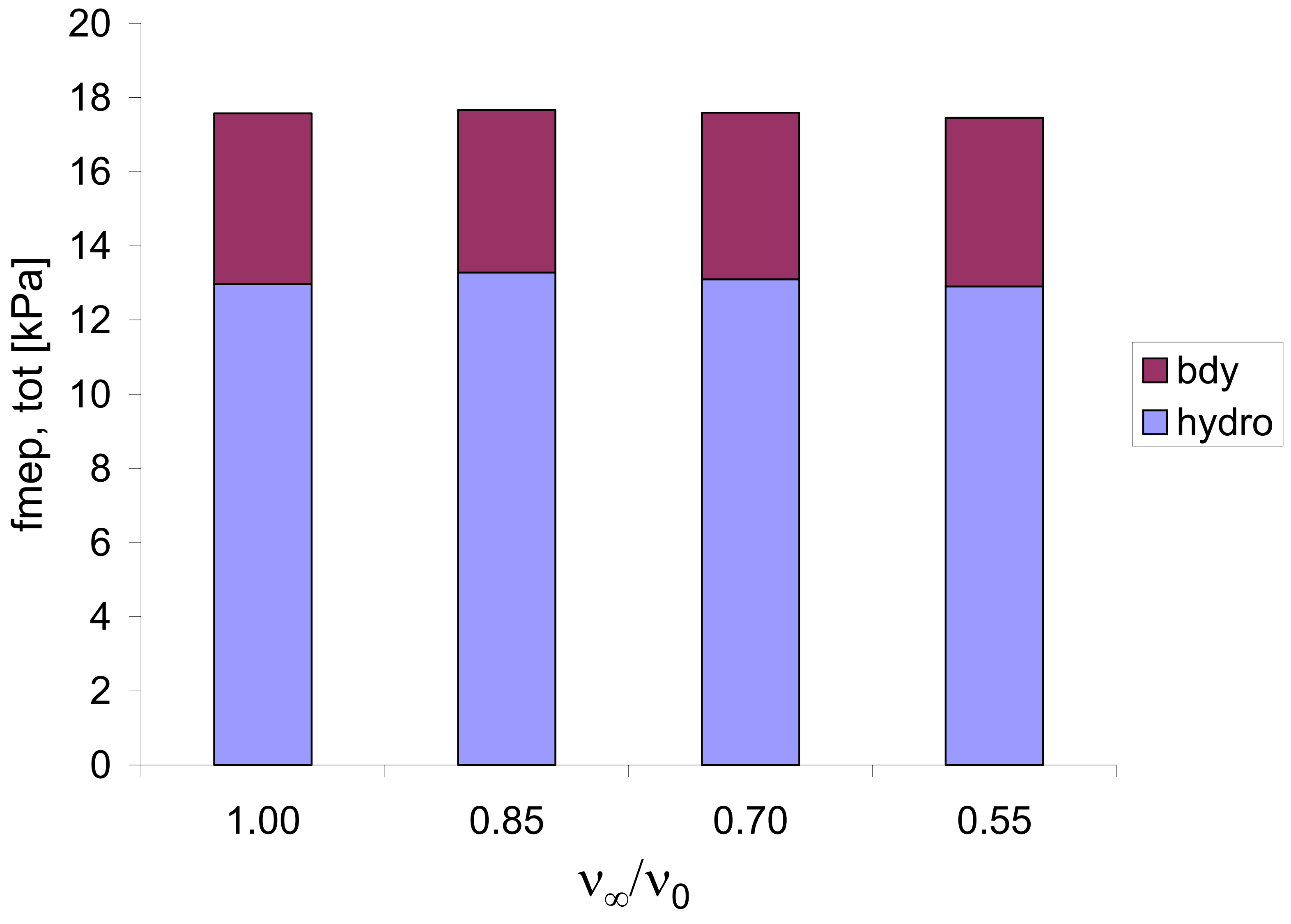
m = correlation constant; governs width of transition region

c_1, c_2 = correlation constants

Ring pack friction dependence on ν_∞/ν_0: total effect



Ring pack friction dependence on ν_∞/ν_0: total effect



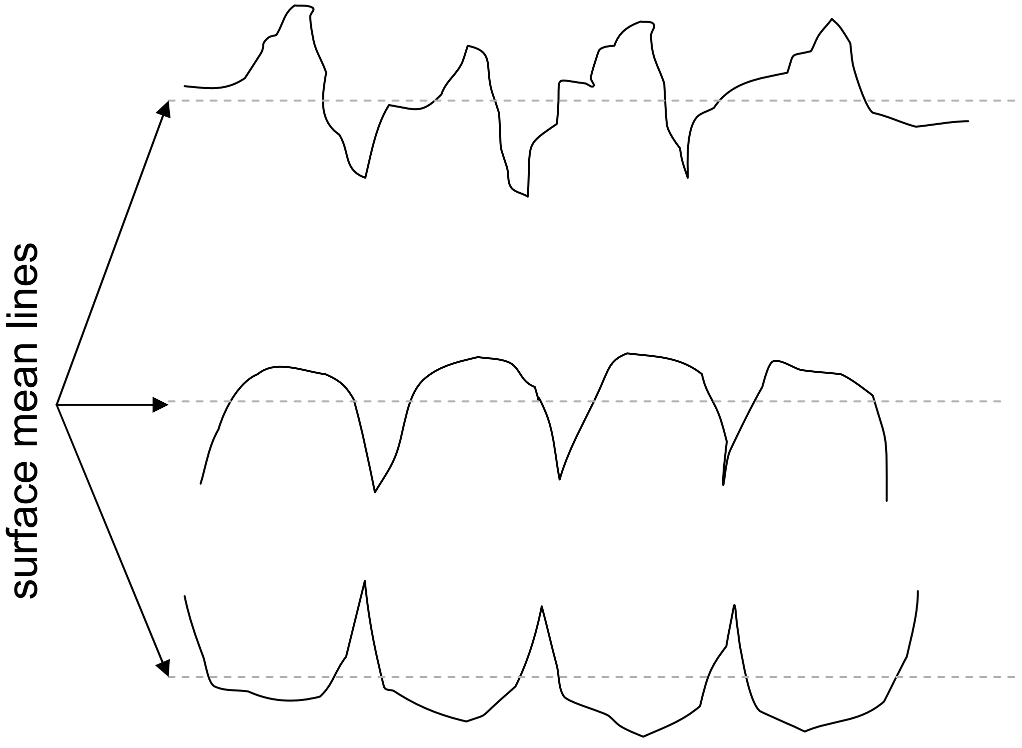
Summary: Lubricant Effects on Ring-Pack Friction

- An optimal range of viscosities for given mechanical design
- Shear thinning, temperature dependence & control, viscosity, and friction modifiers all affect ring-pack friction appreciably. However, additional potential improvement depends on the current baseline, *i.e.* how close we are to having optimized the oil and engine system
- An additional 10% ring-pack friction reduction via lubricants (towards 50% goal), above all other approaches, appears feasible

Effects of Cylinder Liner Surface Characteristics

- Surface Skewness
- Honing Cross-Hatch Angle

Statistically Characterizing Surfaces



Gaussian Surface - Symmetrical

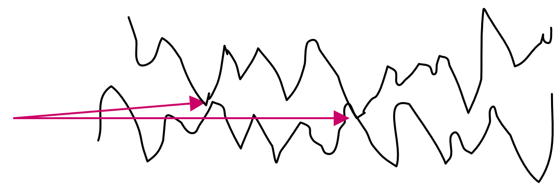
Negatively Skewed Surface

Positively Skewed Surface

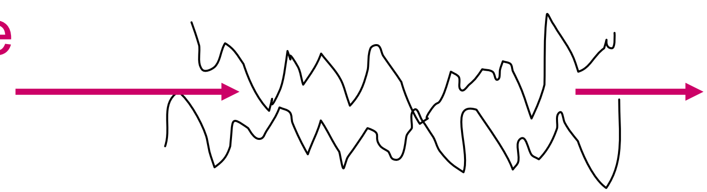
Surface Effects on Friction

Surface Characteristics affect friction in the following ways:

Asperity contact pressure affected

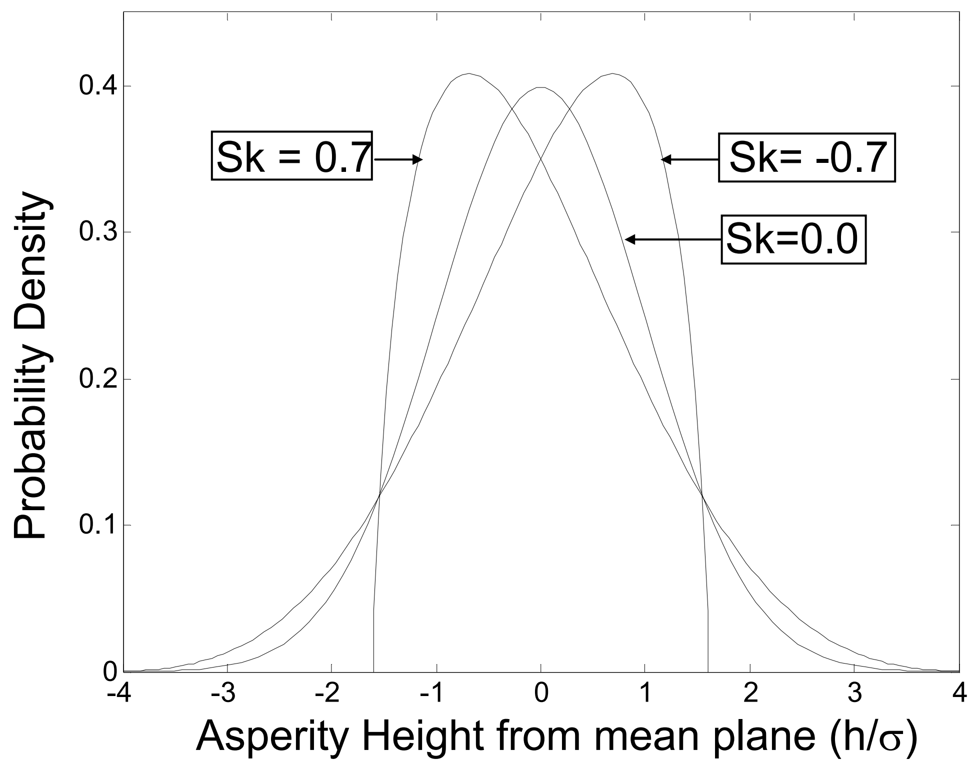


Flow resistance affected



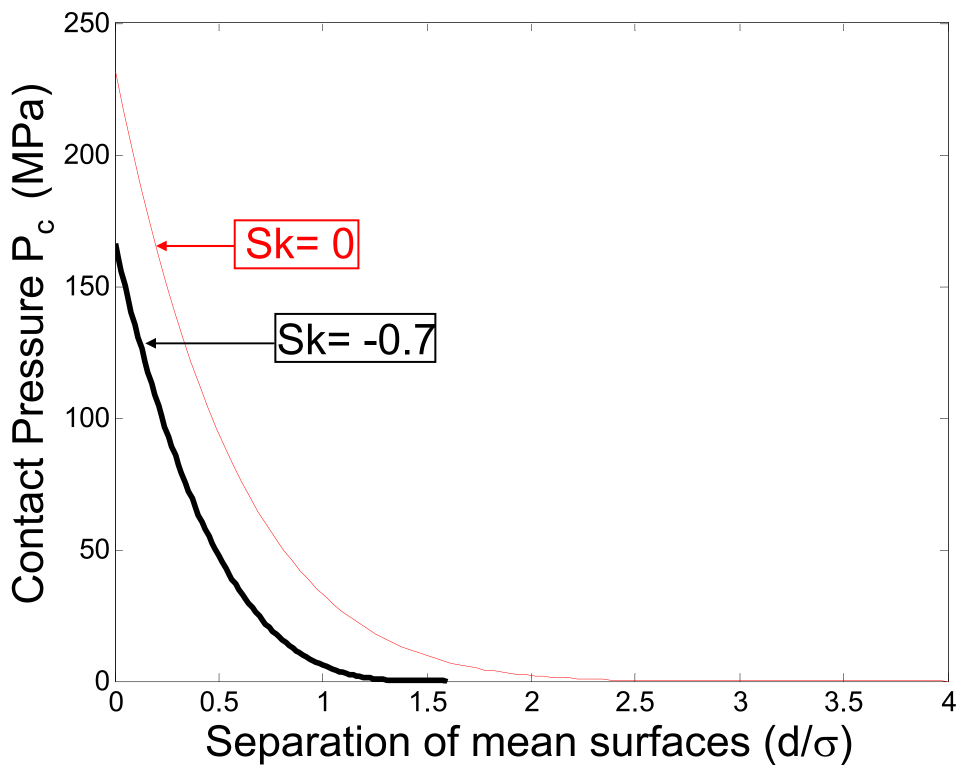
Non-Gaussian Surfaces

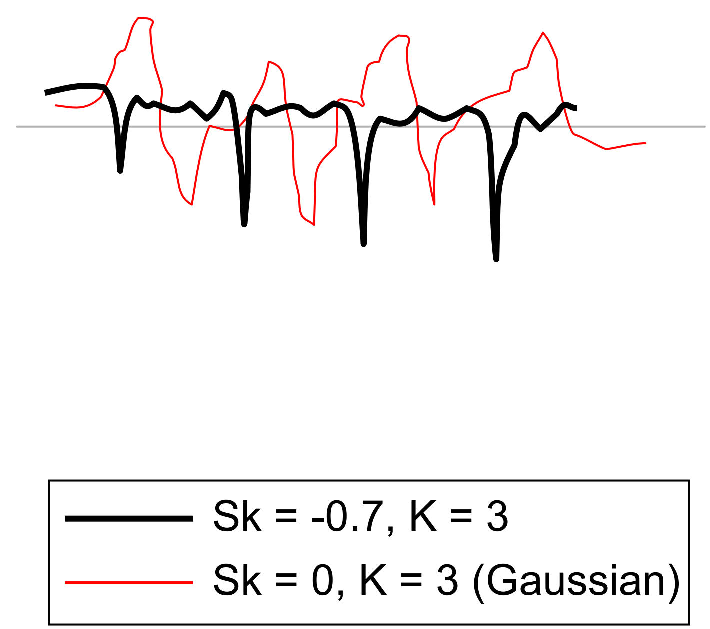
First, surfaces with different skewness are described by different probability density functions (PDF) for asperity heights



Non-Gaussian Surfaces

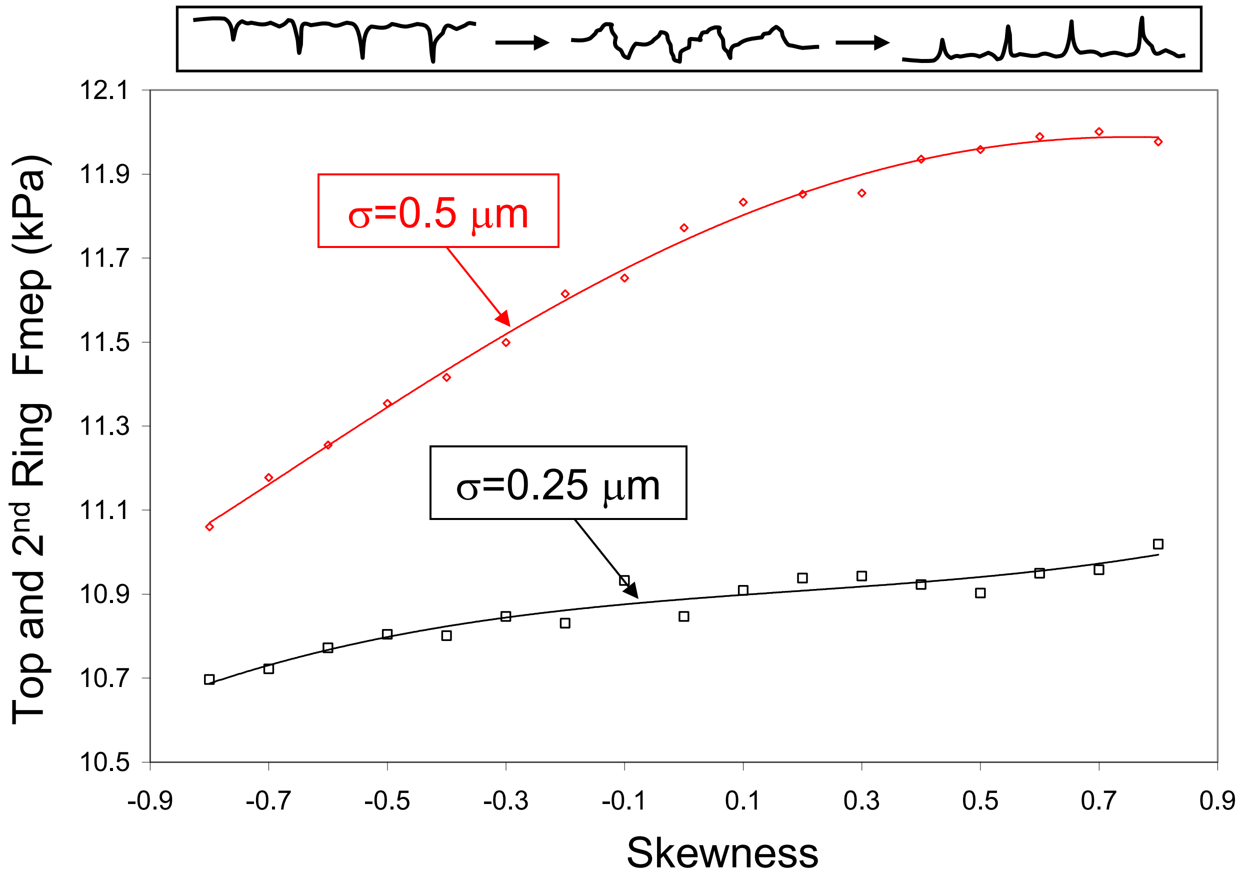
Then, the PDF (height distribution characteristics) are applied to contact pressure model to obtain the contact pressures





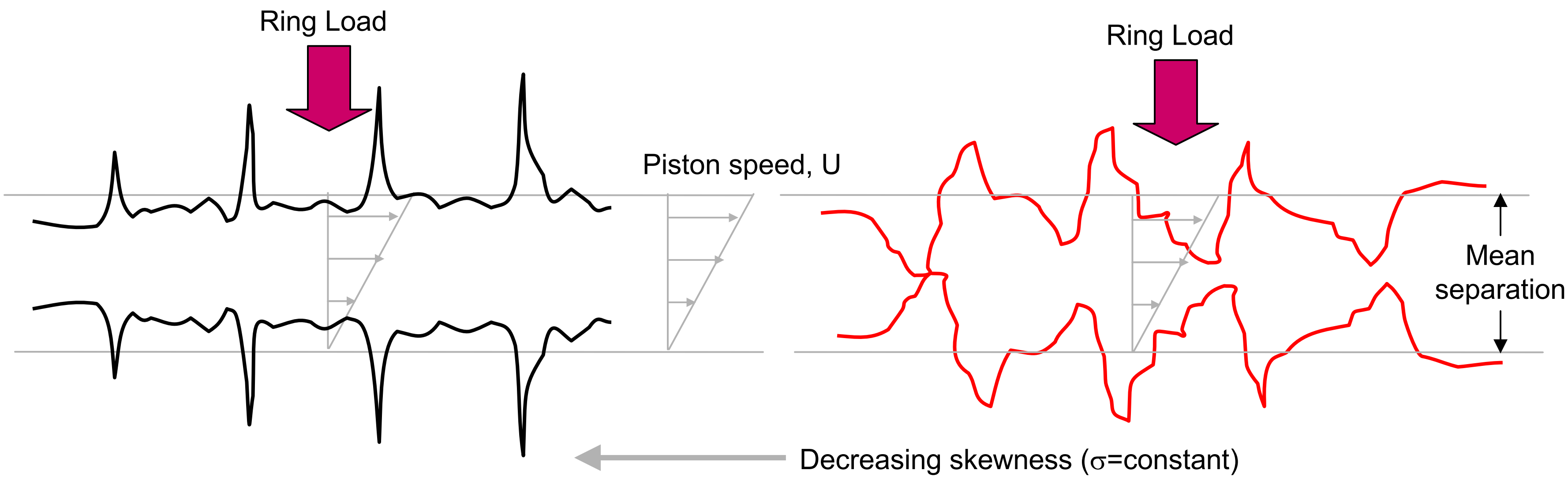
Results: Friction Surface Skewness

Decreasing skewness decreases ring pack friction primarily during mixed lubrication



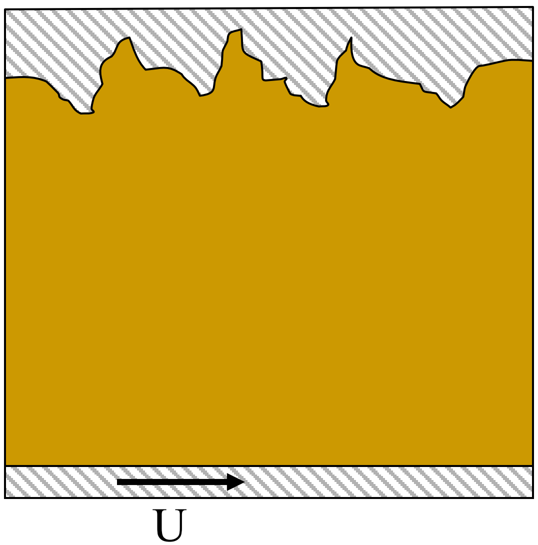
Explanation of Results: Boundary Contact

- Friction reduction will be realized in the mixed lubrication regime



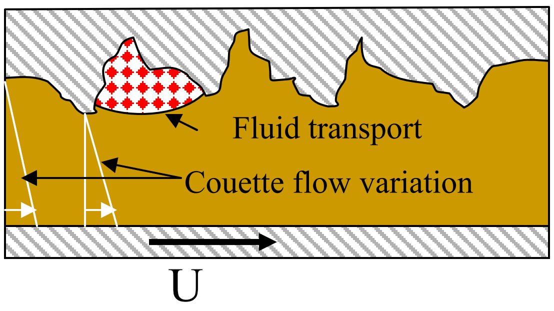
- When surface skewness decreases, hydrodynamic pressure will carry an increasing proportion of the total ring load
- Increasing the relative proportion of the load supported by hydrodynamic pressure will reduce friction

Flow Factor Effect on Friction



• At large separations, flow factors have little effect

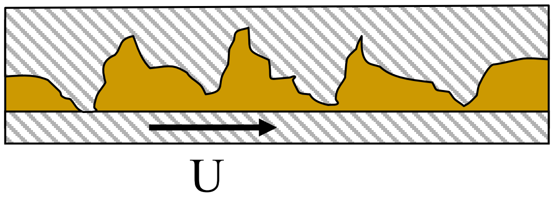
• Smooth surface solution applies



• As separation decreases, effect of surface roughness increases

• Shear flow factor reflects fluid transport in valley of roughness

• Pressure flow factor reflects pressure-driven flow blockage due to rough surface

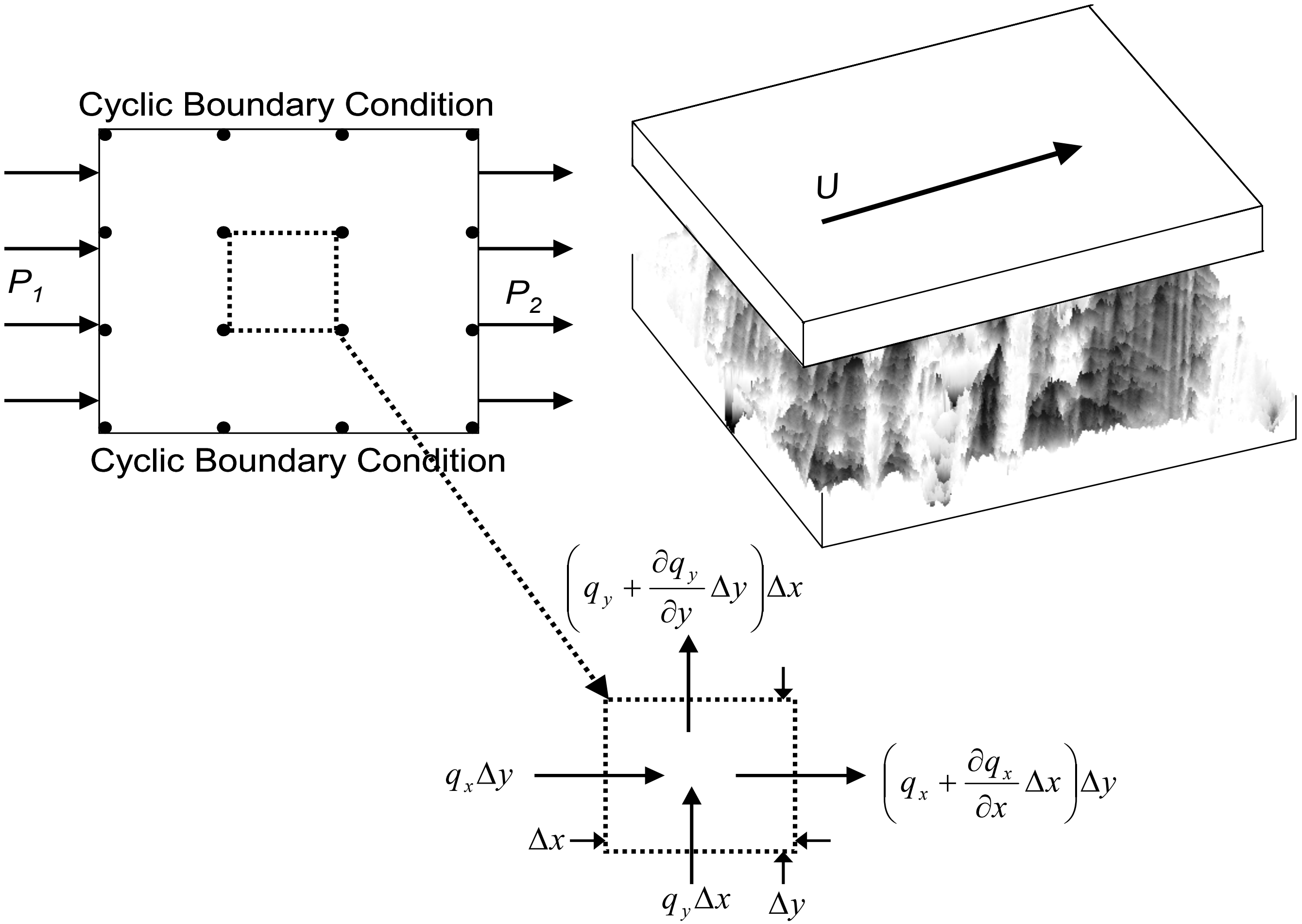


• At small separations, effect of surface roughness dominates

• Flow in valleys very important

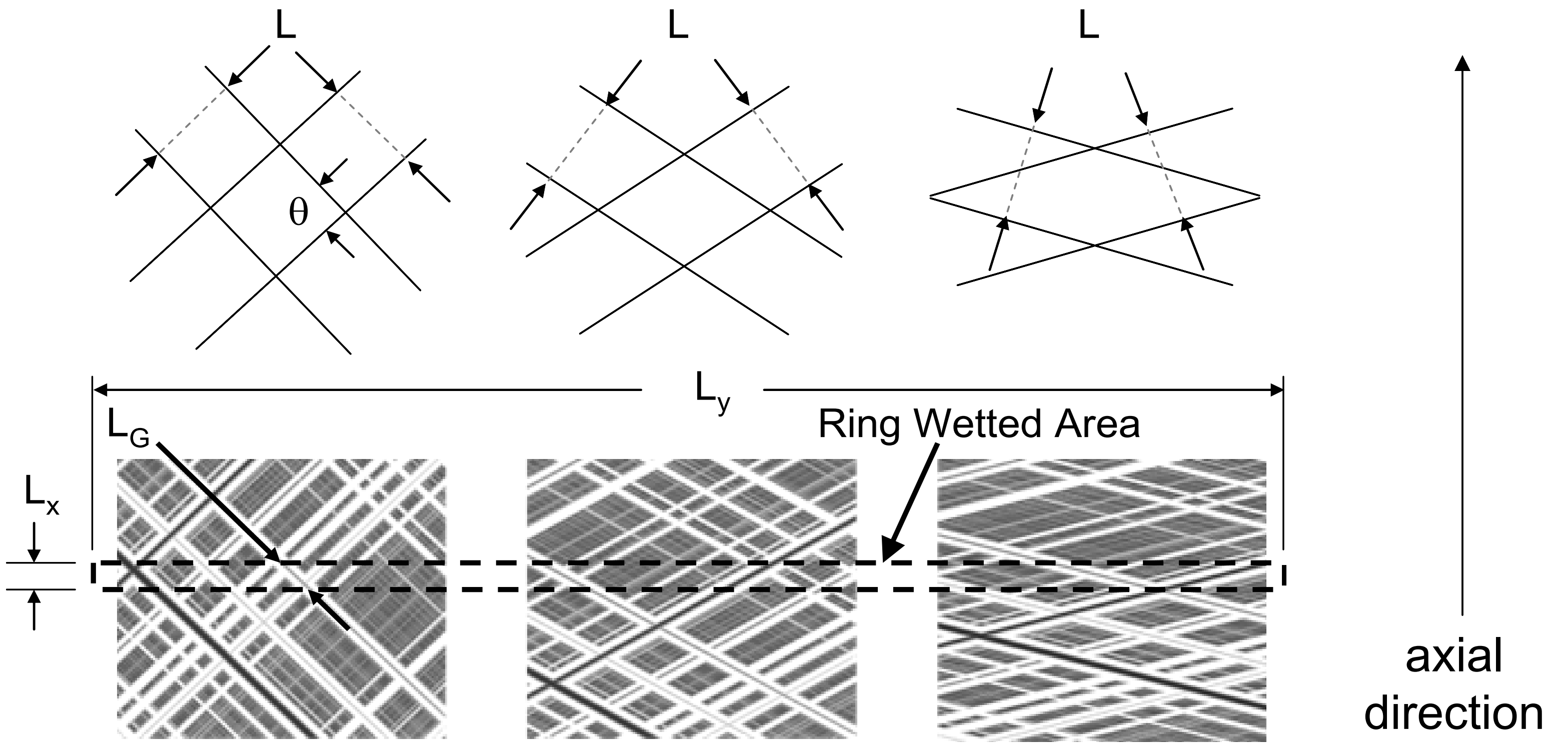
• Complete flow blockage can occur

Flow Factor program



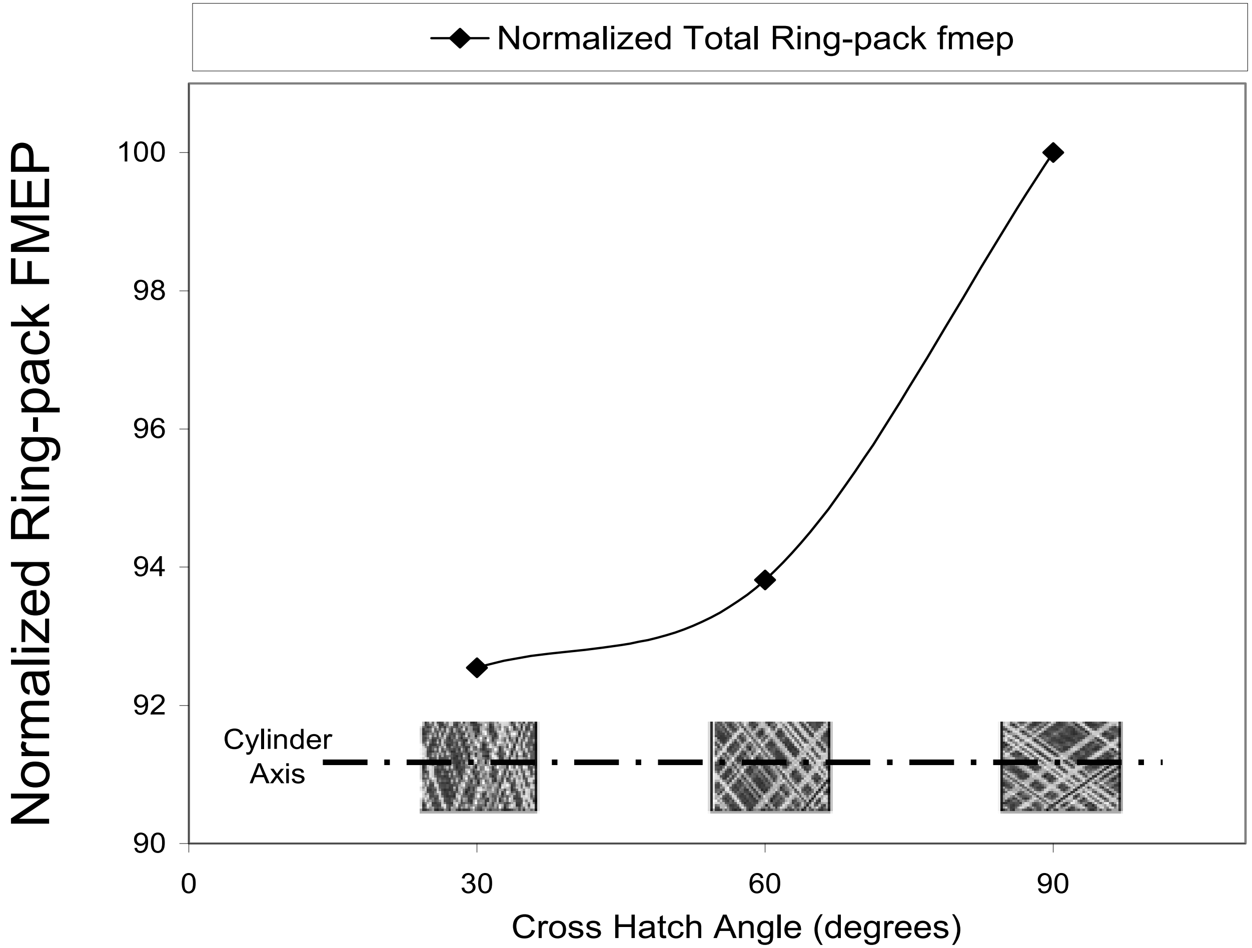
Cross-hatch angle

• Surface generator used to simulate surfaces with different honing angles, using same honing process
• A lower cross-hatch angle corresponds to hatch marks more perpendicular to the flow direction



90° Cross-hatch 60° Cross-hatch 30° Cross-hatch

Reducing honing cross-hatch angle **reduced** predicted friction



- Less asperity contact occurred because the more perpendicular grooves increased flow resistance, generating more hydrodynamic pressure

Summary: Surface Effects

Skewness

- 5% friction improvement max in practice

Honing Cross-Hatch Angle

- 5-10% friction improvement extent

Actual Benefits

Combine with liner surface roughness design

Summary of Progress To Date

- Tests on full-scale Waukesha engine at CSU measured friction reduction of 30% with low-friction OCR design. Additional confirming experiments are continuing

- There appears to be an optimal viscosity for total ring-pack friction due to the tradeoff between hydrodynamic and boundary friction, as both phenomena occur in the engine cycle

- Piston Skirt Profile studies show preferred profile shapes, which vary with selected lubricant properties

- Surface textures with transverse grooves perpendicular to flow can provide friction benefits

Continuing Research

✓ **Continue experimental validation of reduced friction piston/ring designs on full-scale Waukesha engine at CSU:**

- Development of practical designs to reduce piston and ring friction for experimental validation on a natural-gas engine

- Detailed investigation of the impact of material and lubricant effects on friction

Immediate Work Plan:

- **Piston Design**
- **Surface/Material Application**
- **Lubricants**

Progress Towards DOE Objectives

Technical Impact

- Friction reduction of 30-50% power-cylinder friction translates to 2% engine efficiency or 5% fuel economy improvement
- Simple component replacements. No additional parts
- No additional cost anticipated

Educational Impact

- Students carried out research and testing towards program goals, attended conferences and published papers (5) to promote research

Technology Transfer with other University Team(s) and Industry

- Monthly phone conferences and semi-annual meetings with Waukesha
- Started technical alliance with Purdue and engine manufacturers for periodic interactions (possible student exchanges/internships)

Project Team

Project: Low-Engine-Friction Technology for Advanced Natural Gas Reciprocating Engines

Laboratory for Energy and the Environment
Massachusetts Institute of Technology
Faculty/Staff: Victor W. Wong, T. Tian, J. Heywood,
Graduate Students: G. Smedley, J. Jocsak, L. Moughon, R. Takata

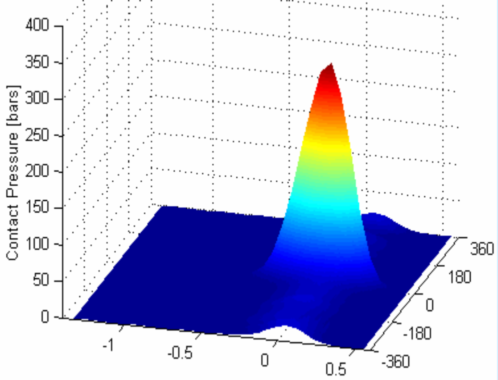
Sub-Contractor:

Engines and Energy Conversion Laboratory
Colorado State University
Faculty/Staff: Bryan Willson, Rudy Stanglmaier,Ted Bestor
Graduate Students: Nathan Lorenz , K. Evans, K. Quillan
Undergraduate Student: Travis Mathis

With support from
Waukesha Engine Dresser, Inc.

Edward Reinbold, Rick Donahue, Jim Drees

Questions?



Project: Low-Engine-Friction Technology for Advanced Natural Gas Reciprocating Engines