A Compressible Hydrodynamic Analysis of Journal Bearings Lubricated with Supercritical Carbon Dioxide

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5^{th} International SCO2 Power Cycles Symposium

- Introduction
- Viscosity and density
- Journal Bearings and Reynolds equation
- Numerical results
- Gas-foil bearings
- Summary, conclusions

OUTLINE

- Sandia National Labs
- SCO2 Hydrodynamic bearings
- Gas-foil bearings

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Closed Brayton Cycle

- *Sandia National Laboratory*
- SCO2 as the working fluid
- Liquid like density of SCO2,
- Less pumping power required in compressor
- Significant increase of the thermal-to-electric energy conversion efficiency
- Would replace traditional steam Rankine cycles.

http://energy.sandia.gov/energy/renewable-energy/supercritical-co2

Goal:

"By the end of FY 2019, Sandia National Laboratories shall develop a fully operational 550˚C, 10 MWe R&D Demonstration s-CO2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology."

Challenge (one of them):

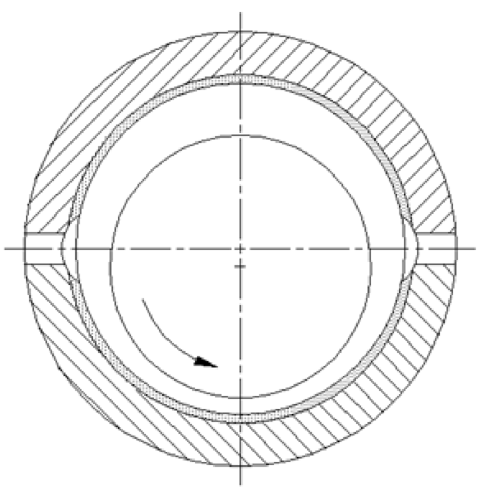
Bearings and their lubrication:

- ***Gas-foil bearings***
- ***Oil bearings***
- Ball bearings
- ***Magnetic bearings***
- ***SCO2 lubricated journal bearings***

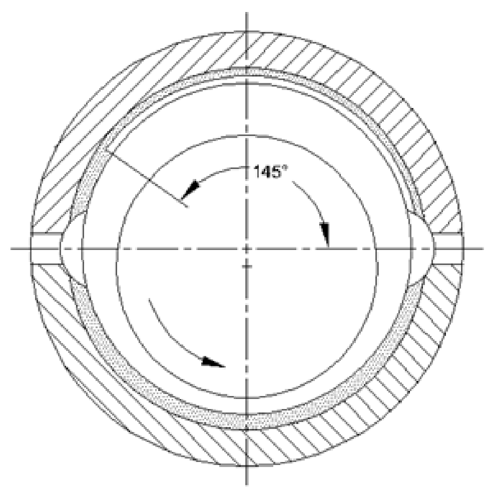
Hydrodynamic Bearings

- Shaft supported in lubricant fim due to positive pressure
- Lubricant forced into converging wedge

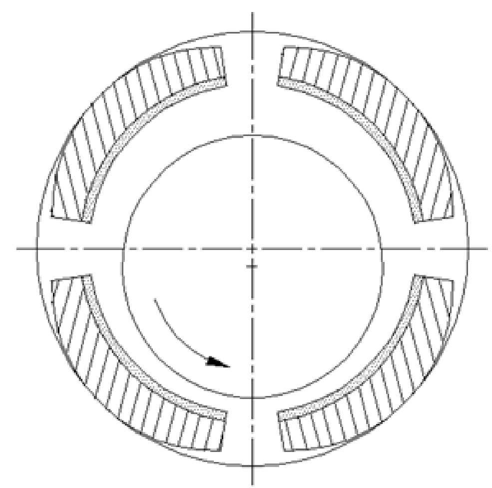
2 AXIAL GROOVE



PRESSURE DAM



TILTING PAD



Journal Bearing Advantages

- Self starting tilting pad bearings at low speed due to converging film
- Very long life
- Can make any needed diameter
- High load capacity
- Excellent capability for taking unexpected external loads
- Zero cross-coupled stiffness – not a source of instability
- High damping
- Turbulence tends to reduce power loss

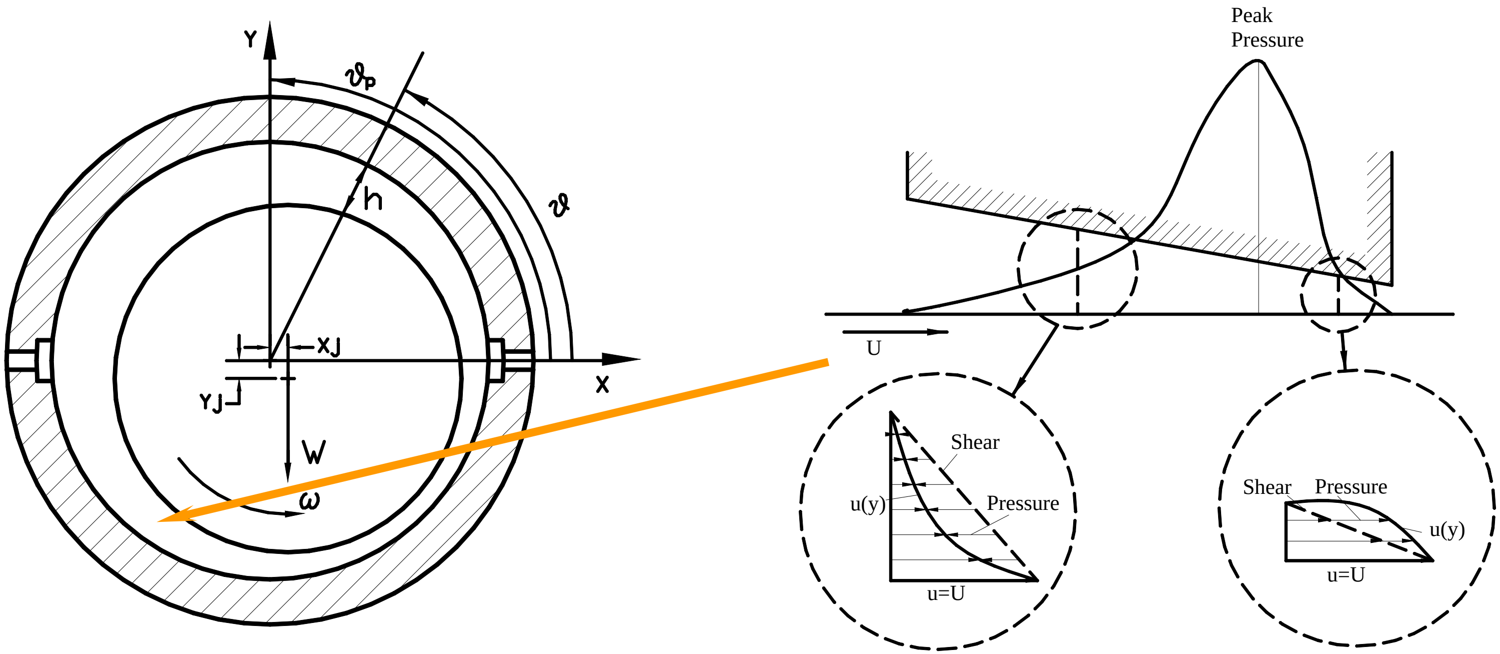
Oil Lubricated Bearings

- Good load capacity at high speed
- Special oil supply system required for each bearing
- Large sealing problem to keep oil out of SCO2
- High friction power loss – local heating problem at high rotating speeds
- Probably quite expensive system
- Not very practical for this application

SCO2 Lubricated Hydrodynamic Bearings

- Very limited mention in literature
- Almost no design/computational models in literature
- Complex pressure/density/viscosity relations
- Not incompressible (liquid) and not gas so no current computational models have been published
- Need new Reynolds equation for bearing design
- New complete model developed in this work

Fundamental Physics (Hydrodynamic, Steady State)



1. **Moving surface**
2. **Viscous fluid**
3. **Converging wedge**

Steady state load capacity
(Hydrodynamic pressure)

Load Capacity

(*nice comparison*)

Max Load on bearings:

ω=6000 rpm, D= 5 in

- Oil lubricated bearing $$P_{av} = \frac{W}{LD} = 500 \text{ lbf/in}^2$$
- SCO2 lubricated bearing $$P_{av} = \frac{W}{LD} = 100 \text{ lbf/in}^2$$
- Foil bearing (probably high) $$P_{av} = \frac{W}{LD} = \frac{k(LD)(D\omega)}{(LD)}$$

$$= 1 \frac{\text{lbf}}{\text{in}^3\text{krpm}} \text{ x } 5\text{in x } 6\text{krpm}$$

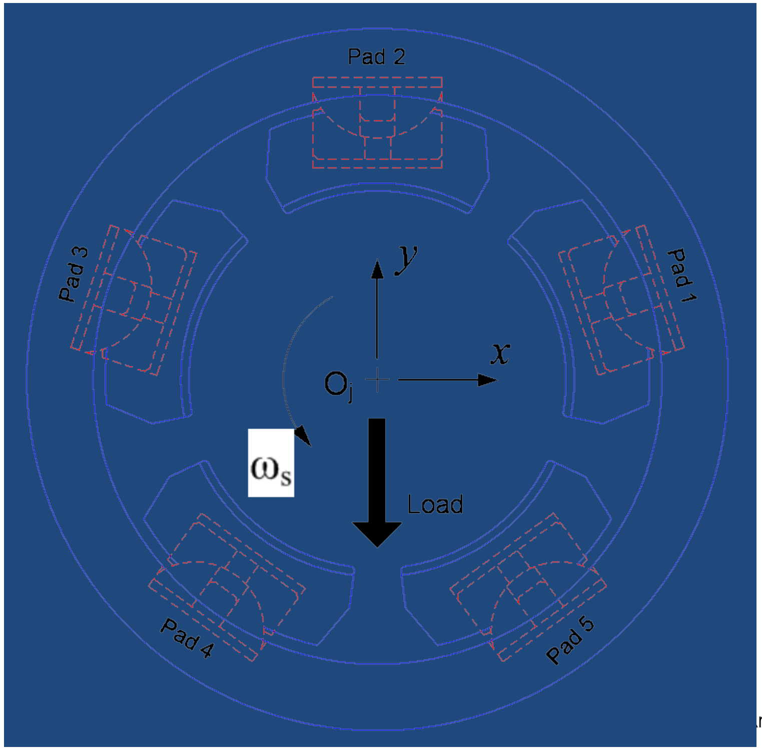
$$= 30 \text{ lbf / in}^2$$

Tilting Pad Journal Bearings

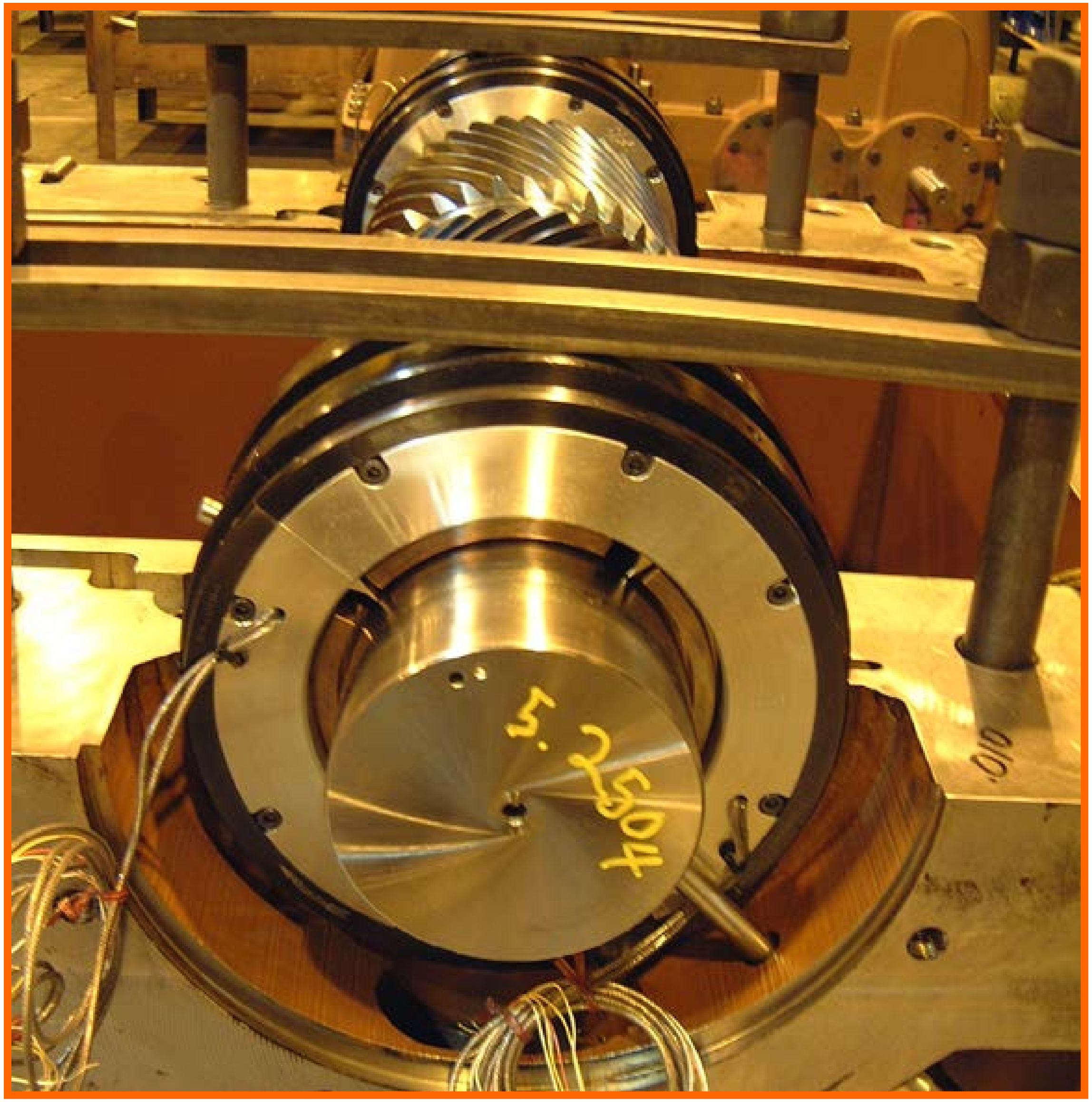
	Inboard	Outboard
Static Load (lbf)	82.52	101.85
Journal Diameter* (in) (±.0001)	2.7515	2.7517
Pad Length (in)	2.060	2.060
Pad Arc Length (°)	55	55
Diametral Housing Crush (in)(±.0002)	-.0014	-.0009
Pivot Diameter (in)	1.000	1.000

L/D = 0.75
Ball & Socket Pivots
Load Between Pad
Two Preload Designs:

- **0.3**
- **0.1**



Example industrial radial oil bearing geometry



Critical Point of CO2

$$T_{cr} = 304.1(^\circ K) = 31.1(^\circ C) = 547(^\circ R) = 88(^\circ F)$$

$$P_{cr} = 7.38(MPa) = 72.8(bar) = 1070(psia)$$

$$\rho_{cr} = 469(kg/m^3)$$

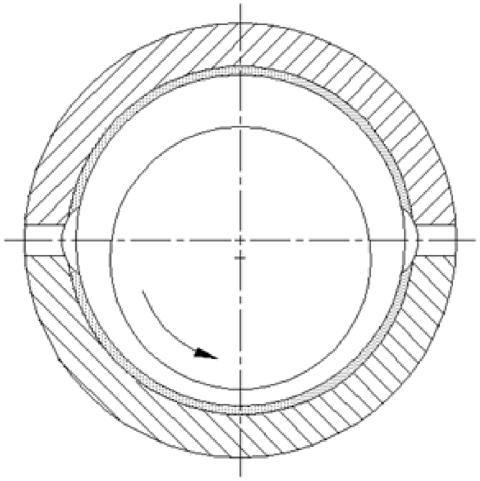
[Experiment by Stephan Passon]

Incompressible Reynolds Equation

- Traditional theory: constant density

$$\frac{\partial}{\partial x}\left(\frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{12\mu}\frac{\partial p}{\partial z}\right)=\frac{\partial h}{\partial t}+\frac{1}{2}U\frac{\partial h}{\partial x}$$

2 AXIAL GROOVE



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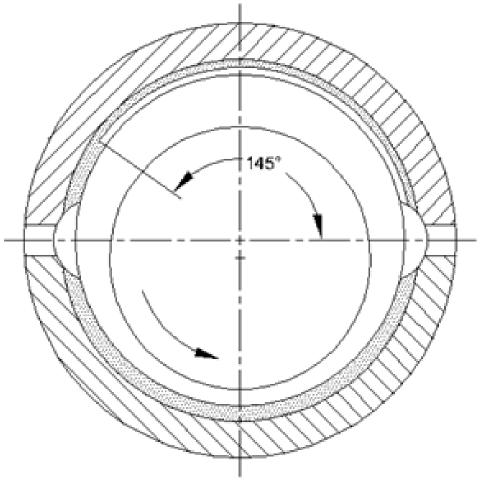
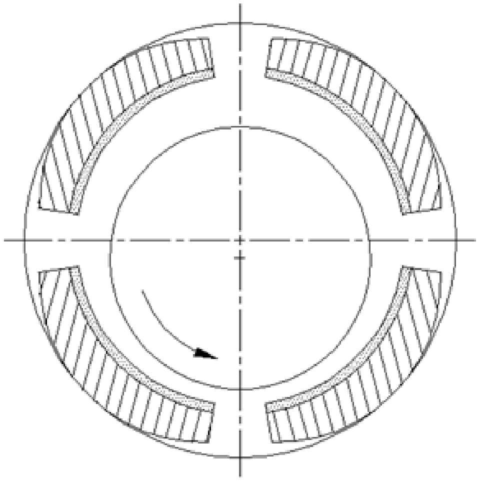


TILTING PAD



sCO2 Pressure/Density/Viscosity

- Complex relation between pressure/density/viscosity
- Hydrodynamic bearing only operates in supercritical region
- Leads to very difficult, nonlinear analysis
- Compressibility important

Supercritical CO2

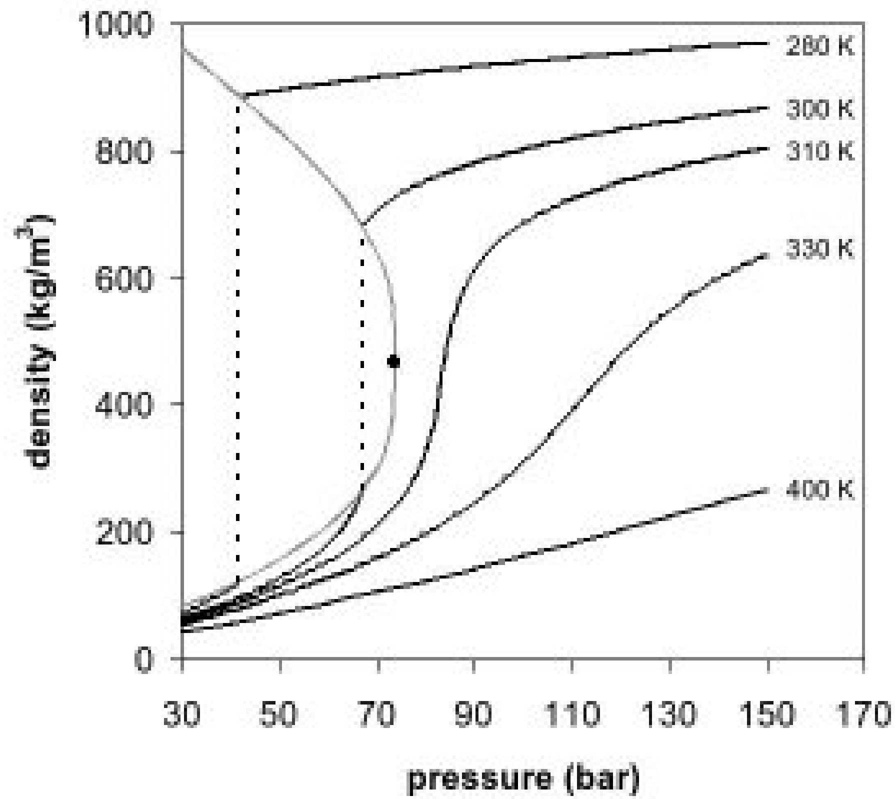
Supercritical fluids: between gas & liquid

Comparison of Gases, Supercritical Fluids and Liquids[2]

	Density (kg/m^3)	Viscosity (μPa·s)	Diffusivity (mm²/s)
Gases	1	10	1–10
Supercritical Fluids	100–1000	50–100	0.01–0.1
Liquids	1000	500–1000	0.001

Supercritical CO2

- Rapid changes in transport properties, e.g., viscosity and density around critical point
- Highly nonlinear behavior
- Temperature and pressure dependent



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Density

- Wang, et al. model (2015)
- Density vs. pressure and temperature
- Polynomial expression
- Easier to use
- Yet nonlinear

$$
\begin{aligned}
\rho \; = \; & \left(a_1 T_r^3 + a_2 T_r^2 + a_3 T_r + a_4\right) p_r^6 \\
& + \left(b_1 T_r^3 + b_2 T_r^2 + b_3 T_r + b_4\right) p_r^5 \\
& + \left(c_1 T_r^3 + c_2 T_r^2 + c_3 T_r + c_4\right) p_r^4 \\
& + \left(d_1 T_r^3 + d_2 T_r^2 + d_3 T_r + d_4\right) p_r^3 \\
& + \left(e_1 T_r^3 + e_2 T_r^2 + e_3 T_r + e_4\right) p_r^2 \\
& + \left(f_1 T_r^3 + f_2 T_r^2 + f_3 T_r + f_4\right) p_r \\
& + \left(g_1 T_r^3 + g_2 T_r^2 + g_3 T_r + g_4\right)
\end{aligned}
$$

Viscosity

- Fenghour and Wakeham (1998)
- Viscosity vs. density and temperature
- Analytical expression
- Easier to use
- Yet nonlinear

$$\mu = \mu_o(T) + \Delta\mu(\rho, T)$$

$$\mu_o(T) = \frac{1.00697\sqrt{T}}{G(T^*)}$$

$$\Delta\mu(\rho, T) = d_{11}\rho + d_{21}\rho^2 + \frac{d_{64}\rho^6}{T^{*3}} + d_{81}\rho^8 + \frac{d_{82}\rho^8}{T^*}$$

Hydrodynamic Journal Bearings

- Cylindrical sleeve bearings
- Multi-lobe fixed pad Bearings
- Tilting pad bearings
- SCO2 bearings almost not reported in literature
- New semi-Linear Reynolds equation solution method developed
- Existing tilting pad bearing code – just replace old Reynolds equation with new Reynolds equation
- Numerical examples
- Show feasibility of SCO2 bearings

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Compressible Reynolds Equation

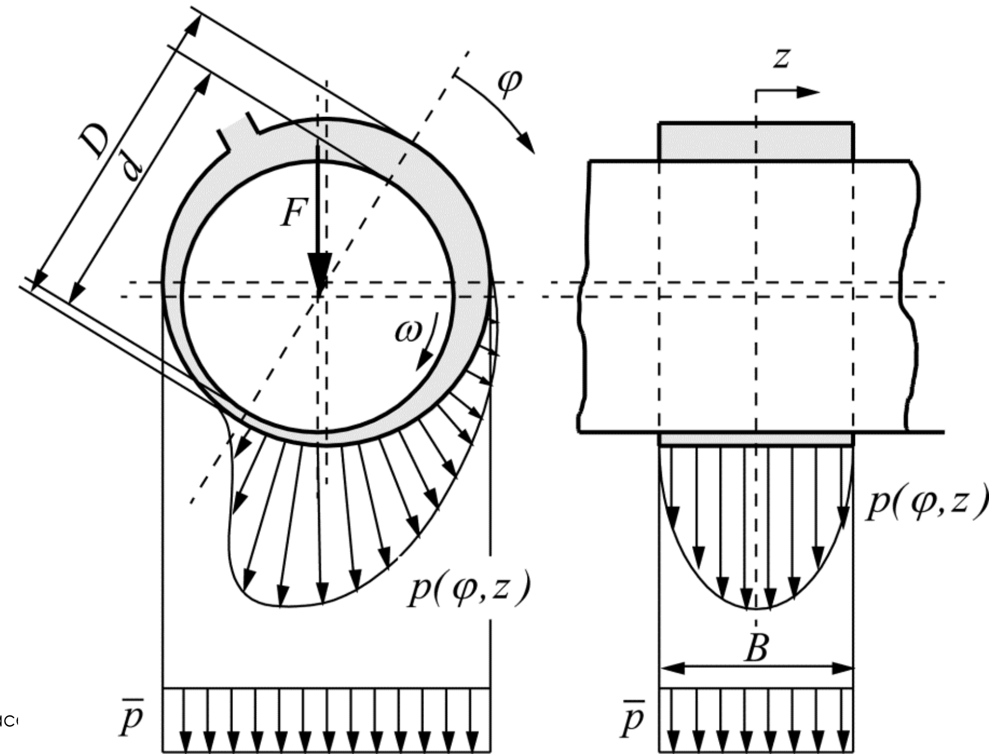
- Variable density

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{k_x \mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\rho h^3}{k_z \mu}\frac{\partial p}{\partial z}\right)=\rho\frac{\partial h}{\partial t}+\frac{1}{2}U\frac{\partial(\rho h)}{\partial x}$$

Turbulence

$$\rho = \rho(p, T)$$

nonlinear



Hydrodynamic Pressure

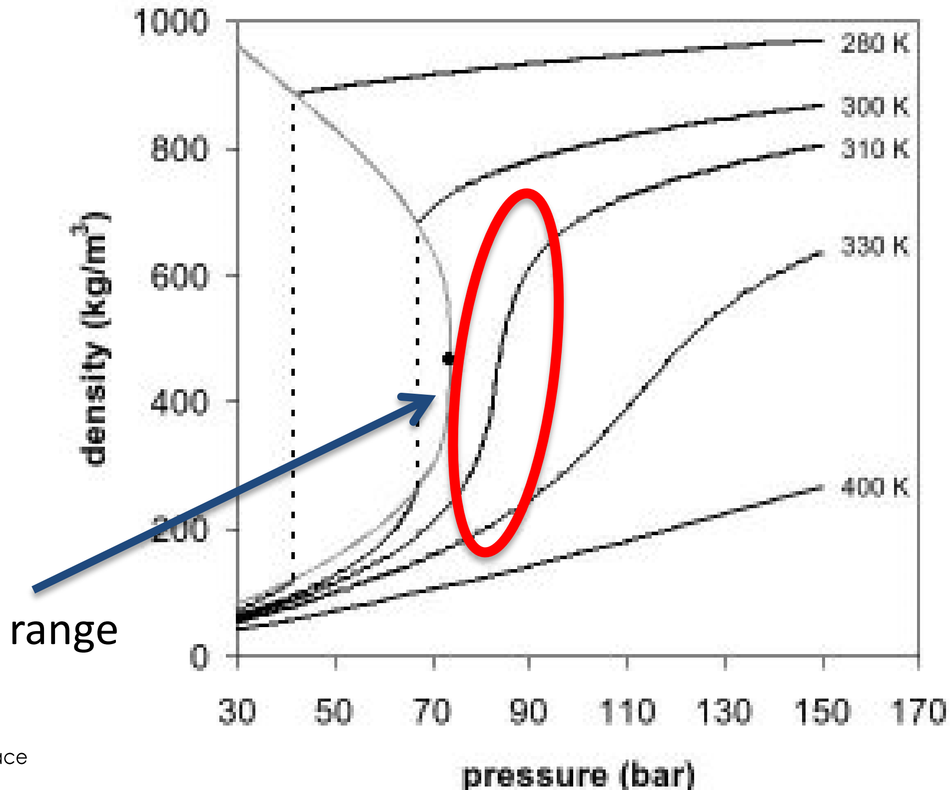
Supply P: 8 (MPa)=80 (bar)

Hydrodynamic:

$$\Delta p_{max} \leq 1\text{-}2(MPa) = 10\text{-}20(bar) = 145\text{-}290(psia)$$

linearization

$$\rho = \alpha(T)p + \rho_o$$



Linear range

New Supercritical Reynolds Equation

Supercritical portion

$$\frac{\partial}{\partial x}\left(\alpha(T)\frac{h^3}{2k_x\mu}\frac{\partial p^2}{\partial x}\right)+\frac{\partial}{\partial z}\left(\alpha(T)\frac{h^3}{2k_z\mu}\frac{\partial p^2}{\partial z}\right)=$$
$$+\rho\frac{\partial h}{\partial t}+\frac{1}{2}U\frac{\partial(\rho h)}{\partial x}-\rho_o\left\{\frac{\partial}{\partial x}\left(\frac{h^3}{k_x\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{k_z\mu}\frac{\partial p}{\partial z}\right)\right\}$$

- Account for supercritical behavior
- Linear in p^2 in the left hand side
- Nonlinear in the right hand side
- Iterative scheme to solve – see paper
- FEA solution, very robust

Numerical Results

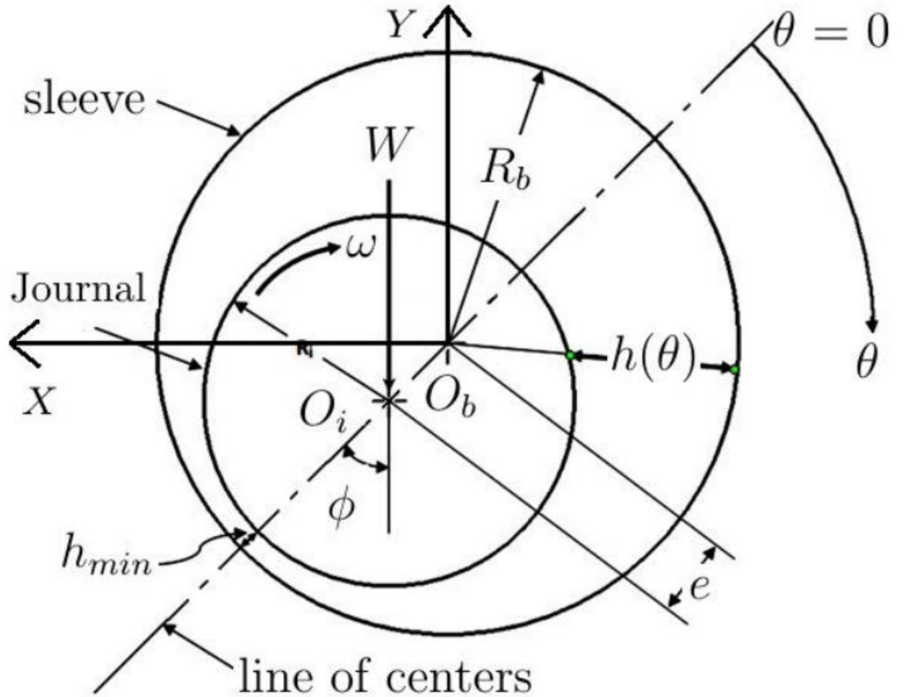
- Cylindrical bearing
- 60,000 rpm and 20,000 rpm
- Density variation included
- Viscosity variation included
- Comparison with incompressible case
- Load capacity for SCO2 bearings is suitable for industrial use in SCO2 power cycle machines

Cylindrical Sleeve Bearing

- Eccentricity ratio: $\varepsilon = \frac{e}{c}$

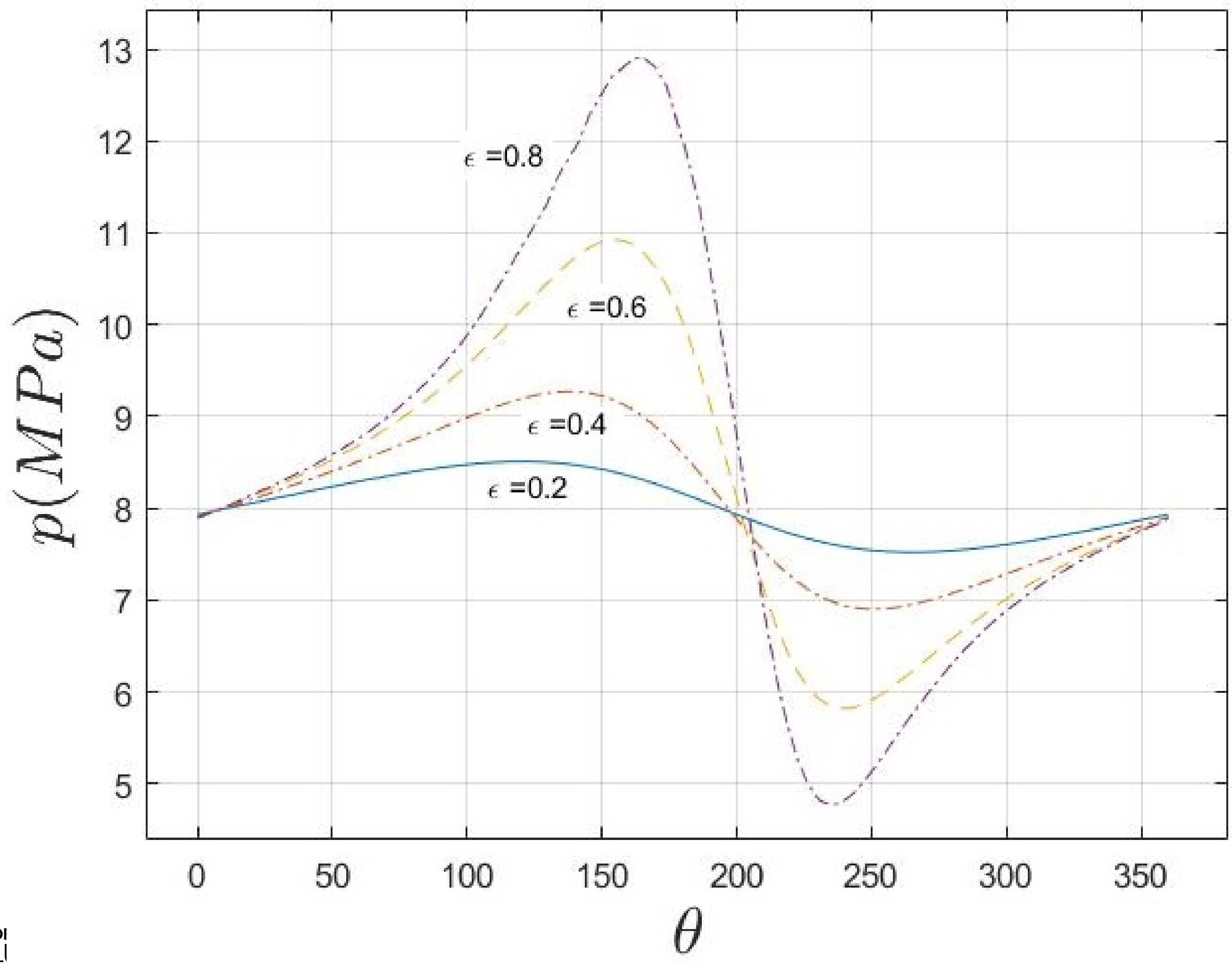
Table 1: Bearing geometry and operation conditions.

Diameter, $D(mm)$	40
Clearance ratio, c/R	0.001
Length, $L(mm)$	40
Temperature,$T(K)$	320
Supply pressure,$P_s(MPa)$	8
Supply viscosity,$\mu(\mu Pa.s)$	24.7
Supply density,$\rho(kg/m^3)$	321.051
Rotational speed, $\omega(rpm)$	$\boxed{60000}$
Bearing type	cylindrical sleeve
Supply condition	fully flooded



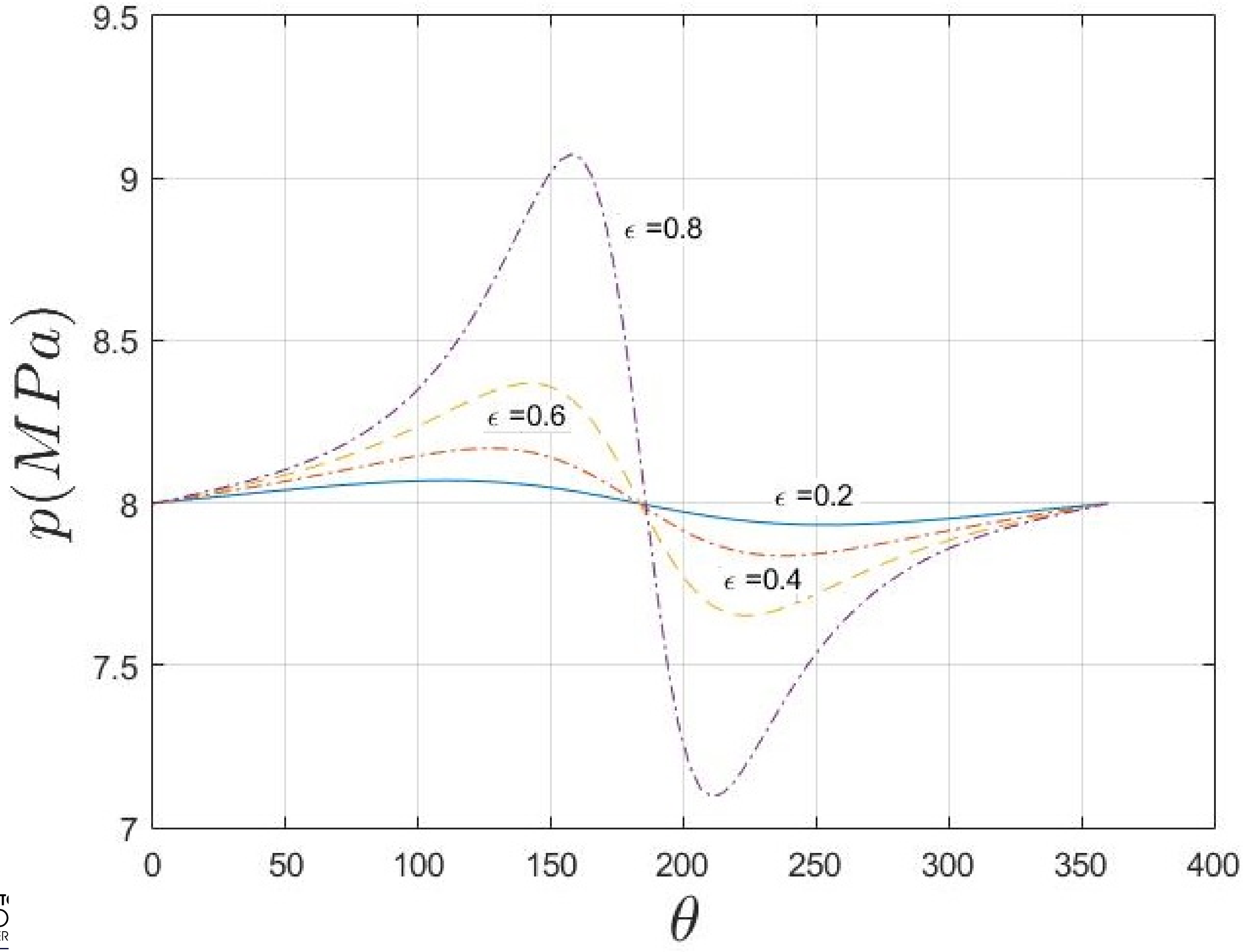
Pressure Profile

$60{,}000(rpm)$



Pressure Profile

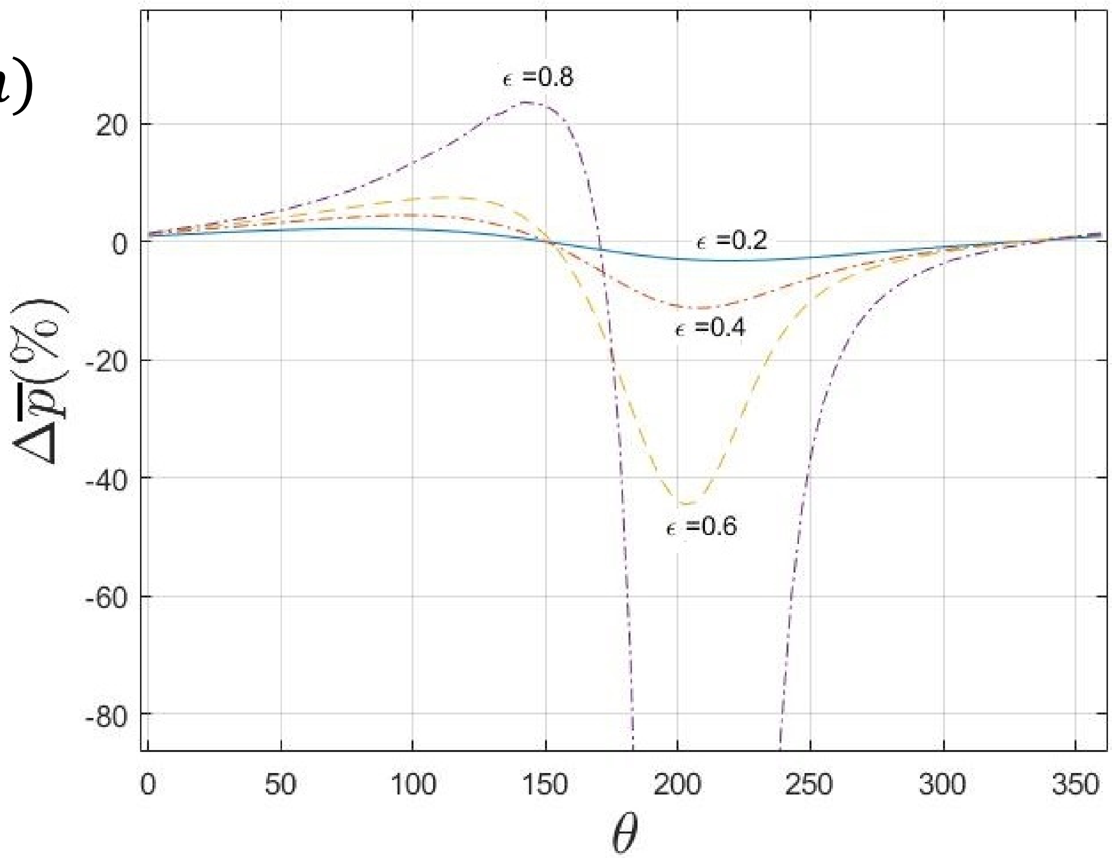
$20{,}000(rpm)$



Pressure Profile

- Comparison between compressible and incompressible analysis $\Delta\bar{p}\% = \frac{p_{in} - p}{p_{in}} * 100$

$60{,}000(rpm)$



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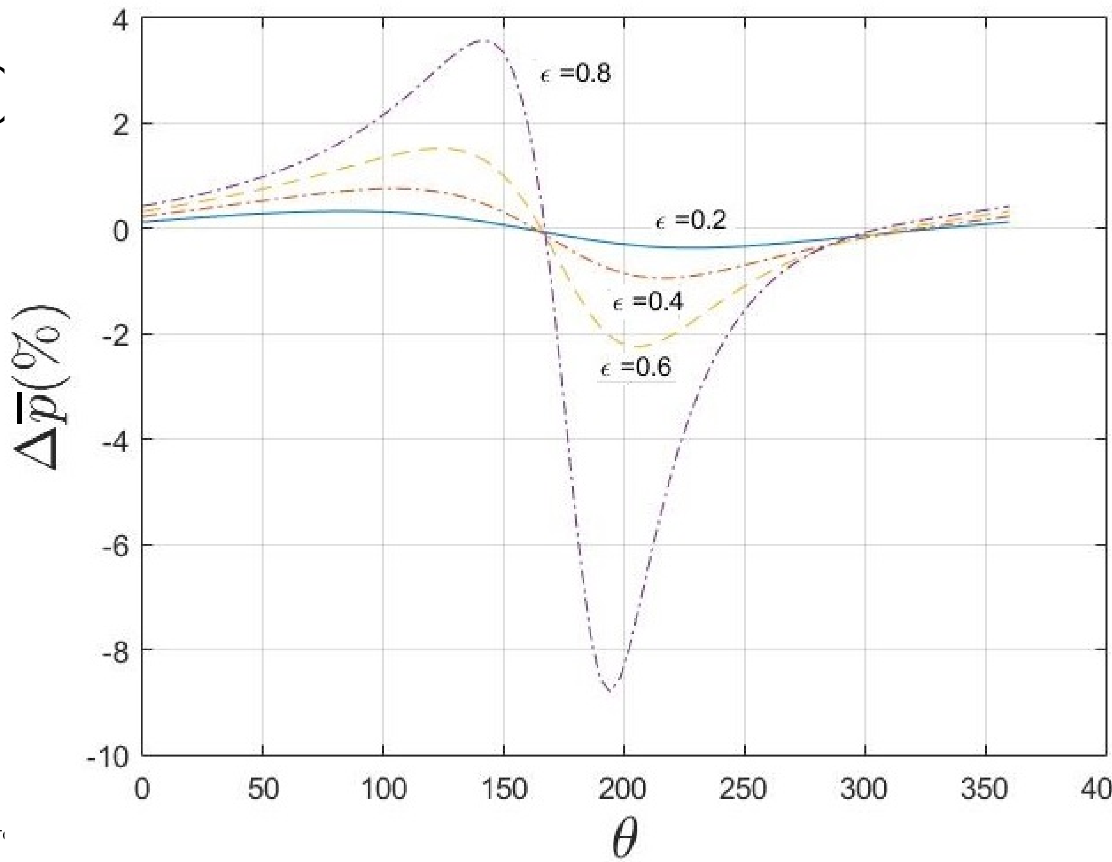
Pressure Profile

- Comparison between compressible and incompressible analysis

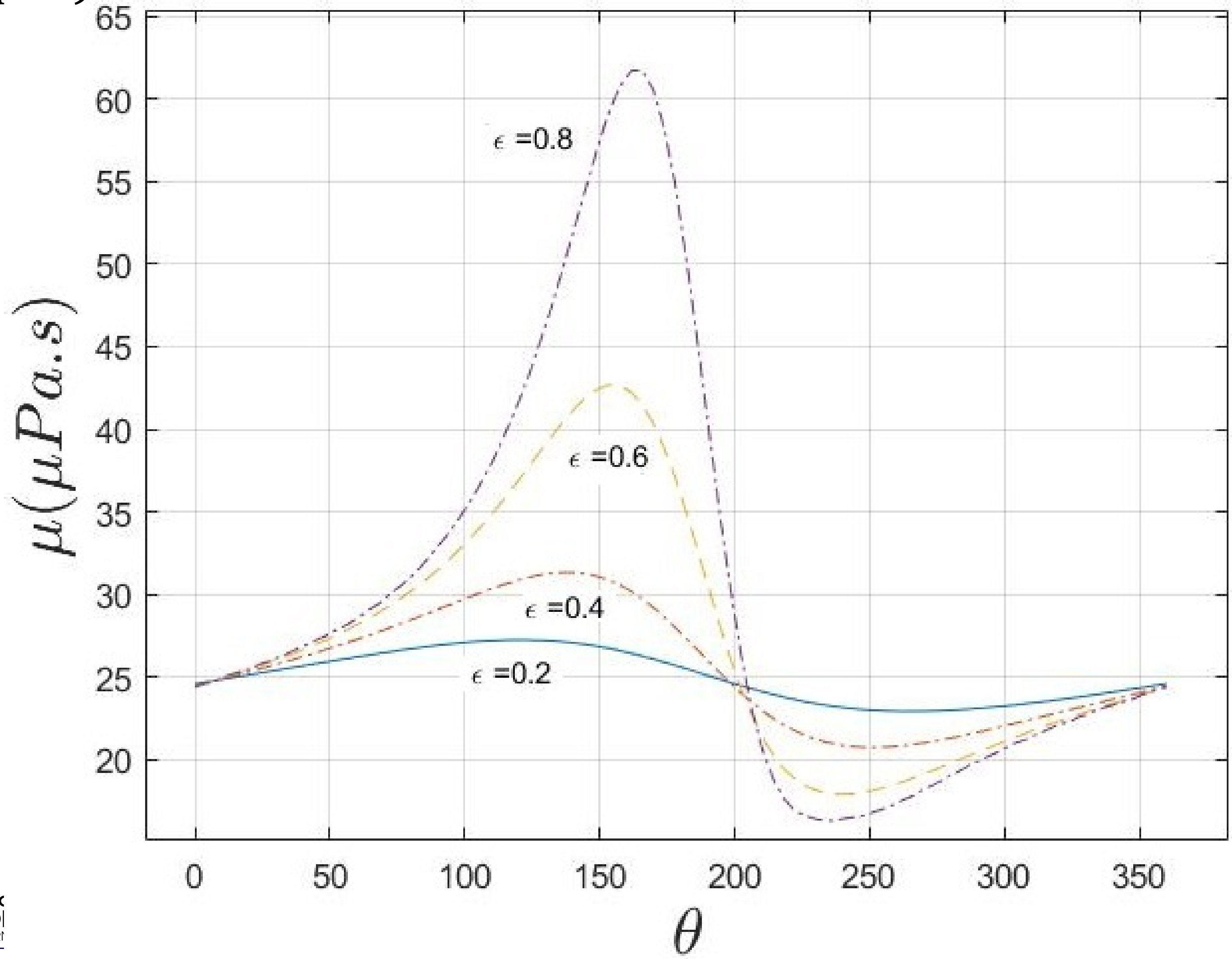
$$\Delta\bar{p}\% = \frac{p_{in} - p}{p_{in}} * 100$$

$20{,}000(rpm$



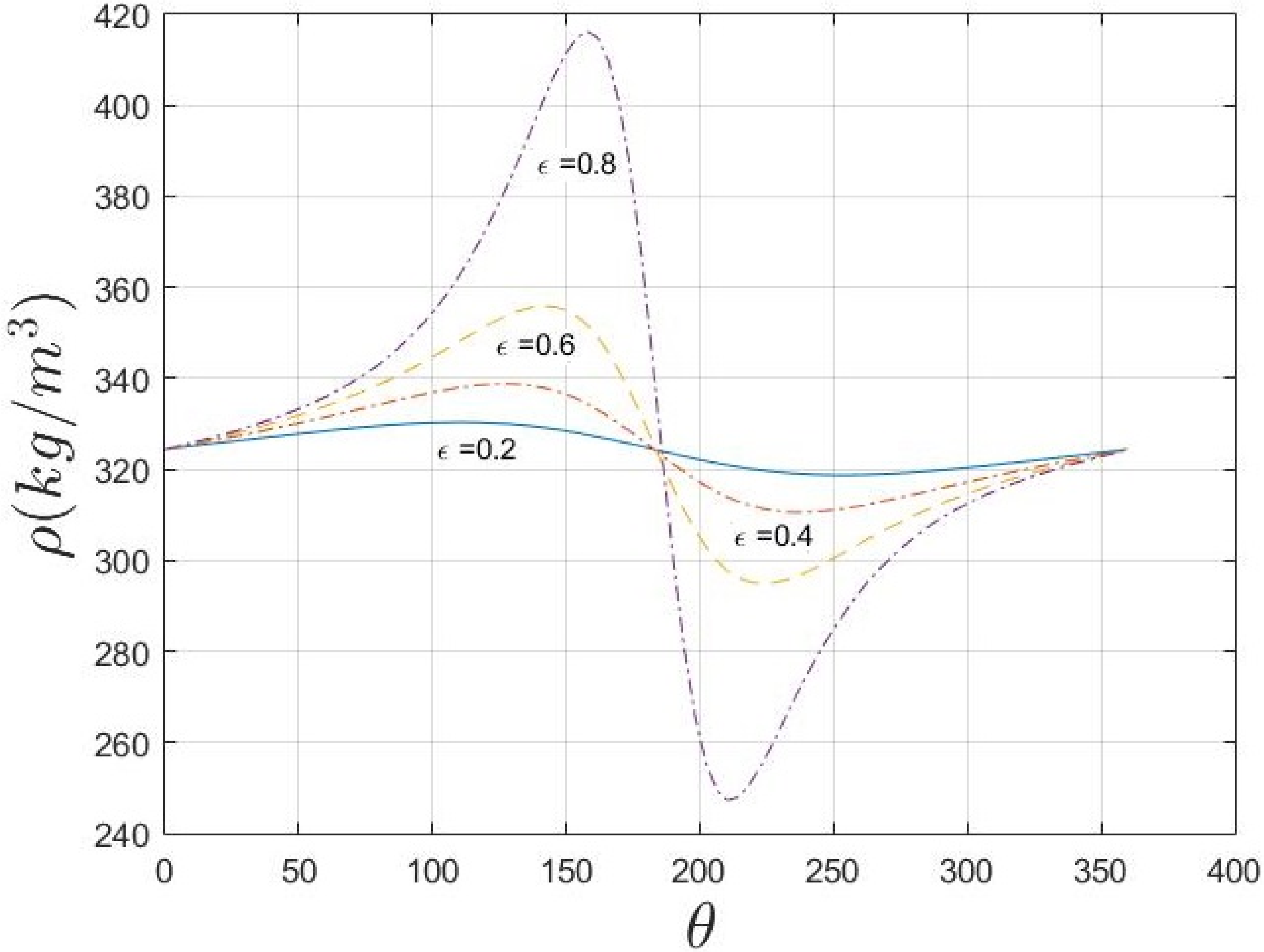
Density Variation

$60{,}000(rpm)$



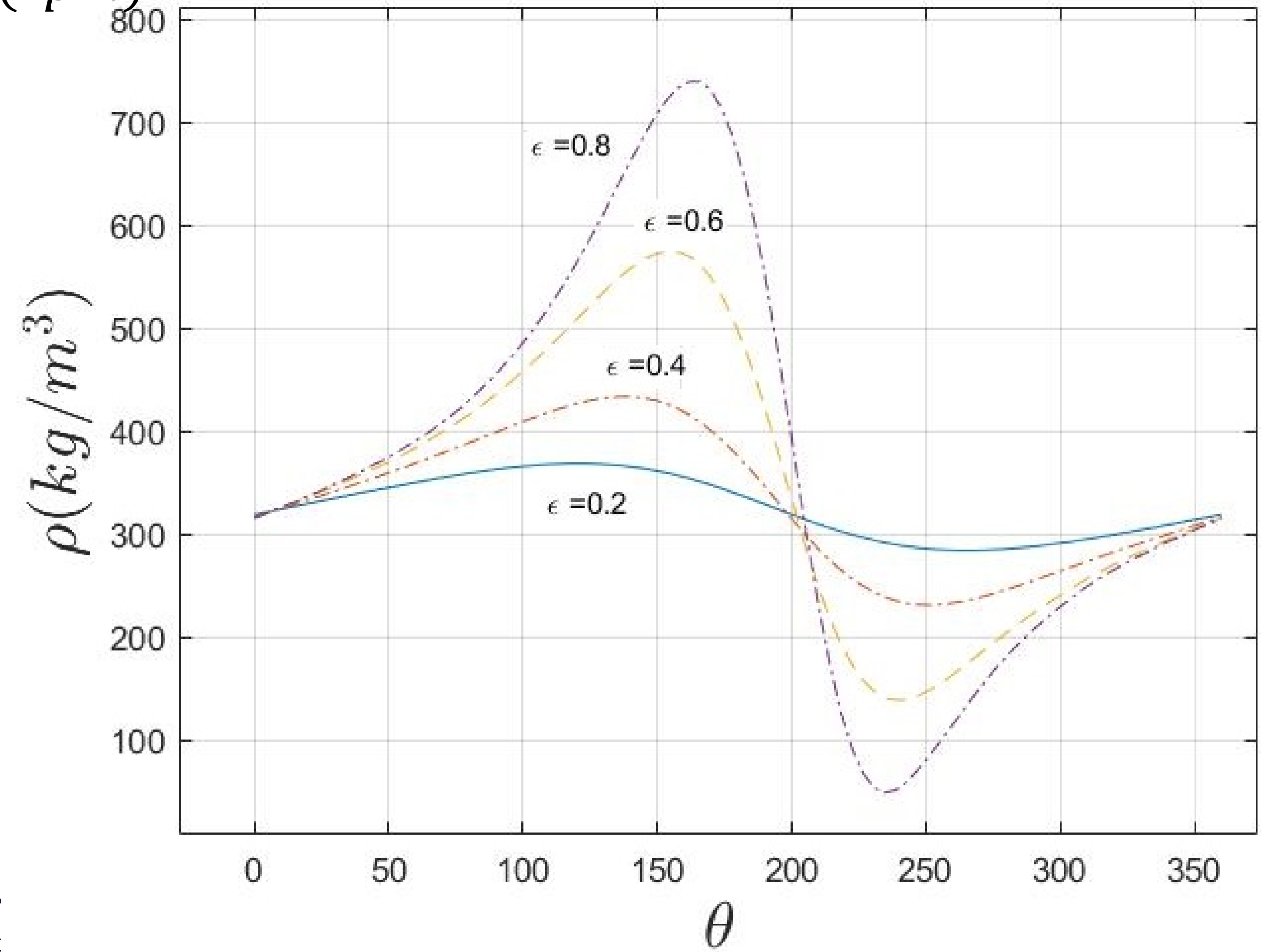
Density Variation

$20{,}000(rpm)$



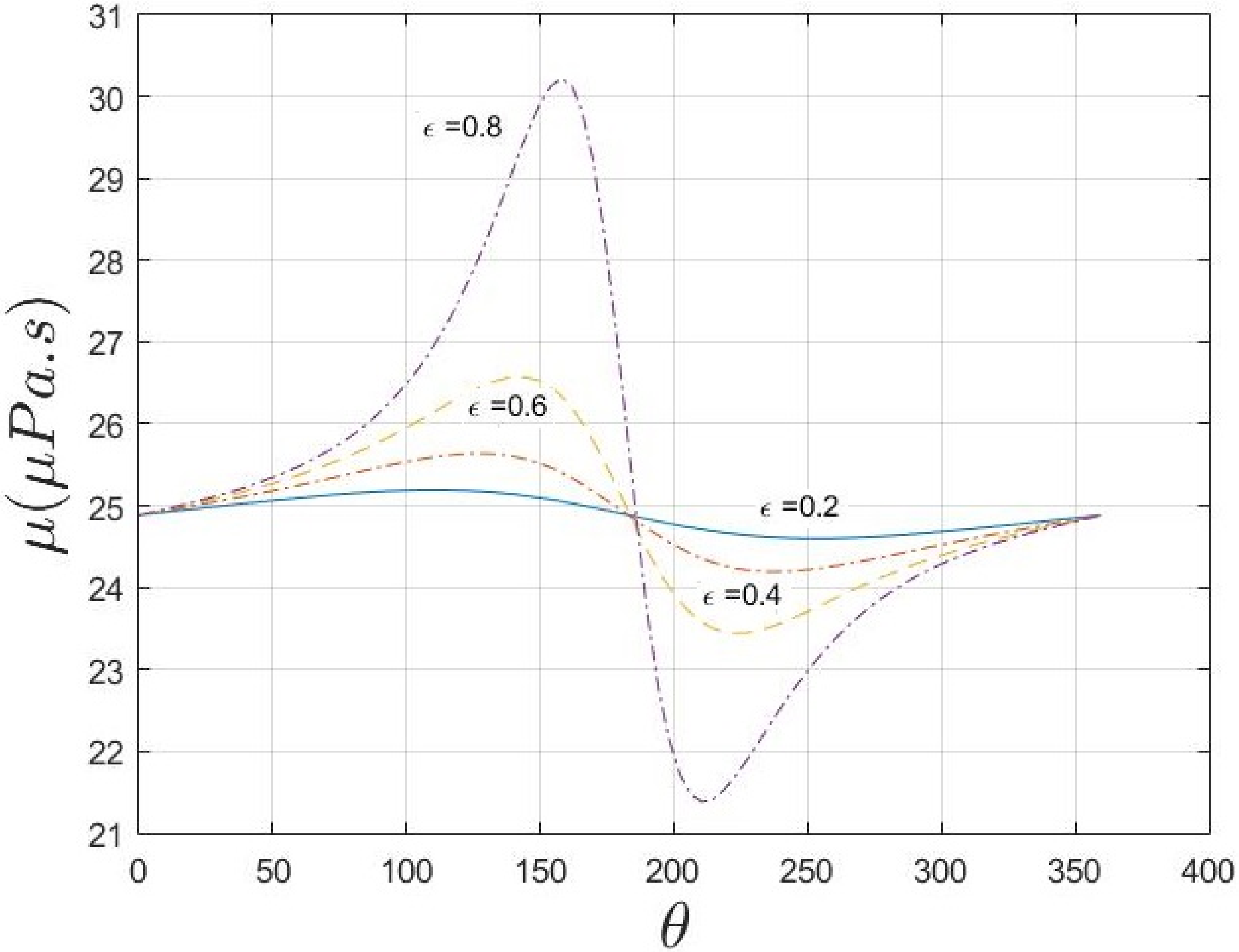
Viscosity Variation

$60{,}000(rpm)$



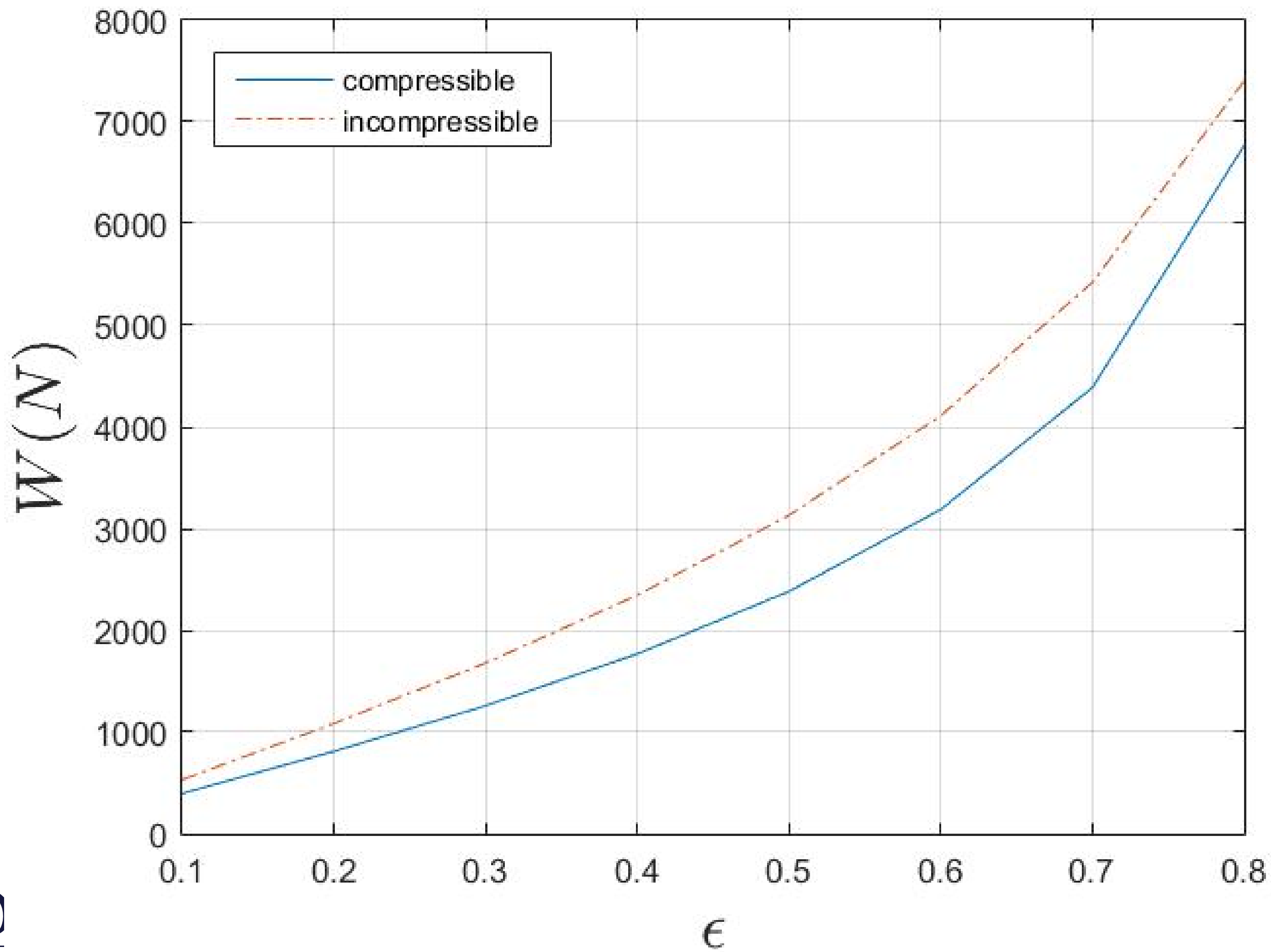
Viscosity Variation

$20{,}000(rpm)$



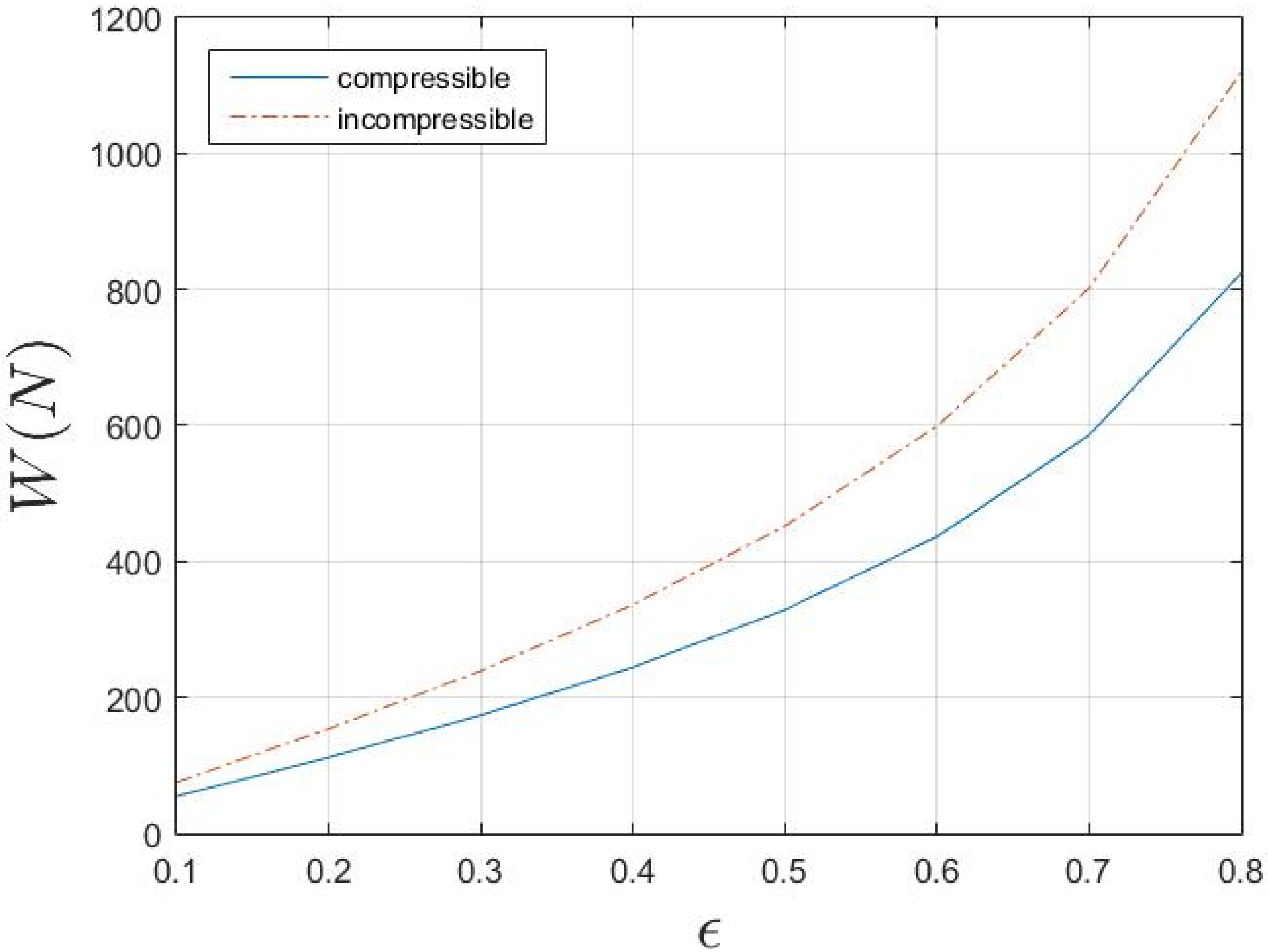
Load Capacity

$60{,}000(rpm)$



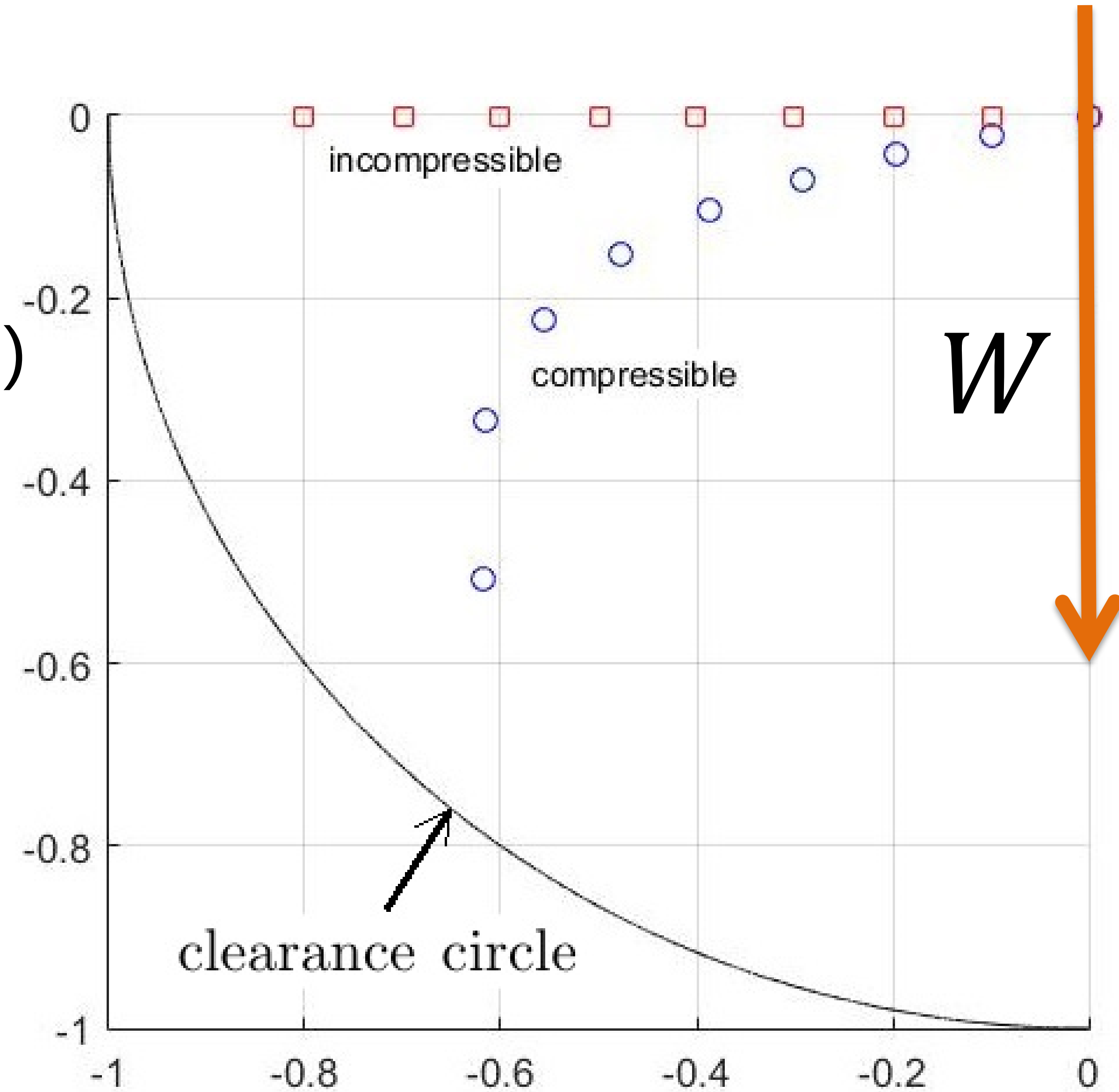
Load Capacity

$20{,}000(rpm)$



Journal Locus

- Attitude angle
- Incomp: =90(deg) unstable
- Comp: <90(deg) more stable



Friction Power Loss

- SCO2 viscosity = 2.5% of typical oil bearing viscosity
- SCO2 bearing at 60,000 rpm = 0.098 kW
- Oil bearing at 60,000 rpm = 4 kW
- SCO2 bearing at 20,000 rpm = 0.011 kw
- Oil bearing at 20,000 rpm = 0.44 kW

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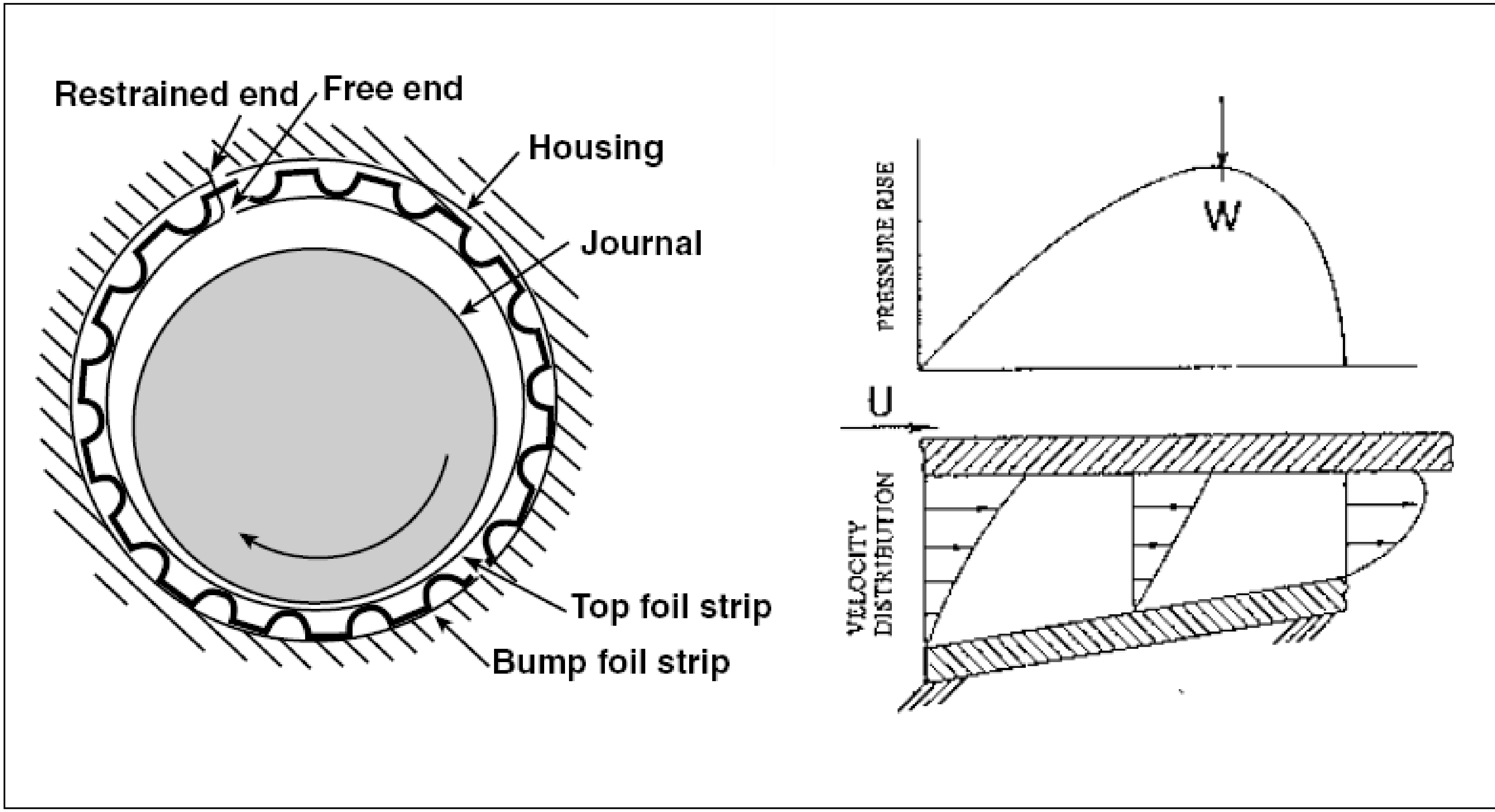
Gas-foil bearing working principle

Gas-foil bearing operation

- As the journal shaft starts to rotate, it drags a film of air between it and the top foil .
- As the hydrodynamic pressure increases a force is exerted on the circumferential top foil.
- This pressure pushes the top foil away from the journal in accordance with the compliance of the backing bump foil.
- At the liftoff speed, the journal 'floats' on this hydrodynamic film of air without touching the top foil

Gas-foil bearing working principle

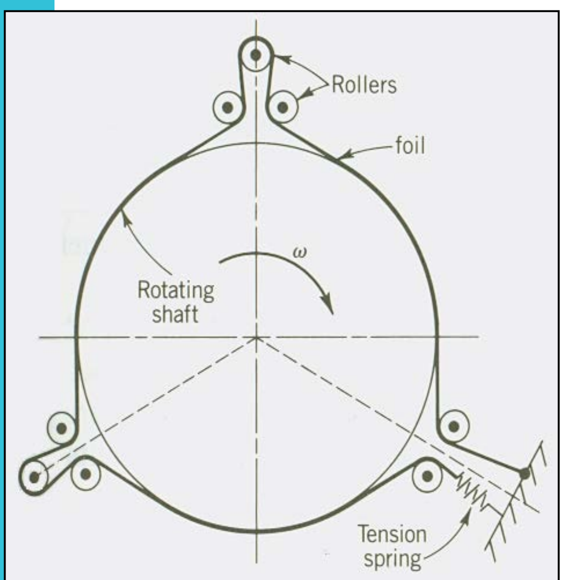


Typical application

A high speed rotating machine called *Air Cycle Machine* (ACM) is the heart of the *Environmental Control System* (ECS) used on aircraft to manage cooling, heating and pressurization of the aircraft. Today, ACM for almost every new ECS system on military and civil aircraft and on many ground vehicles use foil air bearings

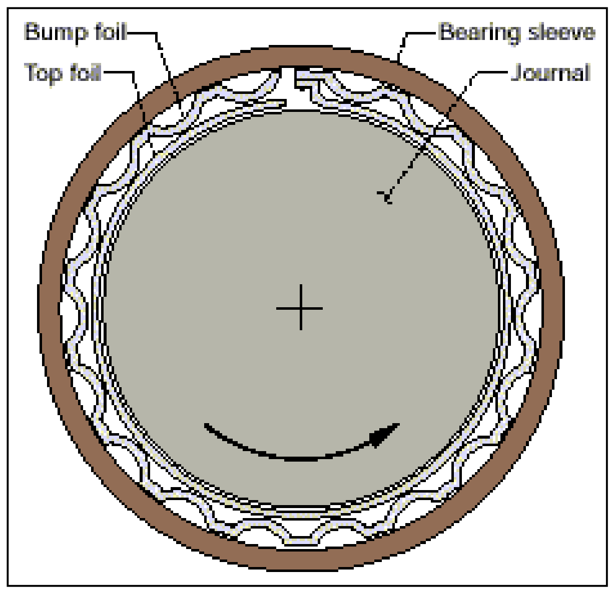
Type & Generation

First Generation: Foil bearings are characterized by axially and circumferentially uniform elastic support elements.



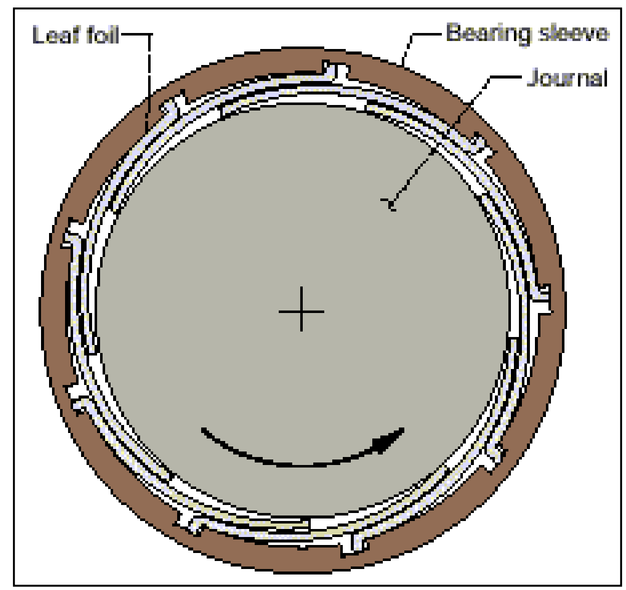
Tension Dominated

Foil bearing



Bending dominated

continuous foil bearing

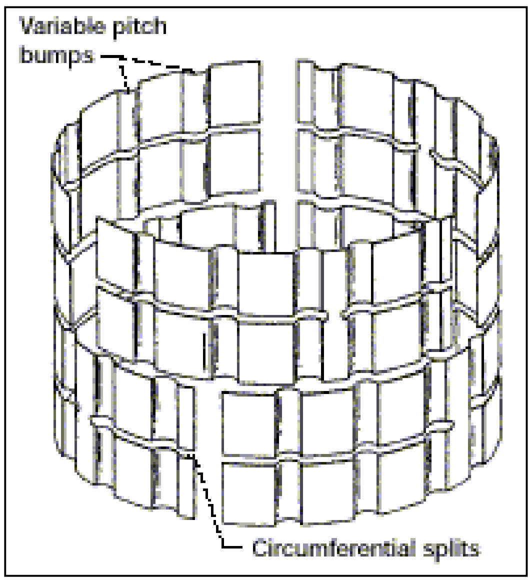


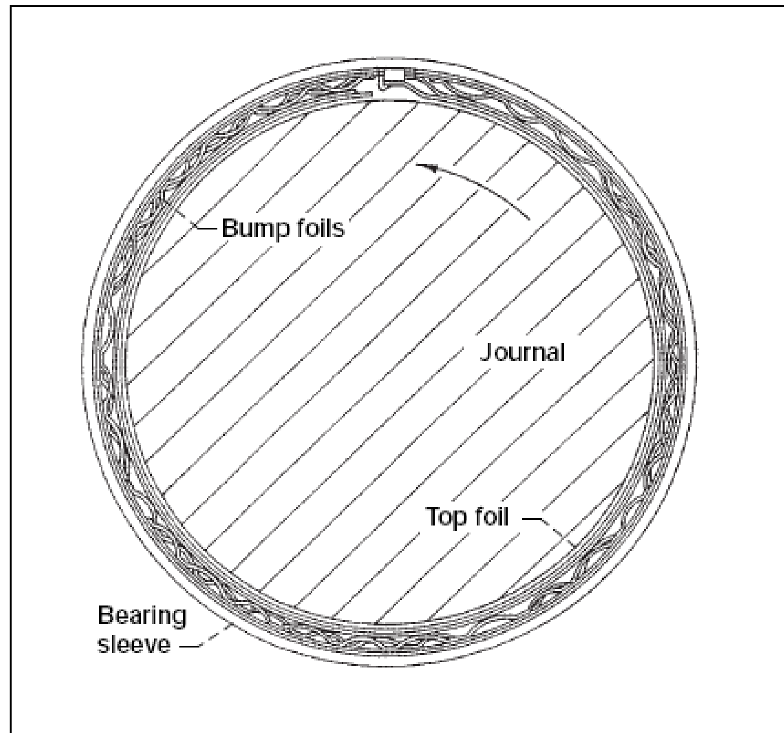
Bending dominated

Segmented foil bearing

Type & Generation

Third Generation: foil bearings tailor the foil support in axial, circumferential AND radial directions to enhance performance.





Load Capacity

$$W = k\,(L \times D)\,(D \times \omega)$$

W Maximum steady-state load (lbf)

k Bearing load capacity coefficient (lb/(in^3 krpm))

L Bearing axial length (in)

D Shaft diameter (in)

ω Shaft speed (krpm)

Gen. I	k= 0.3
Gen. II	k= 0.5
Gen. III	k= 1

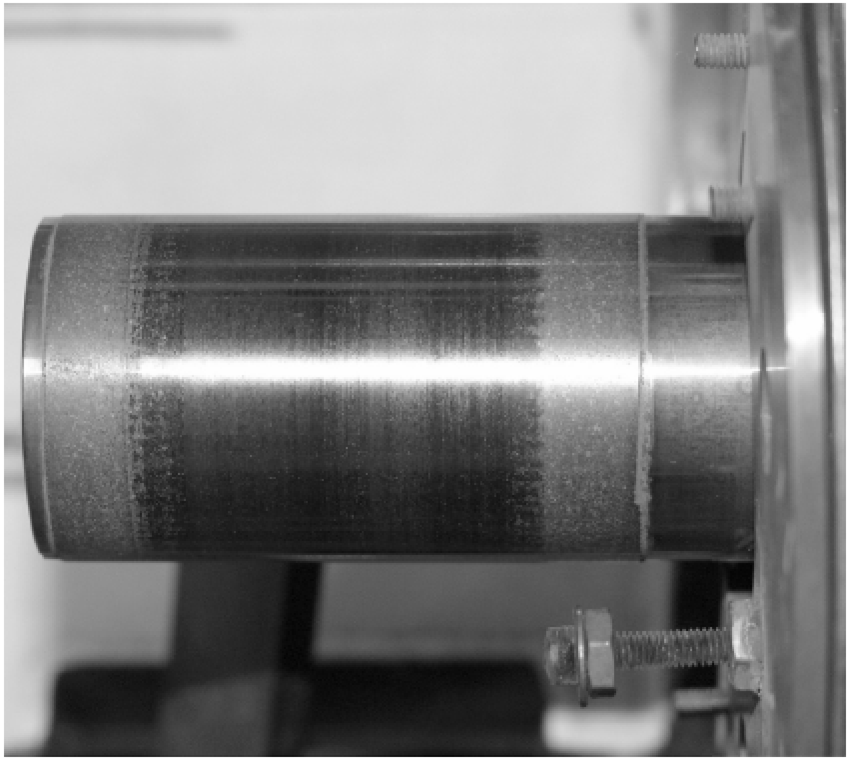
Mnemonic

A pound of load per inch of bearing diameter per square inch of bearing projected area per thousand rpm

Advantages

- **Gas-foil Bearing Advantages**
- 1. Accommodation to distortions and misalignments
- 2. Operation at high temperatures
- 3. No external pressure source required
- 4. Operate in process fluids
- 5. Higher load than rigid gas bearings
- 6. Smaller envelope than conventional bearings

Wear in Foil Bearing



Disadvantages

Foil Bearing Disadvantages:

1. Relatively low load capacity
2. Supporting foil wear can lead to catastrophic fracture.
3. Few analytical tools or design charts are available.
4. Damping mechanism is not well understood.
5. Starting and stopping friction wear can be large.
6. Starting torques are high.
7. Very low stiffness. (Limited industrial experience)

Gas-Foil Sandia Lab Problems

- “Consumed large part of project budget”
- “Limited load capacity”
- “Difficult to start rotors in gas-foil bearings”
- “Turbulence generated increased frictional loss”
- “High sensitivity to gas pressure and running speed”
- “Extensive custom fabrication, iterative design and testing”

[Iverson, Conboy, Pasch, Applied Energy, 2013]

SUMMARY AND CONCLUSIONS

- A new compressible Reynolds equation appropriate for supercritical working fluids is developed
- No previous solution has been published
- Takes into account the complex viscosity and density
- An FEA robust fast solution algorithm
- Considerable load is generated in SCO2 lubricated bearing
- The density and viscosity variations are speed dependent and are considerable
- Turbulence model included
- Journal location is correctly predicted with the new theory and is important in dynamic analysis
- Much lower power loss compared to oil bearing
- Dynamic properties on the way
- Tilting pad bearing modeling in place
- High Reynolds number applications and inertia inclusion for future applications
- Looks much better and simpler than gas-foil or hydrostatic bearings

References

- See Paper

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