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[#$K] Introduction

This advanced spiral groove face seal program was developed to accurately predict the performance of hydrodynamic spiral grooves and other groove shapes (oblique groove and radial groove) for face seals in gas applications such as air or other gases. The governing equation is the compressible Reynolds equation with rarefied gas dynamic effect, so that a high degree of accuracy can be obtained for low-pressure applications in the aerospace industry. Two types of slip flow correction methods are presented. Pressures are specified at both ID and OD of the seal. The groove depth can be a function of radial and circumferential coordinates, although a constant depth is commonly used. Both the inward and outward pumping geometries are included. The analysis option includes a single run analysis and multiple run. Multiple run allows for the design iteration and multiple cases comparison for optimization purposes. Various postprocessor graphics allows for easy presentation and result comparison.

[#] HID_INTRODUCTION
[$] Introduction
[K] Introduction

[#][$K] **Governing Equation**

The governing pressure distribution for a compressible Reynolds equation with rarefied gas effect (slip flow correction) in polar coordinate (r,θ) system is given below:

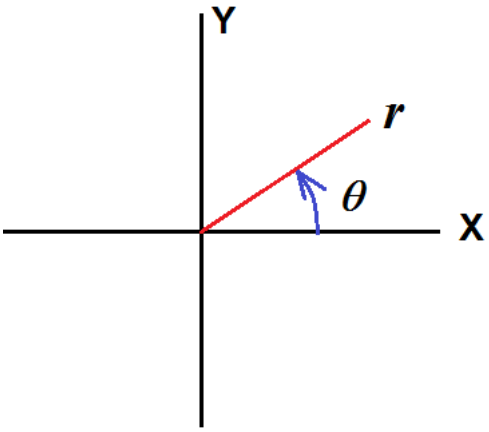
$$\frac{\partial}{r\partial\theta}\left(ph^3\frac{\partial p}{\partial\theta}Q\right)+\frac{\partial}{\partial r}\left(rph^3\frac{\partial p}{\partial r}Q\right)=6\mu\omega r\frac{\partial ph}{\partial\theta} \qquad (1)$$

where

(r,θ) = polar coordinate (defined by seal geometry)

$$x = r\cos\theta$$

$$y = r\sin\theta$$



$p = p(r,\theta)$ Pressure to be solved (psi)

$h = h(r,\theta)$ Film thickness (given) (in)

μ = Dynamic viscosity (given) (Lbf-s/in^2, Reyns)

ω = angular velocity (rad/sec) = rpm (given) * 2PI / 60 (rpm is given)

Direction of rotation same as the theta coordinate, CCW is positive, CW is negative

Q = Slip Flow Factor (non-dimension) a function of (p, h, μ, R, T).
Q = 1 in Eq (1), no slip flow correction is included. With slip flow correction included, the Q factor is determined below:

$$Q=\frac{Q_p}{Q_c} \qquad (2a)$$

[#] HID_THEORY
[$] Theory - Governing Equation
[K] Theory - Governing Equation

$$Q_p = \frac{D}{6} + \left[\frac{3-\alpha f^3}{\alpha} - \frac{3D}{\sqrt{\pi}}\left(1-f^2\right)\right]\frac{\sqrt{\pi}}{3} + \left[f^4 + \frac{8D^2}{\pi}\left(1-f^2\right)\right]\frac{\pi}{8D} \quad (2b)$$

$$Q_c = \frac{D}{6} \quad (2c)$$

The above equation is based on Lin Wu's paper "**A slip model for rarefied gas flows at arbitrary Knudsen number"** Published in *2008 American Institute of Physics.* Note that the software also includes the well-known F-K model presented by S. Fukui and R. Kaneko , **"A Database for Interpolation of Poiseuille Flow Rates for High Knudsen Number Lubrication Problems", 1990 ASME publication.**

where

α = 0.81 ~ 0.93, default 0.89**.**

Knudsen number $K_n = \frac{\mu\sqrt{\pi RT}}{ph\sqrt{2}}$ (3)

Inverse Knudsen number $D = \frac{ph}{\mu\sqrt{2RT}}$ (4)

$$f = \min\left(\frac{2D}{\sqrt{\pi}}\ ,\ 1\right) \quad (5)$$

***R* is** gas constant (for air: 53.34 FT-Lbf/Lbm-^{o}R = 1716 ft^2/s^2·R = **247,127.2 in^2/s^2·^{o}R**)

$$53.34\left(\frac{Ft-Lbf}{Lbm-{}^{o}R}\right) \times 32.174\left(\frac{Lbm-Ft}{Lbf-s^2}\right) \times 144\left(\frac{in^2}{ft^2}\right) \quad (6)$$

Note: R = **247,127.2 in^2/s^2·^{o}R used in Eqs. (3) & (4)**

T temperature in ^{o}R is given. **Note that although English units are used in this presentation, the software is capable of handling both English units and Metric units.**

Once the pressure distribution is solved for a given film thickness, the film force (opening force):

$$F_{open} = \iint p\ dA = \int_{r_i}^{r_o}\int_{\Theta_1}^{\Theta_2} p\ r\,d\theta\,dr \quad \text{(Lbf)} \quad (7)$$

Note that ***A*** is the film area (integration domain) where the Reynolds Eq. is solved. If the entire seal area is used, then Θ_1 = 0 and Θ_2 = 2π are constant. If all the grooves are identical and cyclic (periodic) boundary conditions exist in the circumferential direction, then only one sector (pitch, or pad) is needed. Θ_1 becomes the leading edge of the sector and Θ_2 is the trailing edge of the sector, where $\Theta = \Theta(r)$ is a function of radius, may not be a constant in this application if a sector is used. Solving one sector will save computational time. The total opening force will be the sum of all the sectors.

The radial and circumferential flow velocities in *r* and θ directions are:

$$V = \frac{h^2}{12\mu}\frac{\partial p}{\partial r}Q \qquad \text{(in/sec)} \quad (8)$$

$$U = \left(\frac{h^2}{12\mu}\frac{\partial p}{r\partial\theta}\right)Q + \frac{1}{2}r\omega \qquad \text{(in/sec)} \quad (9)$$

Noted *Q* is multiplied. Leakages (mass flow rate) at any radial and circumferential directions are:

$$\dot{m}_r = \int_{\Theta_1}^{\Theta_2} \rho V\, h\, r\, d\theta = \int_{\Theta_1}^{\Theta_2} \frac{p}{RT} V\, h\, r\, d\theta \qquad \text{(lbm/sec)} \qquad (10)$$

$$\dot{m}_\theta = \int_{r_i}^{r_o} \rho U\, h\ dr = \int_{r_i}^{r_o} \frac{p}{RT} U\, h\ dr \qquad \text{(lbm/sec)} \qquad (11)$$

Very important, *R* used in Eqs. (10) and (11) is 640 in-Lbf/Lbm-^{o}R (53.34 FT-Lbf/Lbm-^{o}R X 12 in/FT).

Use this mass flow rate to check the mass conservation. Flow into the integration area must be the same as the flow out of the area.

Torque due to friction

$$T = \int_{r_i}^{r_o}\int_{\Theta_1}^{\Theta_2}\left(\frac{\mu\omega r^3}{h} + \frac{hr^2}{2}\frac{\partial p}{r\partial\theta}\right)d\theta dr \quad \text{(Lbf-in)} \quad (12)$$

Horsepower

$$hp = \frac{T \times rpm}{63025} \quad \text{(hp)} \qquad (13)$$

The restoring moments:

$$\hat{M} = \iint \left(\hat{r}\times\hat{p}\right)\, dA = \int_{r_i}^{r_o}\int_{\Theta_1}^{\Theta_2}\left((x\hat{i} + y\hat{j})\times(p\hat{k})\right)\, r d\theta dr \qquad \text{(Lbf-in)} \quad (14)$$

i.e.

$$M_x = \iint yp\ dA = \int_{r_i}^{r_o}\int_{\Theta_1}^{\Theta_2} yp\ r d\theta dr \qquad (15)$$

$$M_y = -\iint xp\ dA = -\int_{r_i}^{r_o}\int_{\Theta_1}^{\Theta_2} xp\ r d\theta dr \qquad (16)$$

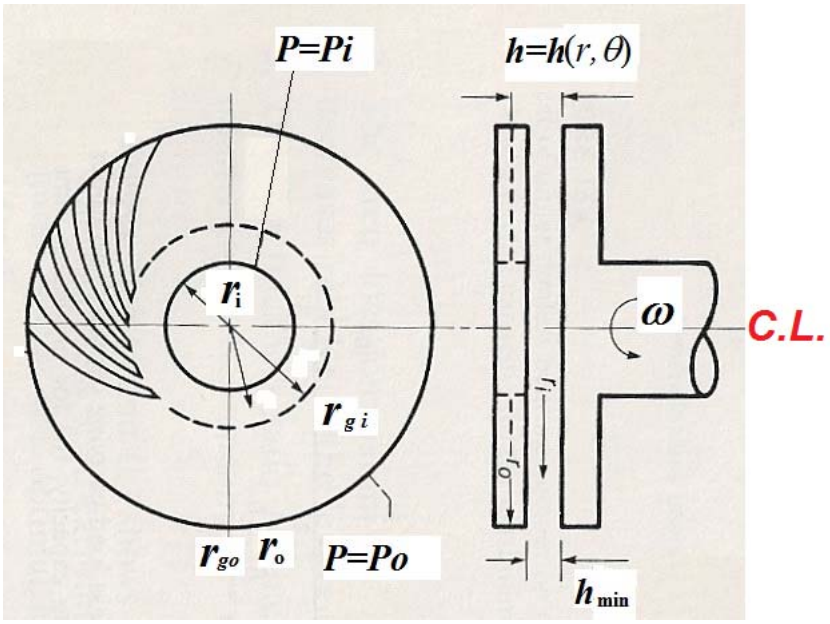
One of the user inputs is seal pressure balance diameter, Γ, which can be a bellow mean effective diameter or a secondary seal pressure diameter. The pressure balance diameter effectively divides the pressure on the back of the seal into two zones. The inner zone is exposed to ID pressure Pi and the outer zone is exposed to OD pressure Po. Usually, there is a spring

force that urges the seal to close. Total closing force = closing force due to pressure + spring force. Let Γ = pressure balance diameter and F_s is the spring force, Total closing force is:

$$F_{close} = F_s + P_o\pi(OD^2 - \Gamma^2)/4 + P_i\pi(\Gamma^2 - \mathrm{ID}^2)/4 \qquad (17)$$

[#][$K] Seal Geometry & Boundary Conditions

A typical inward pumping spiral groove seal with a constant groove depth is shown below:

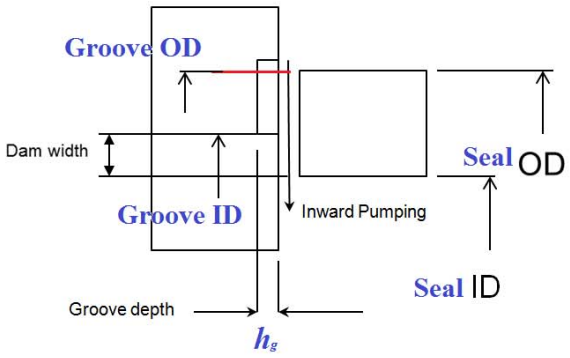


Pressures are specified at Seal Inner Diameter and Outer Diameter boundaries.

- **Constant Groove Depth,** $h_g(r,\theta) = h_g =$ **constant**

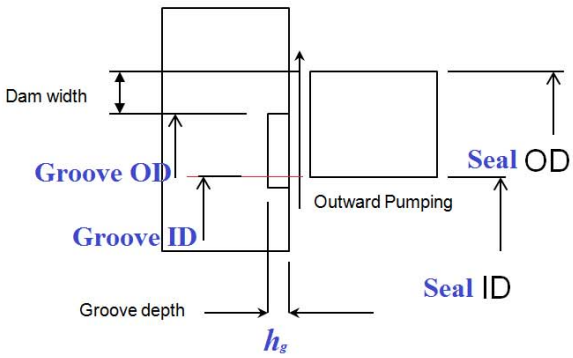
- Basic Inward Pumping Geometry

Groove ID = Seal ID + Dam Width
Groove OD = Seal OD



- Basic Outward Pumping Geometry

Groove ID = Seal ID
Groove OD = Seal OD - Dam Width

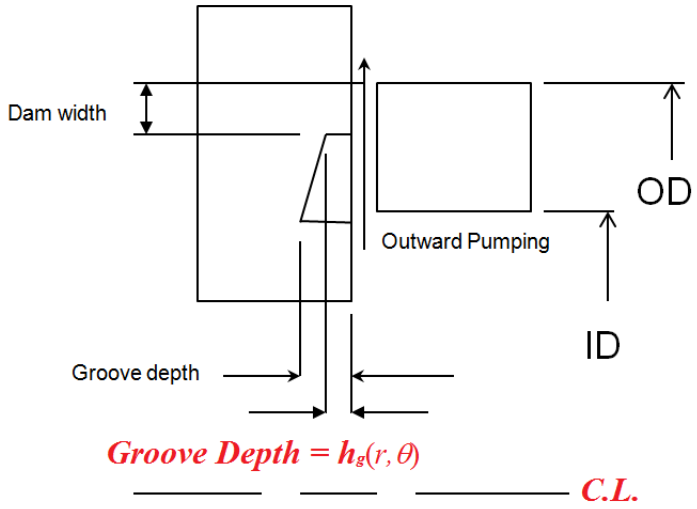


[#] HID_GEOMETRY
[$] Seal Geometry & Boundary Conditions
[K] Seal Geometry & Boundary Conditions

- **Variable Groove Depth,** $h_g(r,\theta) = h_g(r,\theta) =$ **variable depth**

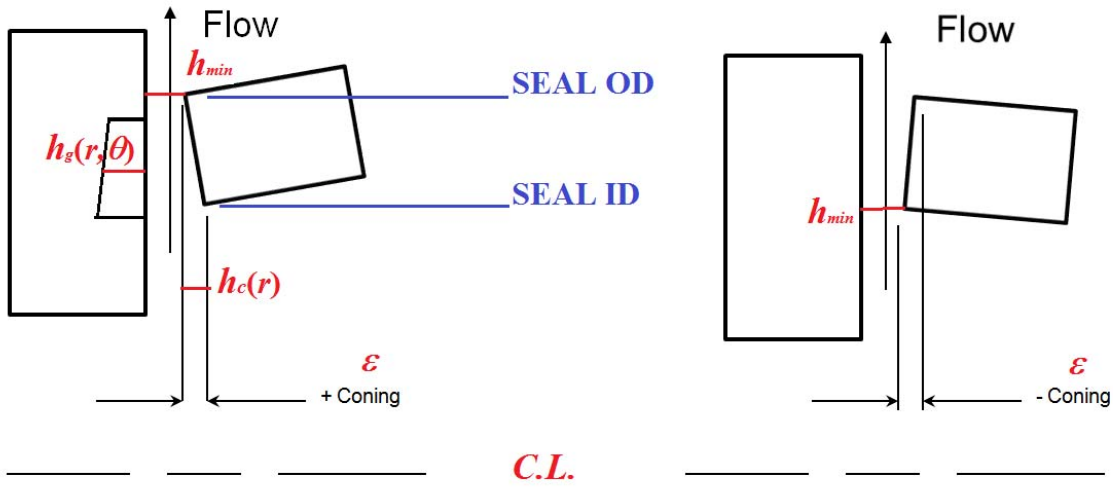
Groove depth can be varying with (r,θ). Groove depth only causes the addition film thickness in the GROOVE area, not in the land area.

- Basic Outward Pumping
  Geometry with "linear" Variable Depth



Coning, ε, addition film thickness $h_c(r) = h_c(r,\varepsilon)$, ε is a constant given value

Additional film thickness can be caused by surface coning in the entire area. Regardless the inward or outward pumping, a **POSITIVE** coning is defined such that the film thickness **DECREASES** with radius. A negative coning will have film thickness INCREASES with radius. Therefore, for a positive coning, the minimum film thickness occurs at the SEAL OD, and a negative coning will have the minimum film thickness at SEAL ID.



if $\varepsilon > 0$, h_{min} at SEAL OD

The additional film thickness over the entire domain due to coning is:

$$h_c(r) = \varepsilon\left(\frac{r_o - r}{r_o - r_i}\right)$$

Check both boundaries:

$$h_c(r_i) = \varepsilon$$

$$h_c(r_o) = 0$$

if $\varepsilon < 0$, h_{min} at SEAL ID

$$h_c(r) = -\varepsilon\left(\frac{r - r_i}{r_o - r_i}\right)$$

Check both ends:

$$h_c(r_i) = 0$$

$h_c(r_o) = -\varepsilon$ (note that this is a positive number since ε is a negative number)

Therefore, the film thickness in Reynolds Eq. (1) becomes:

$$h(r,\theta) = h_{\min} + h_g(r,\theta) + h_c(r,\varepsilon)$$

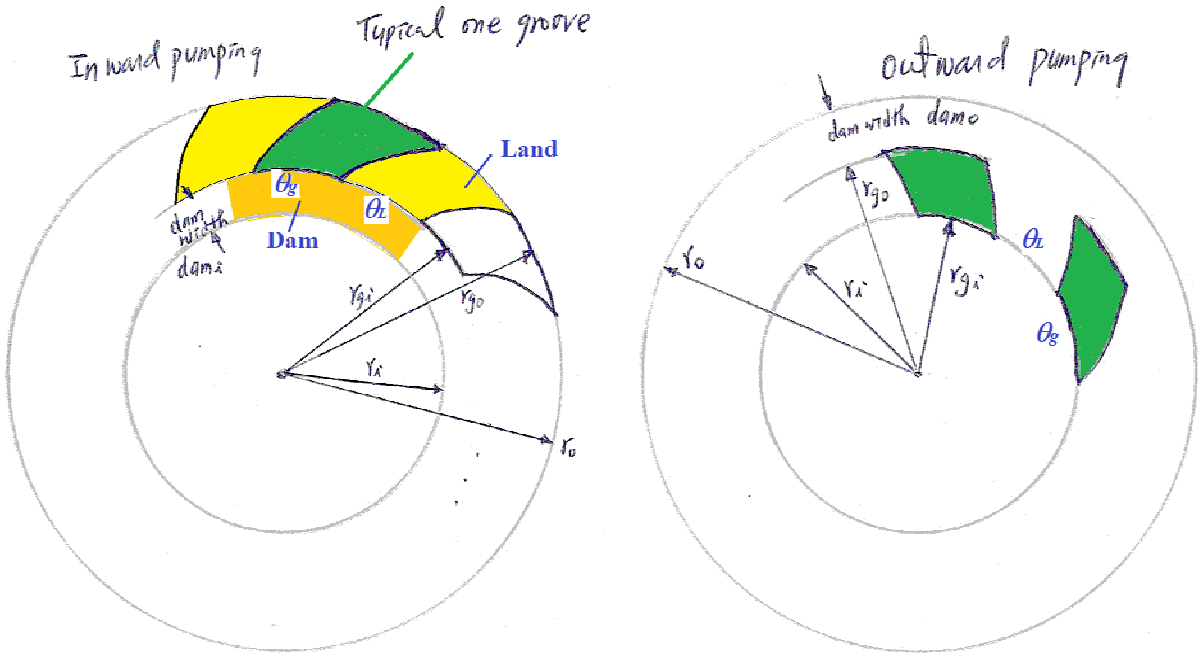
h_{min} is the minimum film thickness which is **a constant** and **is given** in the input.

h_g is the **groove depth** and additional film thickness in the groove area only.

h_c is the additional film thickness in the entire domain due to **coning**.

Other geometry definitions for SPIRAL groove seal are shown below.

Spiral Groove



r_i = Seal Face inner radius = SEAL ID/2

r_o = Seal Face outer radius = SEAL OD/2

r_{gi} = Groove inner radius = GROOVE ID/2

r_{go} = Groove outer radius = GROOVE OD/2

dw = Dam width

For inward pumping SPIRAL GROOVE seal

$r_{gi} = r_i + dw$ = SEAL INNER RADIUS + Dam Width

$r_{go} = r_o$

For outward pumping SPIRAL GROOVE seal

$r_{gi} = r_i$

$r_{go} = r_o - dw$ = SEAL OUTER RADIUS - Dam Width

Note that for SPIRAL Groove seal, the groove inner and outer radii are constant due to constant dam width. However, for the OBLIQUE Groove seal, the corner points are connected by straight lines, then the groove inner radius is NOT constant for inward pumping and groove outer radius is NOT constant for outward pumping. Check the dam width to be sure that the straight lines are within the seal domain.

N_g = # of spirals

θ_g = Groove width at groove inner radius (width between two spiral curves in circumferential direction)

θ_L = Land width at groove inner radius (width between grooves in circumferential direction)

$$\gamma = \frac{\theta_L}{\theta_g}$$ Land/Groove Ratio

$$\varphi = (\theta_L + \theta_g) = \frac{2\pi}{N_g}$$ One pitch

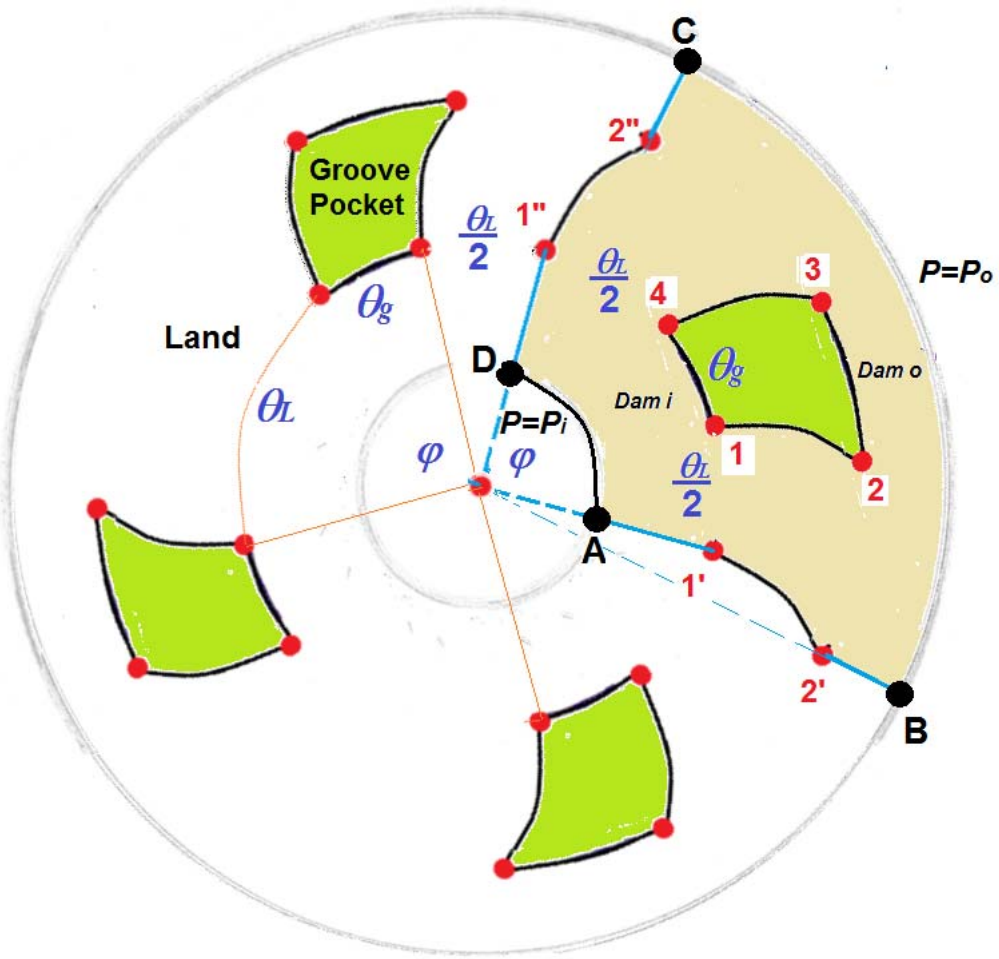
The spiral line is defined as

$$r = r_{gi}\, e^{(\theta-\theta_0)\tan\beta}$$

where β is the spiral angle measured at the beginning of the spiral (at r_{gi}), θ_o is the spiral starting angle at r_{gi}. Or if r is know, the theta θ is:

$$\theta = \theta_{\mathbf{o}} + \frac{\ln\left(r / r_{gi}\right)}{\tan\beta}$$

To illustrate the boundaries and solution domain, a 4 general grooves (or pockets) design is sketched below:



Points (1,2,3,4) form a pocket or groove.
Points (A,B,C,D) form a pitch (sector), if a sector is analyzed.
Curve AD has the same radius, r_i = Seal ID/2. Pressure is specified as P_i on curve AD.
Curve BC has the same radius, r_o = Seal OD/2. Pressure is specified as P_o on curve BC.
For inward pumping, *Dam o* = 0, curve 23 are on the boundary curve BC.
For outward pumping, *Dam i* = 0, curve 14 are on the boundary curve AD.

Curves 12 and 43 are spiral curves for spiral groove and straight lines for oblique groove.
Curve 1'2' on the boundary curve AB is obtained by rotating curve 12 with half of the land width CW. i.e. $\left(-\frac{\theta_L}{2}\right)$.
Curve 1"2" on the boundary curve DC is obtained by rotating curve 12 with groove width + half of the land width CCW. i.e. $\left(\theta_g + \frac{\theta_L}{2}\right)$.

Coordinates for the 8 boundary points:

1: $(r_1, \theta_1) = (r_{gi}, \theta_1)$ $\quad r_{gi} = r_i + Dam\ i$

2: $(r_2, \theta_2) = (r_{go}, \theta_2)$ $\quad r_{go} = r_o - Dam\ o$

3: $(r_3, \theta_3) = (r_{go}, \theta_3)$

4: $(r_4, \theta_4) = (r_{gi}, \theta_4)$

A: $(r_A, \theta_A) = (r_i, \theta_A)$

B: $(r_B, \theta_B) = (r_o, \theta_B)$

C: $(r_C, \theta_C) = (r_o, \theta_C)$

D: $(r_D, \theta_D) = (r_i, \theta_D)$

The radius coordinates are known now and the angular coordinates are all related. Assuming θ_1 is known, it can be any arbitrary number without affecting results. Let β_1 and β_2 be the spiral angles for curves 12 and 43.

$$\theta_4 = \theta_1 + \theta_g$$

θ_2 is determined by Eq. (g), $\theta_2 = \theta_1 + \dfrac{\ln\left(r_2 / r_{gi}\right)}{\tan\beta_1}$, where r_2, r_{gi}, θ_1, and β_1 are known.

θ_3 is determined by Eq. (g), $\theta_3 = \theta_4 + \dfrac{\ln\left(r_3 / r_{gi}\right)}{\tan\beta_2}$, where r_3, r_{gi}, θ_4, and β_2 are known.

Note: if spiral angle $\beta = 90^o$, the spiral line becomes a radial line with constant theta.

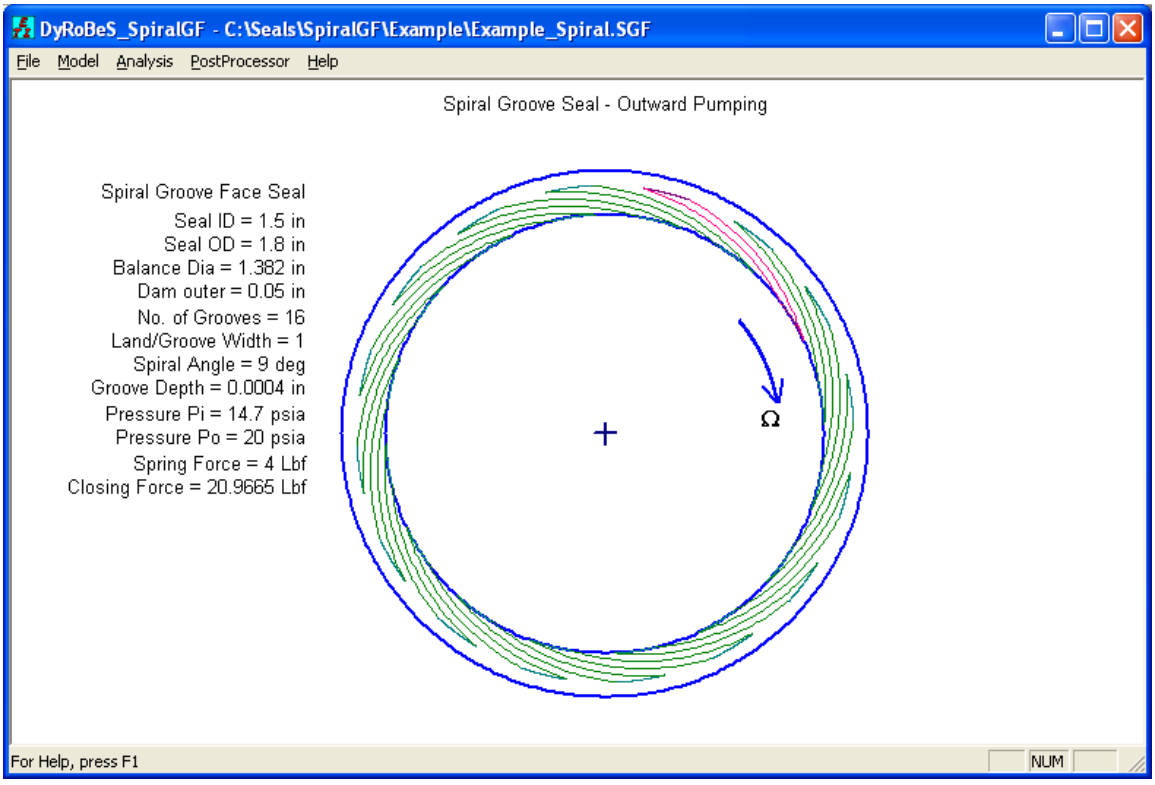
$$\theta_A = \theta_1 - \left(\frac{\theta_L}{2}\right)$$

$$\theta_B = \theta_2 - \left(\frac{\theta_L}{2}\right)$$

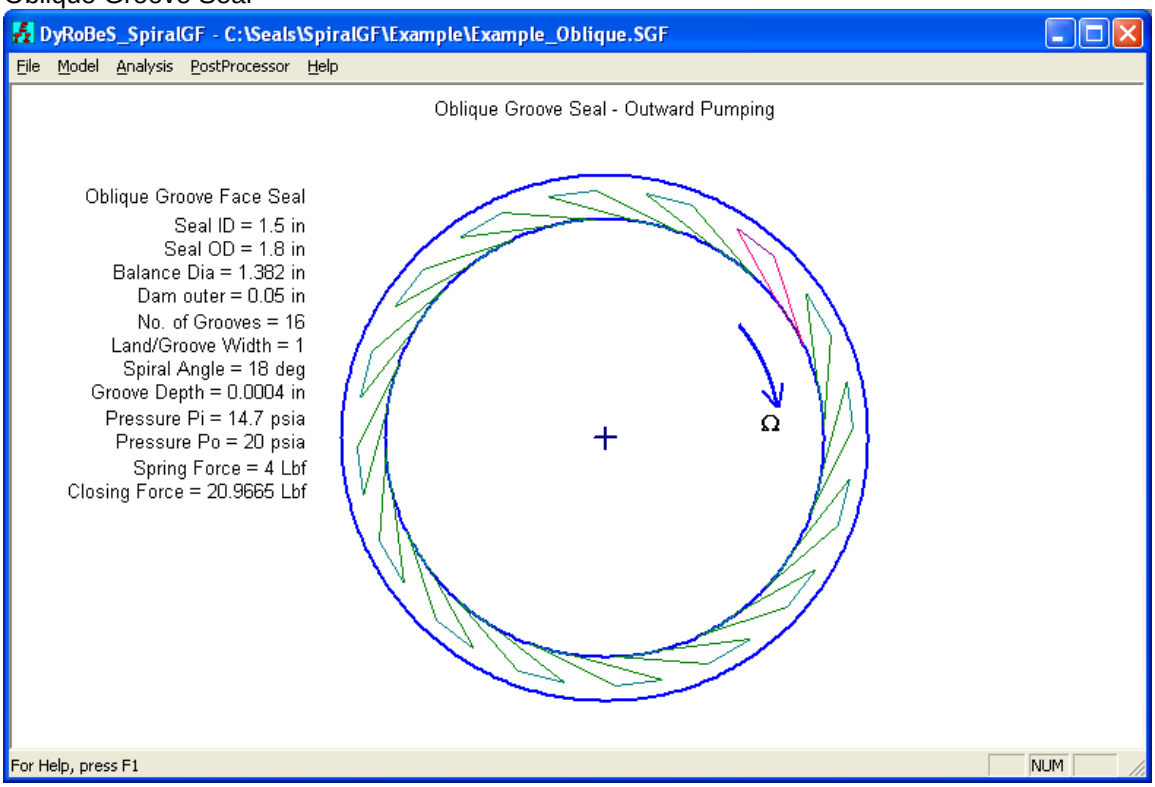
$$\theta_D = \theta_A + \left(\theta_L + \theta_g\right) = \theta_A + \left(\varphi\right)$$

$$\theta_C = \theta_B + \left(\theta_L + \theta_g\right) = \theta_B + \left(\varphi\right)$$

Spiral Groove Seal



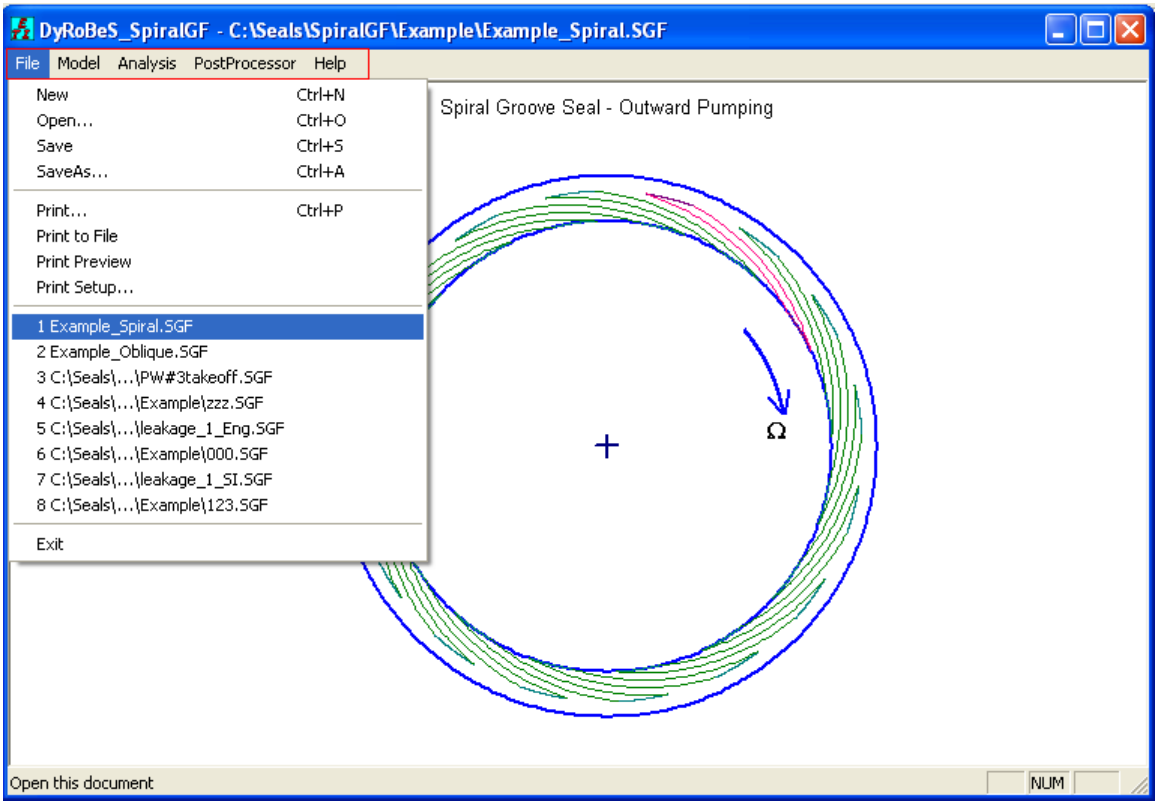
Oblique Groove Seal



[#][$K] **Program Menu Description**

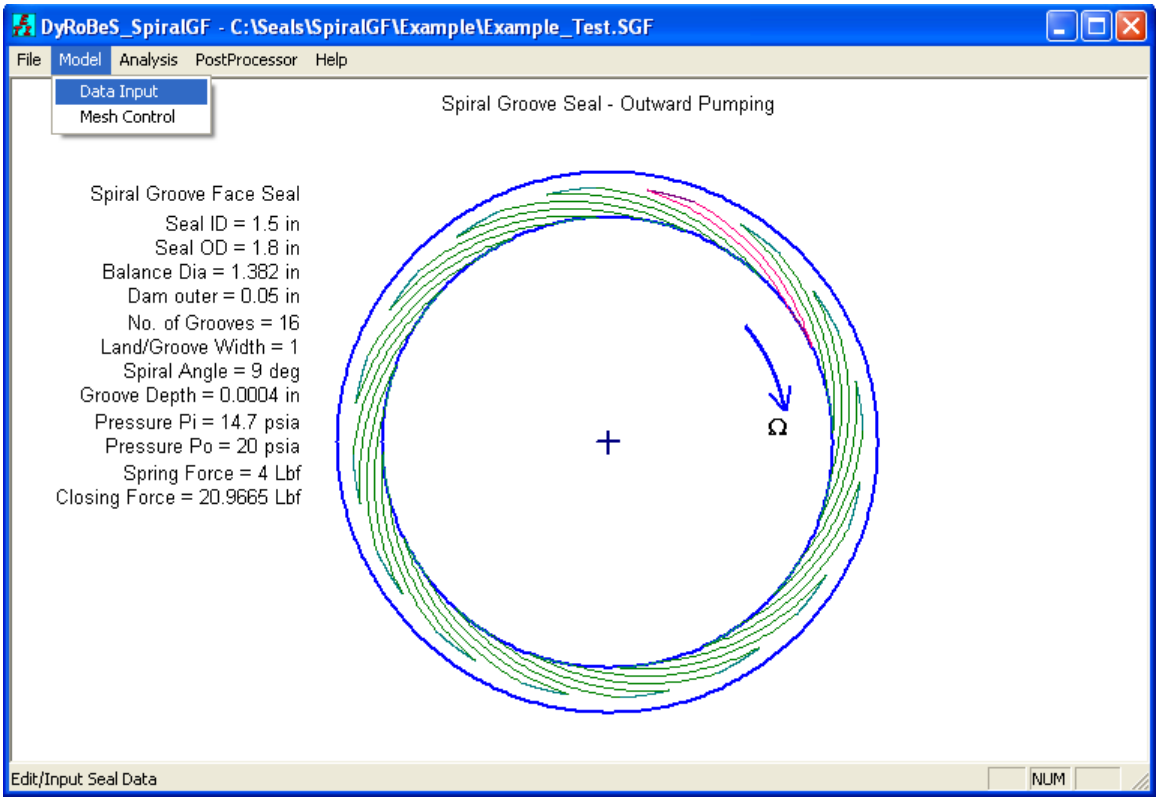
Once the program **SpiralGF** is executed, the main menu appears as below. It contains 5 primary menu options.
File – for file management.
Model – for data entry and mesh control.
Analysis – for analysis option, such as a single case or multiple cases analysis.
Postprocessor – for result display.
Help – for manual and version information.

If an existing file is opened, the main screen area will display that seal geometry and seal related data.



Under Model menu, you may enter the seal data under Data Input or change the finite element mesh density under Mesh Control as shown below.

[#] HID_MENU
[$] Program Menu
[K] Program Menu

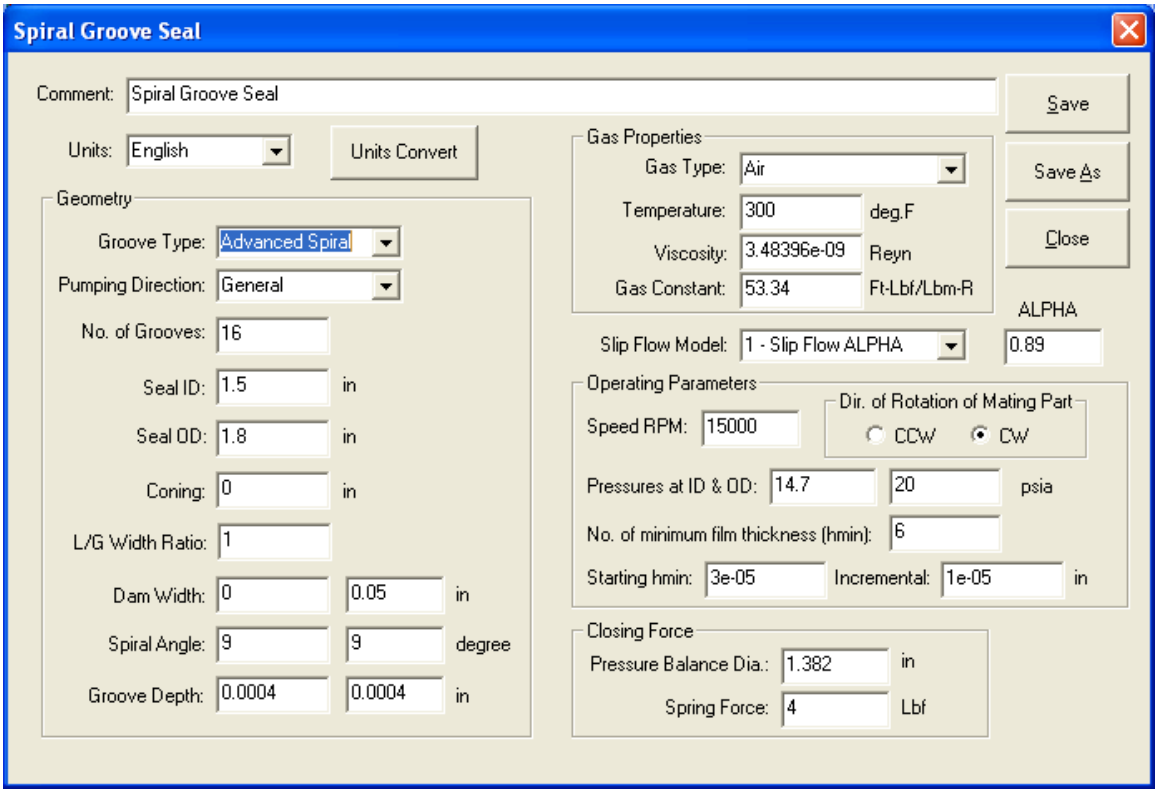


Click below for more information:

- Data Input
- Mesh Control
- Analysis
- Postprocessor

[#$K] Data Input

The data input screen is shown below and brief description is given:



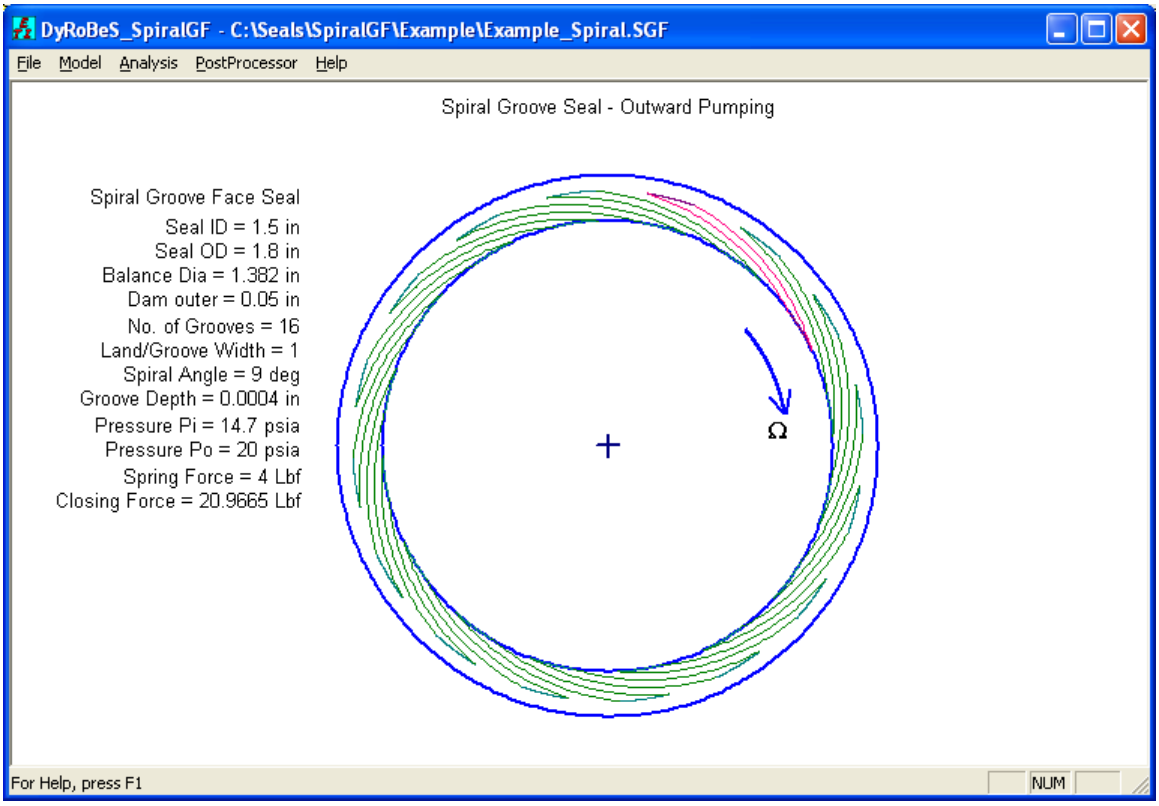
Comment: description for the seal under study.
Units: English or Metric units.
Unit Convert: You may convert the units from English to Metrics or from Metrics to English

Geometry

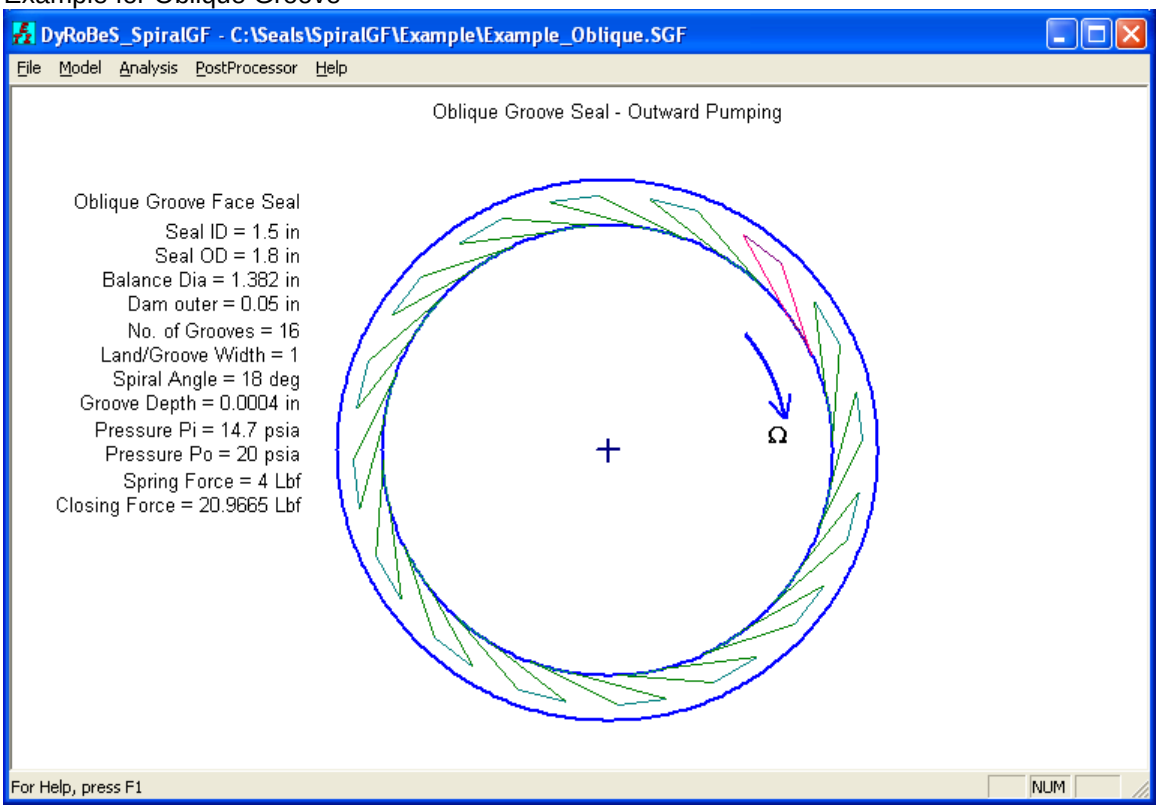
Groove Type: Spiral Groove, Oblique Groove, Radial Groove, and Advanced Groove
For more information see Seal Geometry & Boundary Conditions.

Example for Spiral Groove

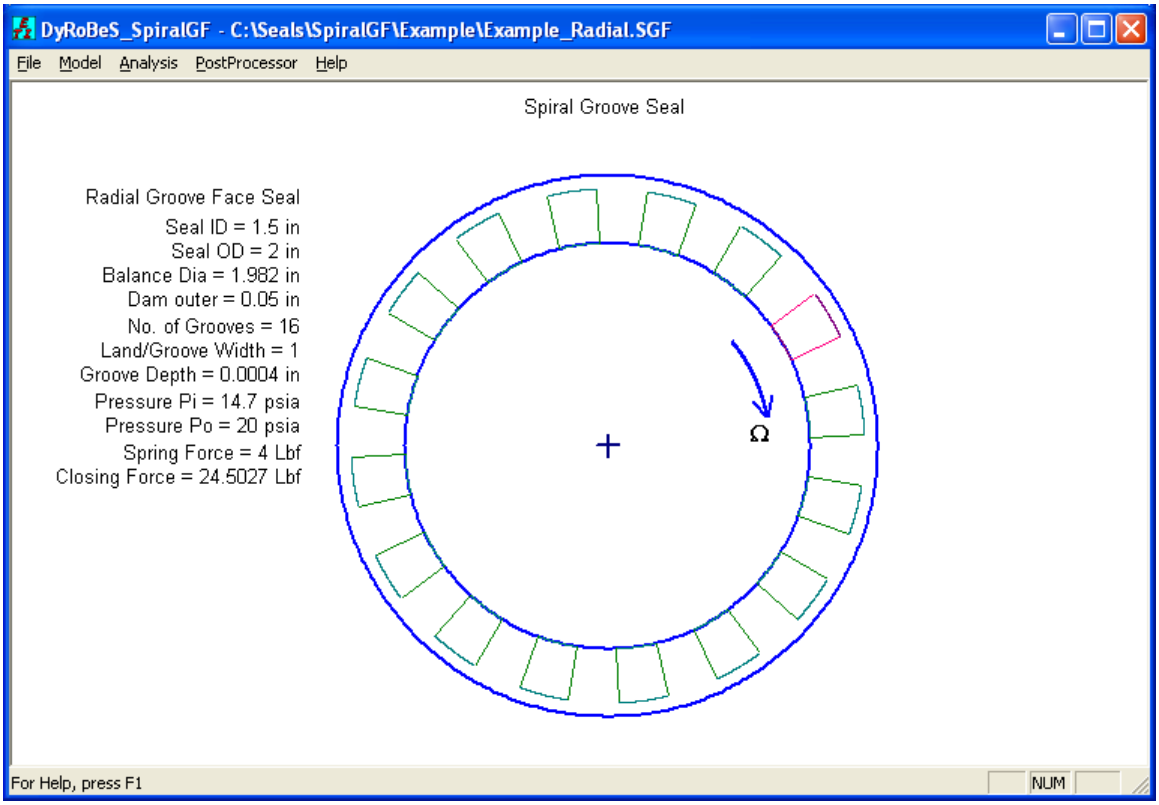
[#] HID_DATA
[$] Data Input
[K] Data Input



Example for Oblique Groove



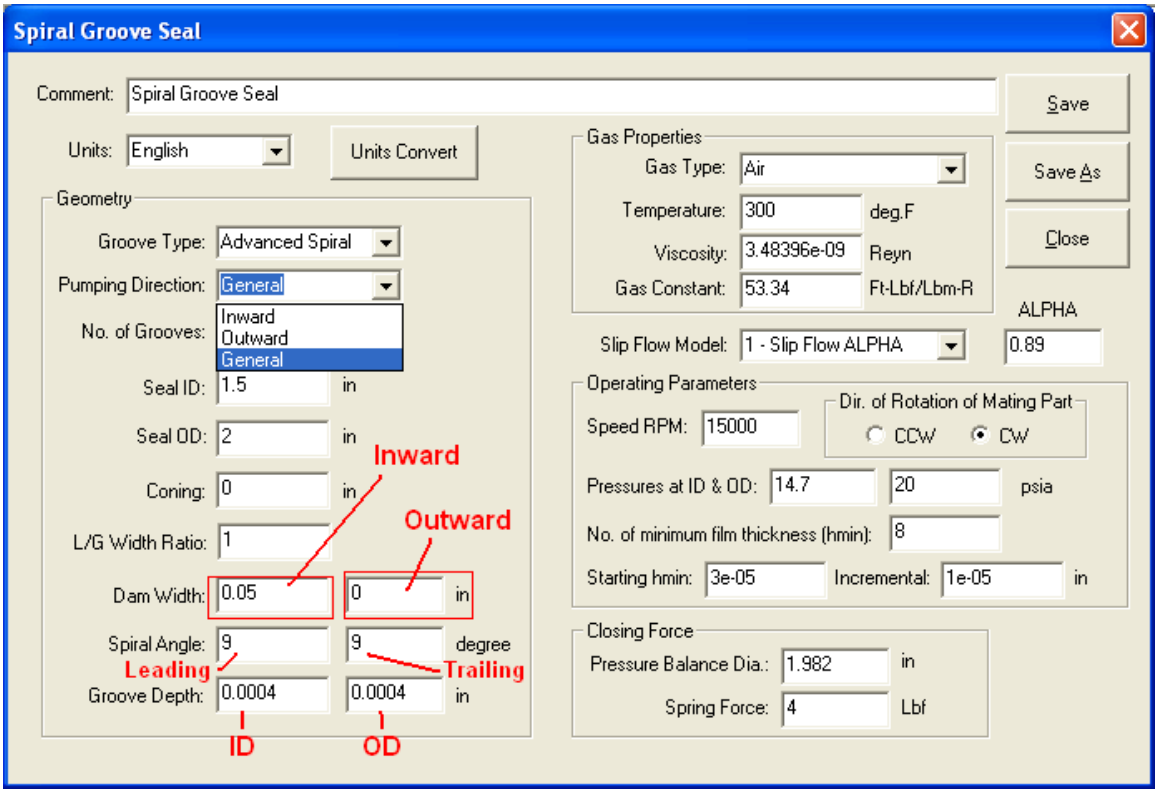
Example for Radial Groove



Advanced Spiral Groove option allows you to build not only the above standard seal geometry, but also many other possibilities.

Pumping Direction: Inward, Outward pumping, or General

A dam exists at the seal ID for inward pumping, and at the seal OD for outward pumping. General options allows for dams at both ID and OD which is NOT common in the face seal applications.



Number of Grooves: Self-explanatory. For more information see Seal Geometry & Boundary Conditions.

Seal ID and OD: Self-explanatory. For more information see Seal Geometry & Boundary Conditions.

Coning: Self-explanatory. For more information see Seal Geometry & Boundary Conditions.

L/G Width Radio: Land / Groove circumferential width ratio. For more information see Seal Geometry & Boundary Conditions.

Spiral Angle: For every spiral groove, there are 2 spiral lines (leading and trailing edges). Commonly there are the same values. In rare cases, they can be different values in advanced spiral groove option. For more information see Seal Geometry & Boundary Conditions.

Groove Depth: Self-explanatory. Typically, the groove depth is a constant value. For advanced groove option, the groove depth can be a linear function from ID to OD. Then the groove depth at ID and OD are entered. For more information see Seal Geometry & Boundary Conditions.

Gas Properties

The **Gas Constant**, **Viscosity**, and **Temperature** are needed for the gas properties. For AIR, once the temperature is specified, the viscosity and gas constant will be auto-updated.

Slip Flow Model

There are 3 options for this selection:
0 – No Slip Flow Correction, then Q = 1 in the Reynolds Equation.
1 – Slip Flow ALPHA – Based on Lin Wu's paper.

2 – F-K model – Based on S. Fukui and R. Kaneko paper.

Operating Parameters

Speed RPM: Self-explanatory.

Direction of Rotation of Mating Part: Self-explanatory. Either CCW or CW.

Pressures at ID and OD: Specify the pressure at boundaries.

No. of Minimum Film Thickness, **Starting Hmin**, and **Incremental Hmin**: Minimum film thickness is specified and the opening force is calculated based on this film thickness. The program will calculate the seal performance for a range of minimum film thickness. The minimum film thickness starts from **Starting Hmin** and **incremental Hmin** for a total number of **No. of Minimum Film Thickness**.

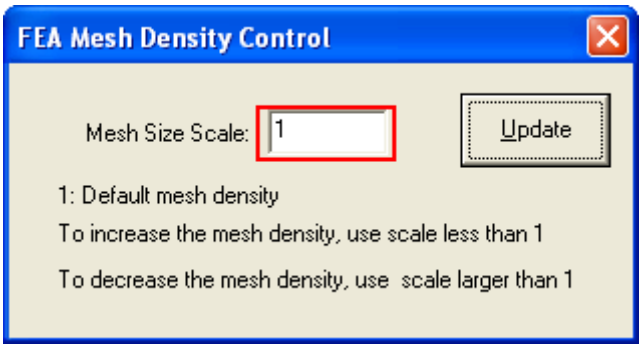
Closing Force

One of the user inputs is seal pressure balance diameter, Γ, which can be a bellow mean effective diameter or a secondary seal pressure diameter. The pressure balance diameter effectively divides the pressure on the back of the seal into two zones. The inner zone is exposed to ID pressure Pi and the outer zone is exposed to OD pressure Po. Usually, there is a spring (or magnetic) force that pushes the seal to close. Total closing force = closing force due to pressure + spring force. Let Γ = pressure balance diameter and F_s is the spring force, Total closing force is:

$$F_{close} = F_s + P_o\pi(OD^2 - \Gamma^2)/4 + P_i\pi(\Gamma^2 - \mathrm{ID}^2)/4$$

[#][$K] **Mesh Control**

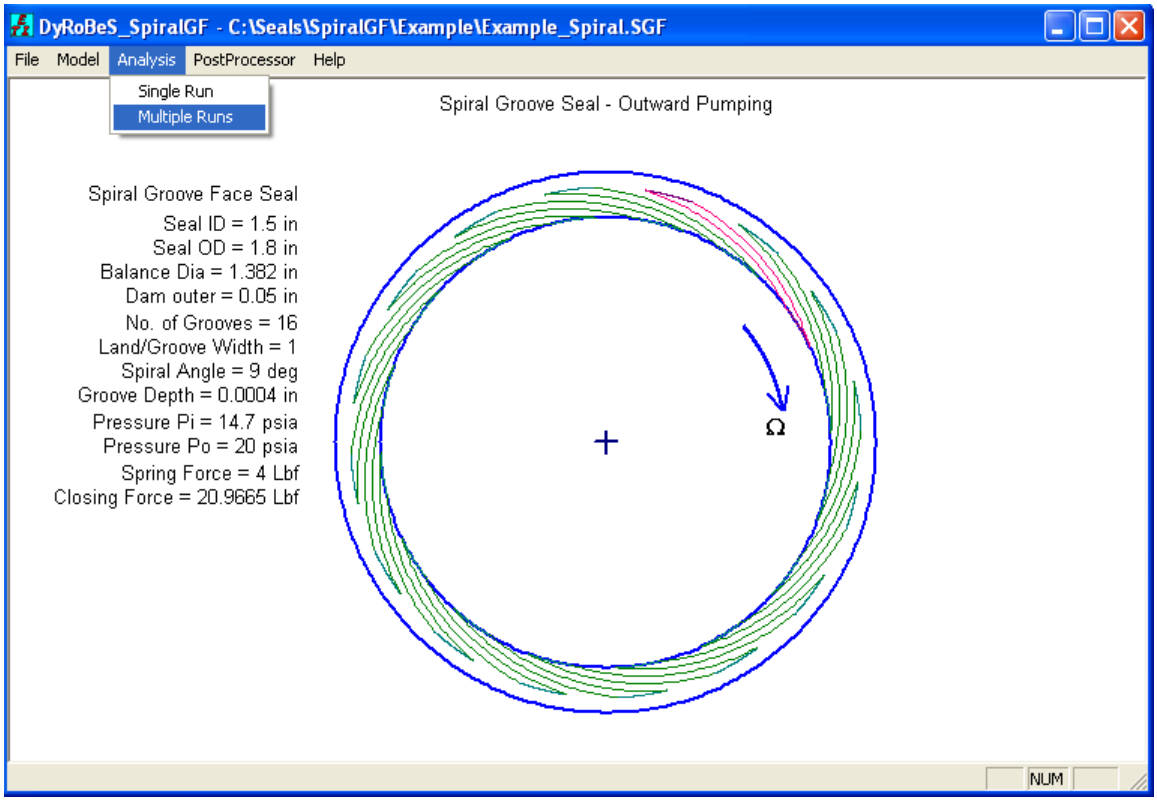
The FEA mesh density control is by the Mesh Size Scale. By default, 1 will create a very reasonable mesh size. In some cases, a finer mesh is needed for the convergence, then use smaller Mesh Size Scale, such as 0.9 or 0.8. Note that lower the Mesh Size Scale will increase the number of meshes and increase the computational time.



[#] HID_MESH
[$] Mesh Control
[K] Mesh Control

[#][$K] Analysis

The Analysis menu has 2 options:
1 – Single Run: This will analyze the seal as given in the Data Input
2 – Multiple Runs: This allows for design iterations and performs design optimization and parametric study.



The following display shows a multiple run example. The spiral angle and groove depth effects are studied. Only the changed values are entered, blank and zero indicate that the default values from Case 1 will be used.

[#] HID_ANALYSIS
[$] Analysis Option
[K] Analysis Option

Spiral Groove Seal Multiple Runs

Enter the values that are changed only. Leave blank if the values are the same as the first case.

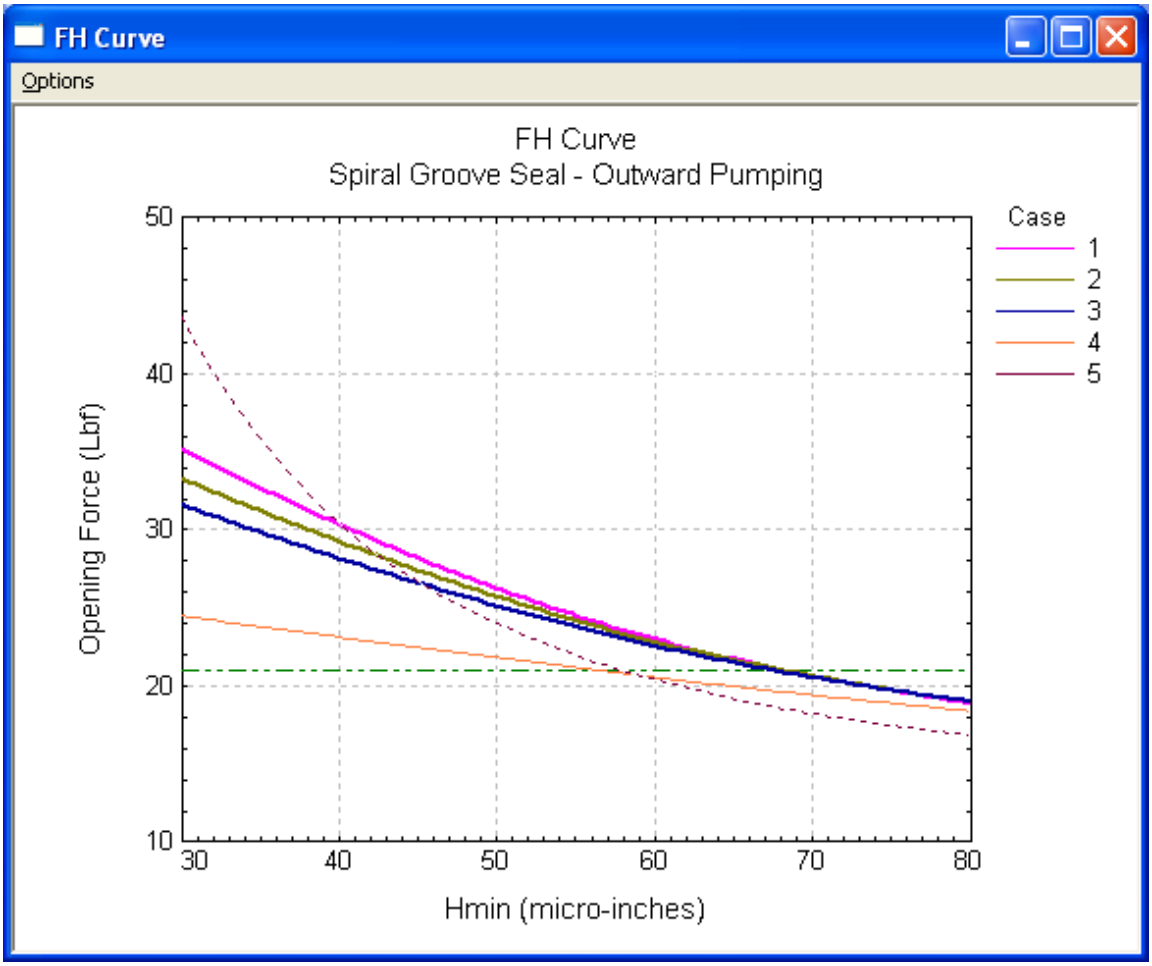
OK Cancel

No.	rpm	Pi	Po	Ng	Seal ID	Seal OD	Coning	L/G	Dam Width	Spiral Angle	Groove Depth
1	15000	14.7	20	16	1.5	1.8	0	1	0.05	9	0.0004
2										10	
3										11	
4											0.0006
5											0.0002
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											

Spiral Angle Effect

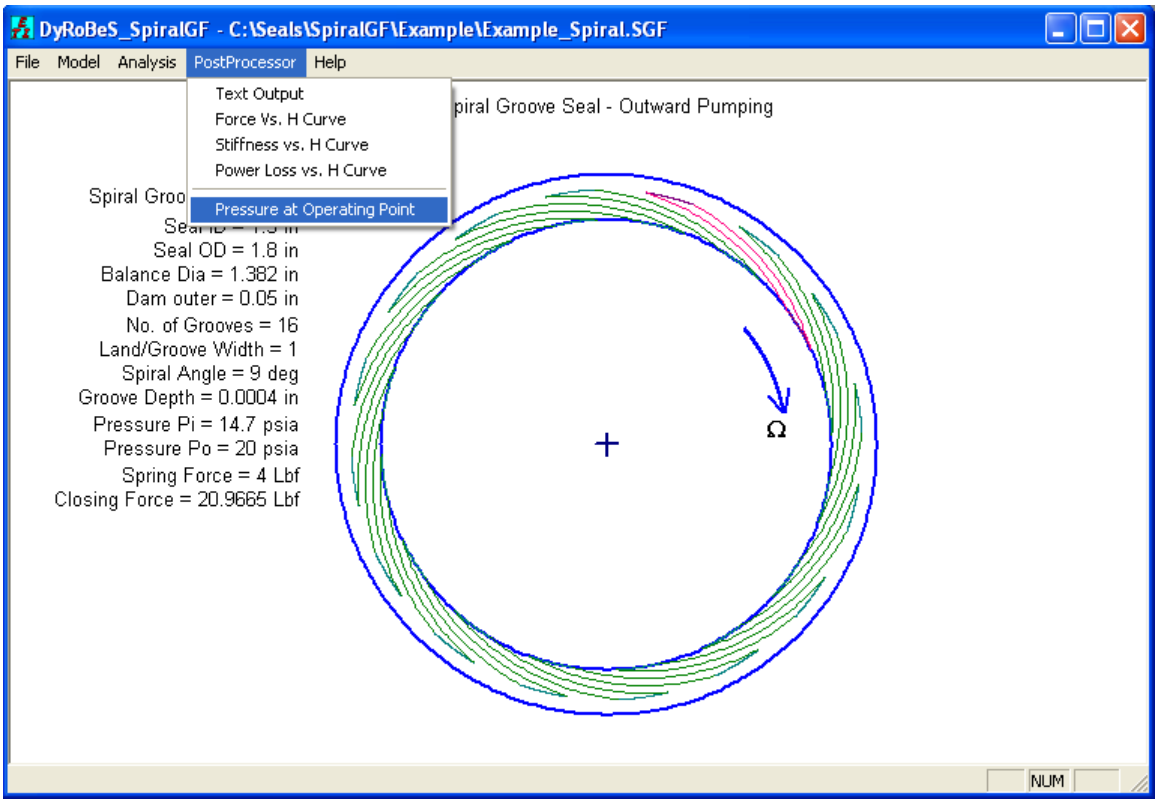
Groove Depth Effect

The F-H curves are shown below for this multiple run:



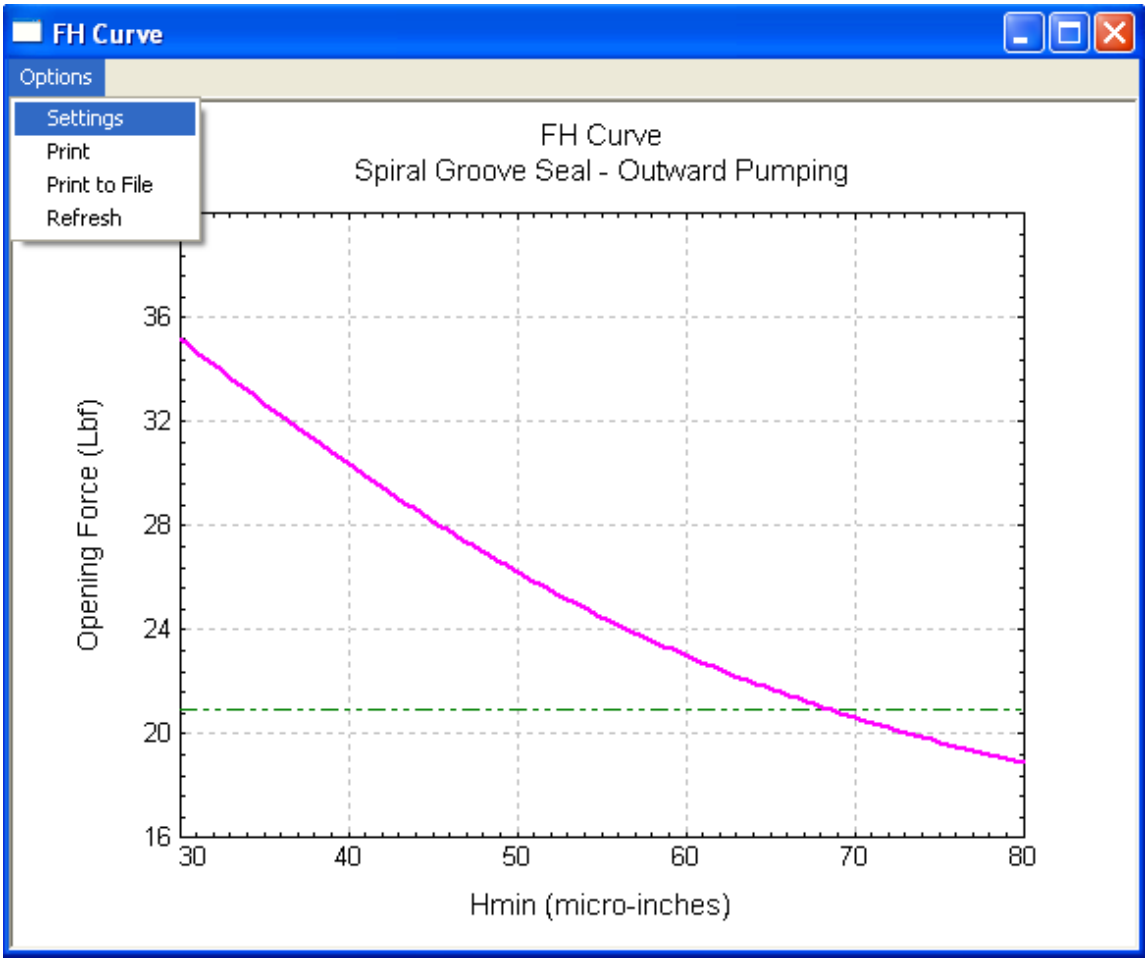
[#$K] Post Processor

After the analysis is performed, one can view the results in text or graphic formats. Since the analysis is performed for a range of minimum film thickness, the opening force, stiffness, and power loss can be plotted versus film thickness. At the operating point, where the opening force equals to the closing force, the pressure distribution, film thickness, Kn, and Q factor can be plotted.

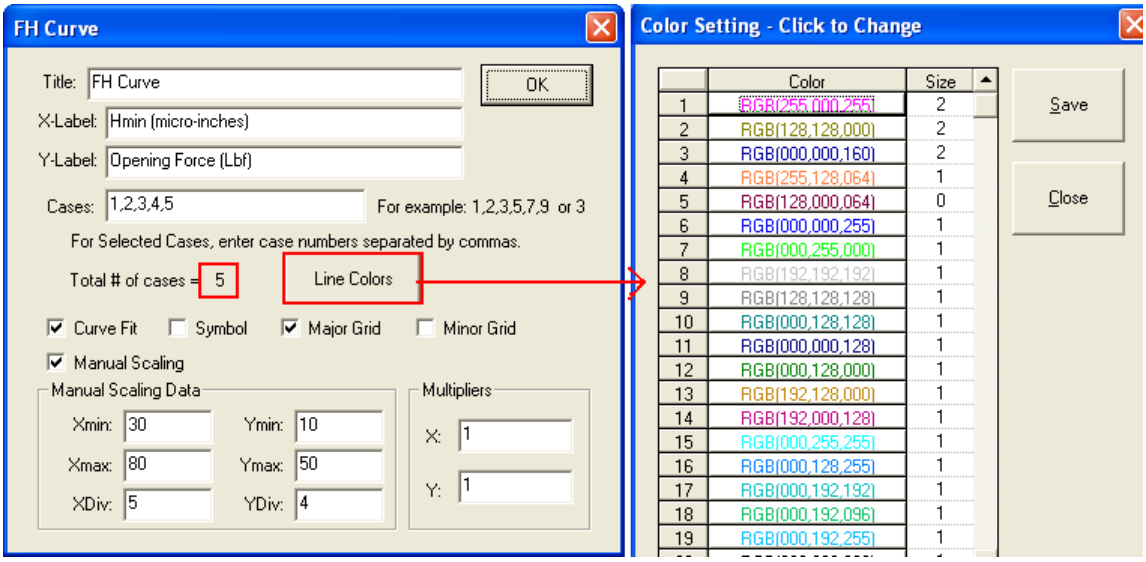


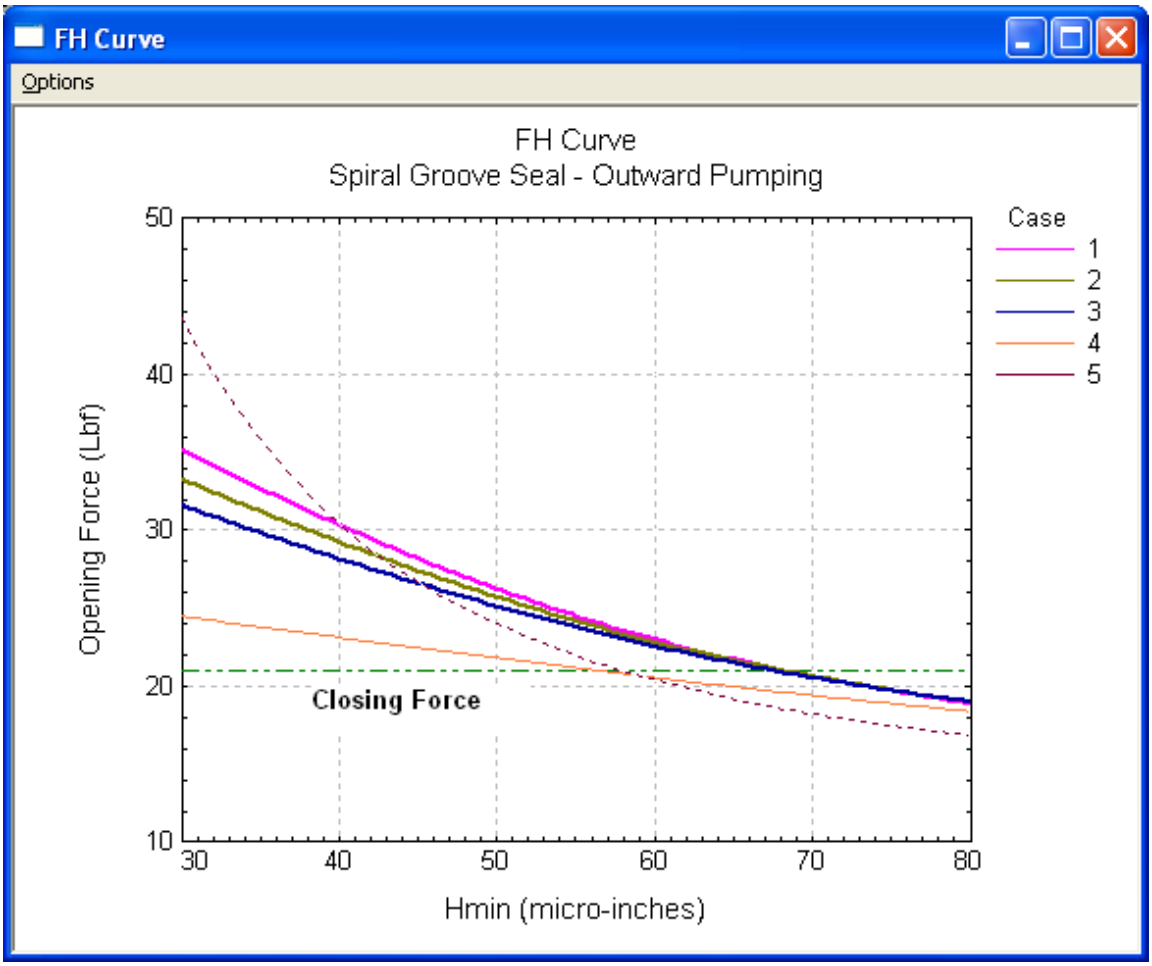
When plotting Force, Stiffness, or Power Loss vs. Hmin curve, the default display will appear as shown below:

[#] HID_POST
[$] Post Processor
[K] Post Processor

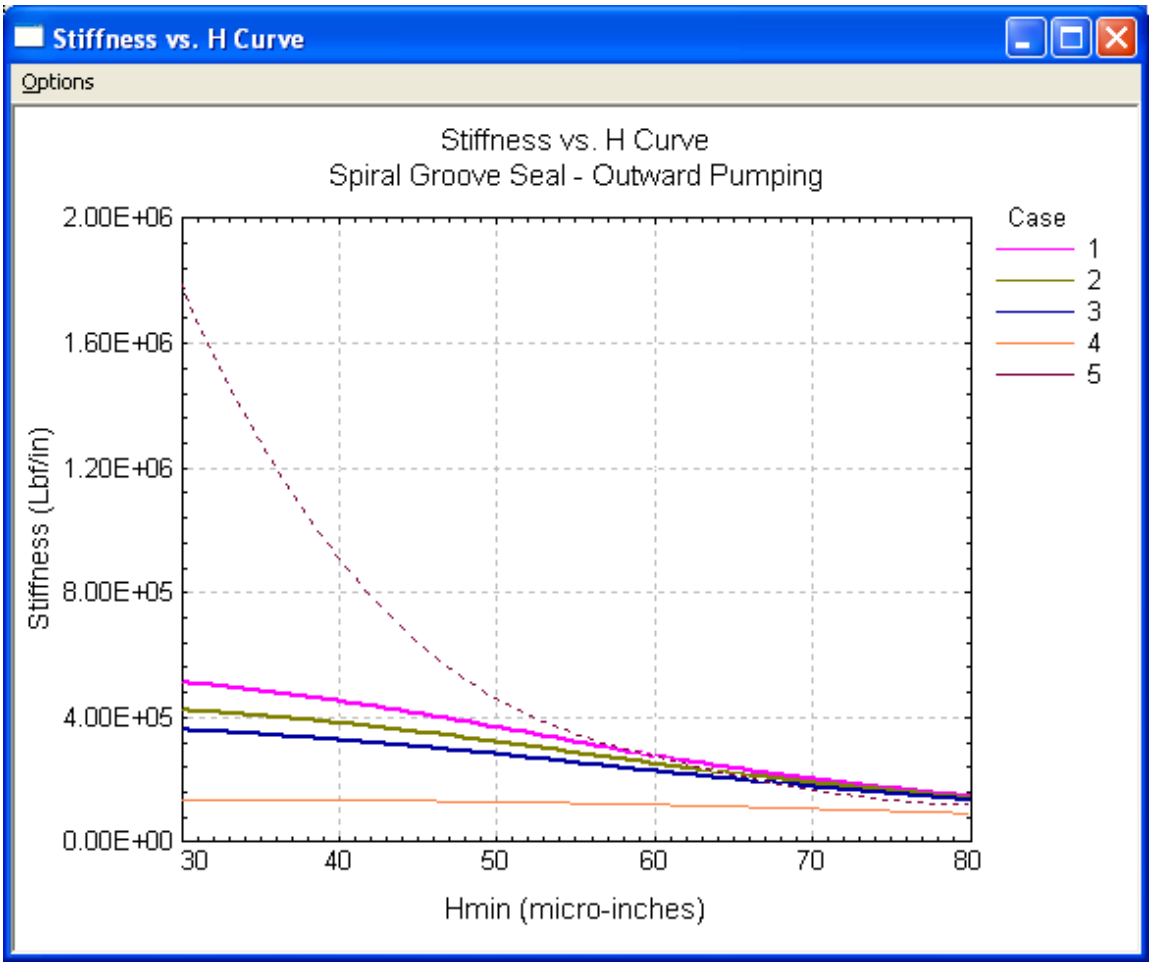


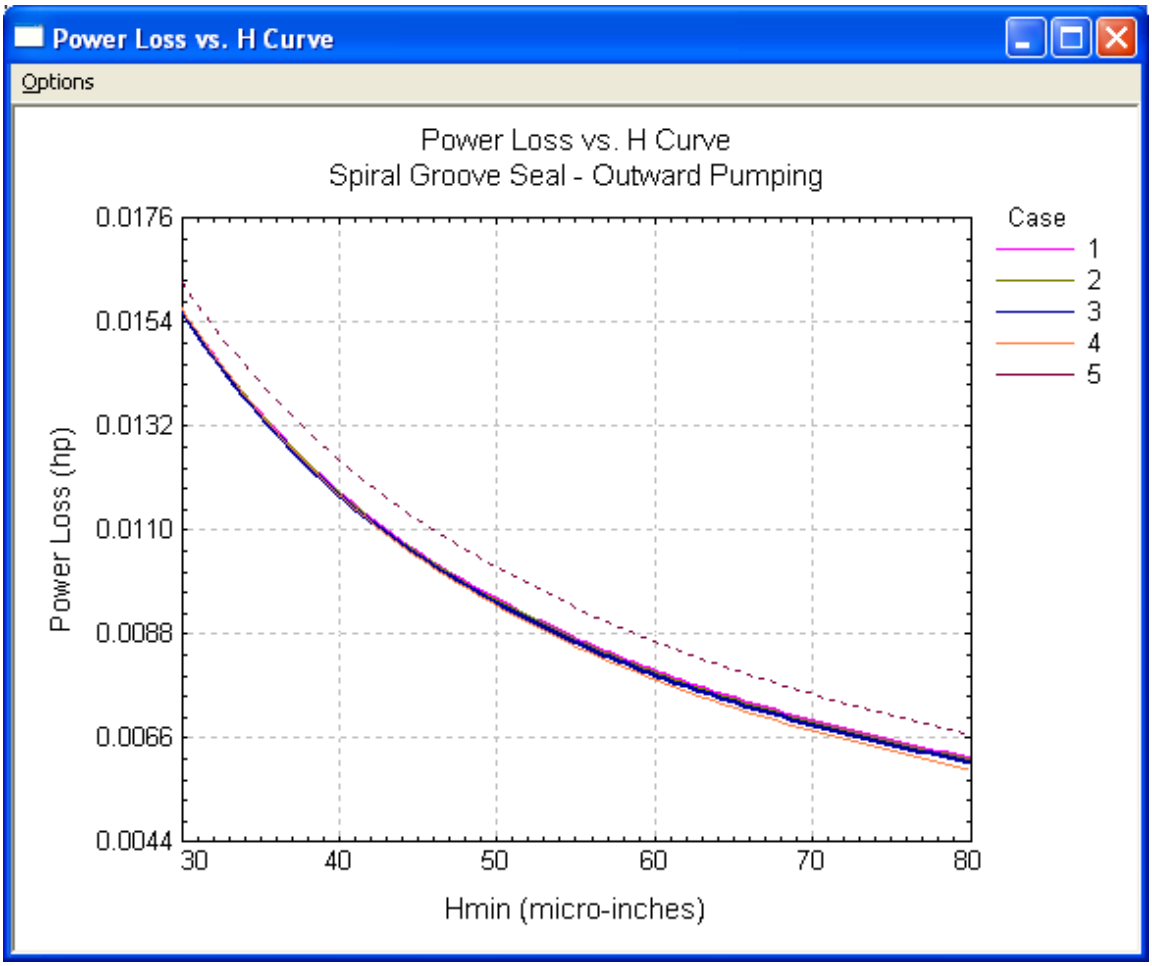
You may go to Options and Settings option to change some default settings. If multiple cases (runs) exist, then you may select cases which you want to be displayed. You may change the line colors, scales, etc. For line color, if size 0 is entered, this line will be plotted in dotted line. The horizontal dash line indicates the closing force.



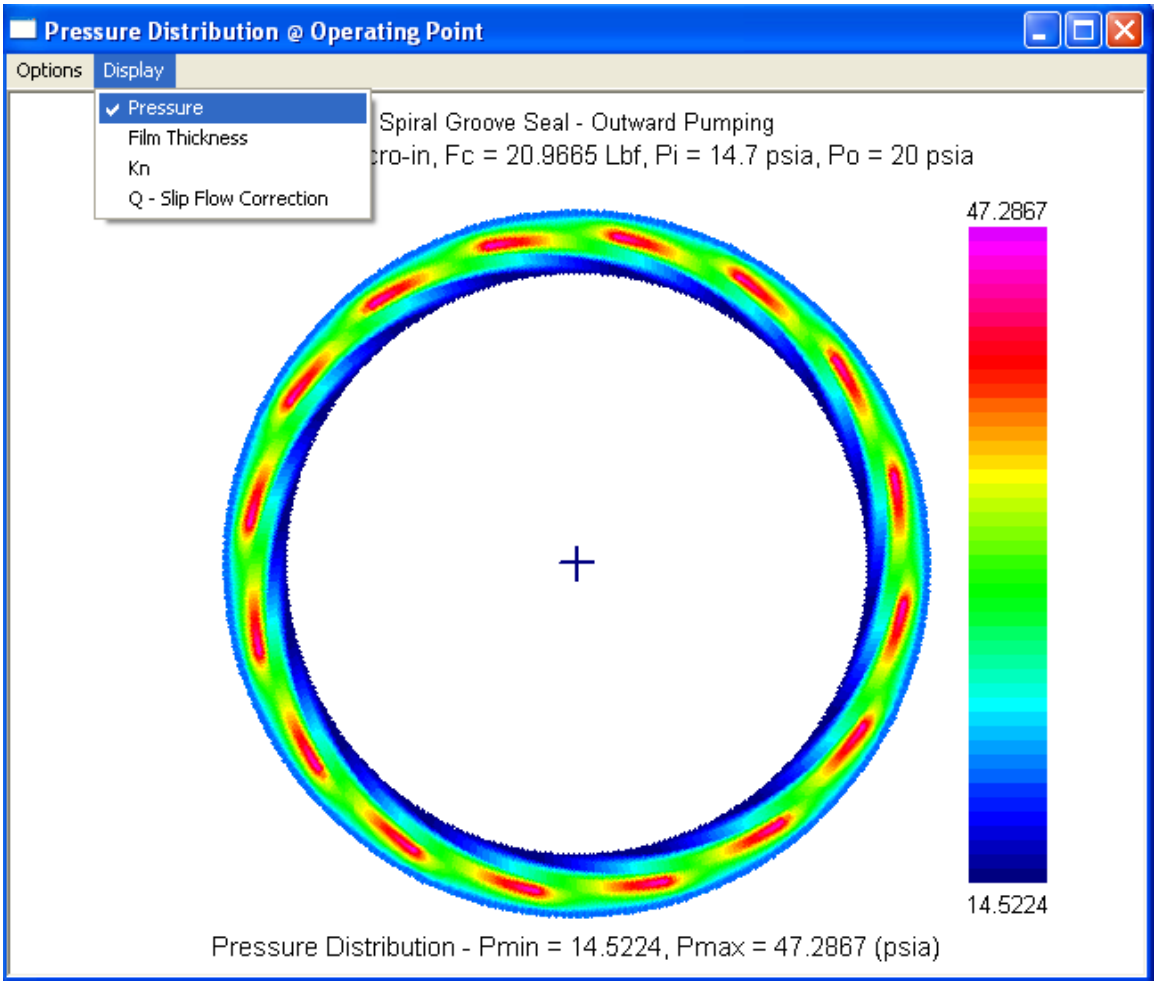


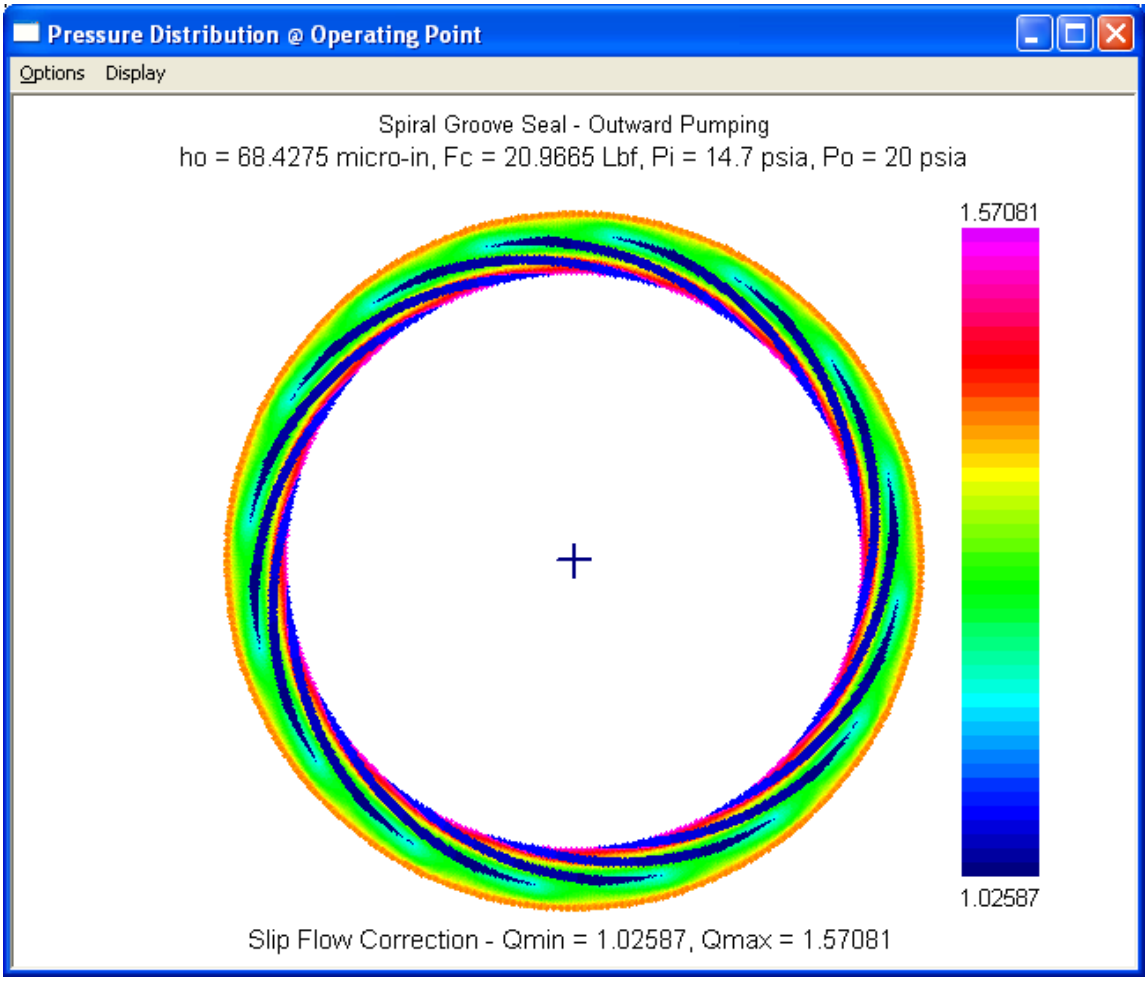
Following figures show the stiffness and power loss.


Stiffness vs. H Curve
Options
Stiffness vs. H Curve
Spiral Groove Seal - Outward Pumping
Case
1
2
3
4
5
2.00E+06
1.60E+06
1.20E+06
8.00E+05
4.00E+05
0.00E+00
Stiffness (Lbf/in)
30
40
50
60
70
80
Hmin (micro-inches)

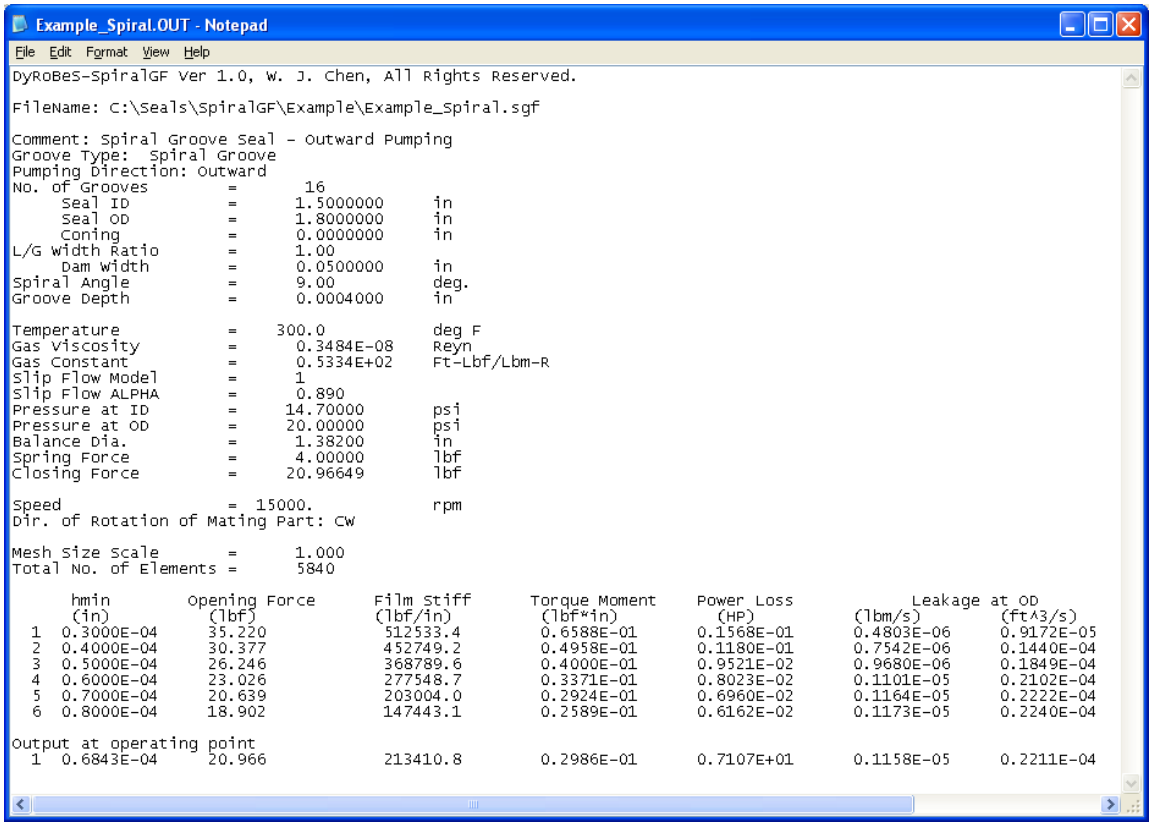


Plots at the operating point – Operating point indicates the opening force and closing force are equal.


Pressure Distribution @ Operating Point
Options
Display
Pressure
Film Thickness
Kn
Q - Slip Flow Correction
Spiral Groove Seal - Outward Pumping
cro-in, Fc = 20.9665 Lbf, Pi = 14.7 psia, Po = 20 psia
47.2867
14.5224
Pressure Distribution - Pmin = 14.5224, Pmax = 47.2867 (psia)

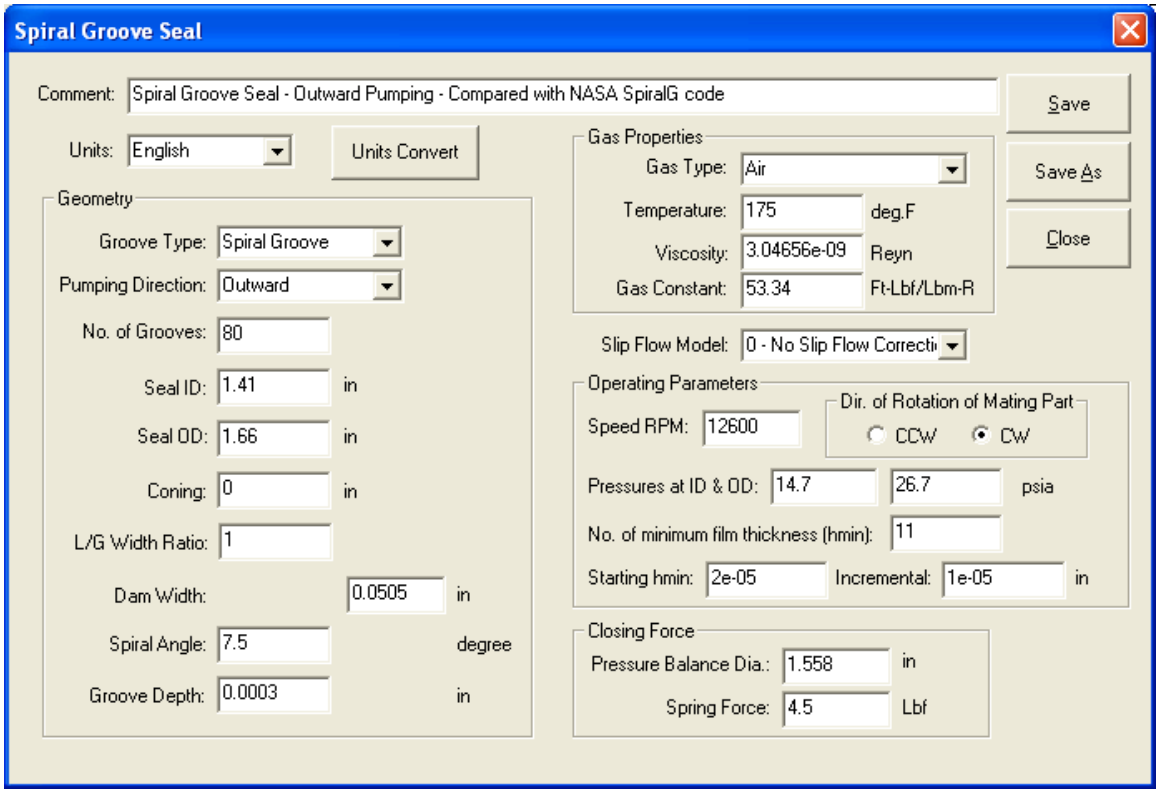


Test Output Example

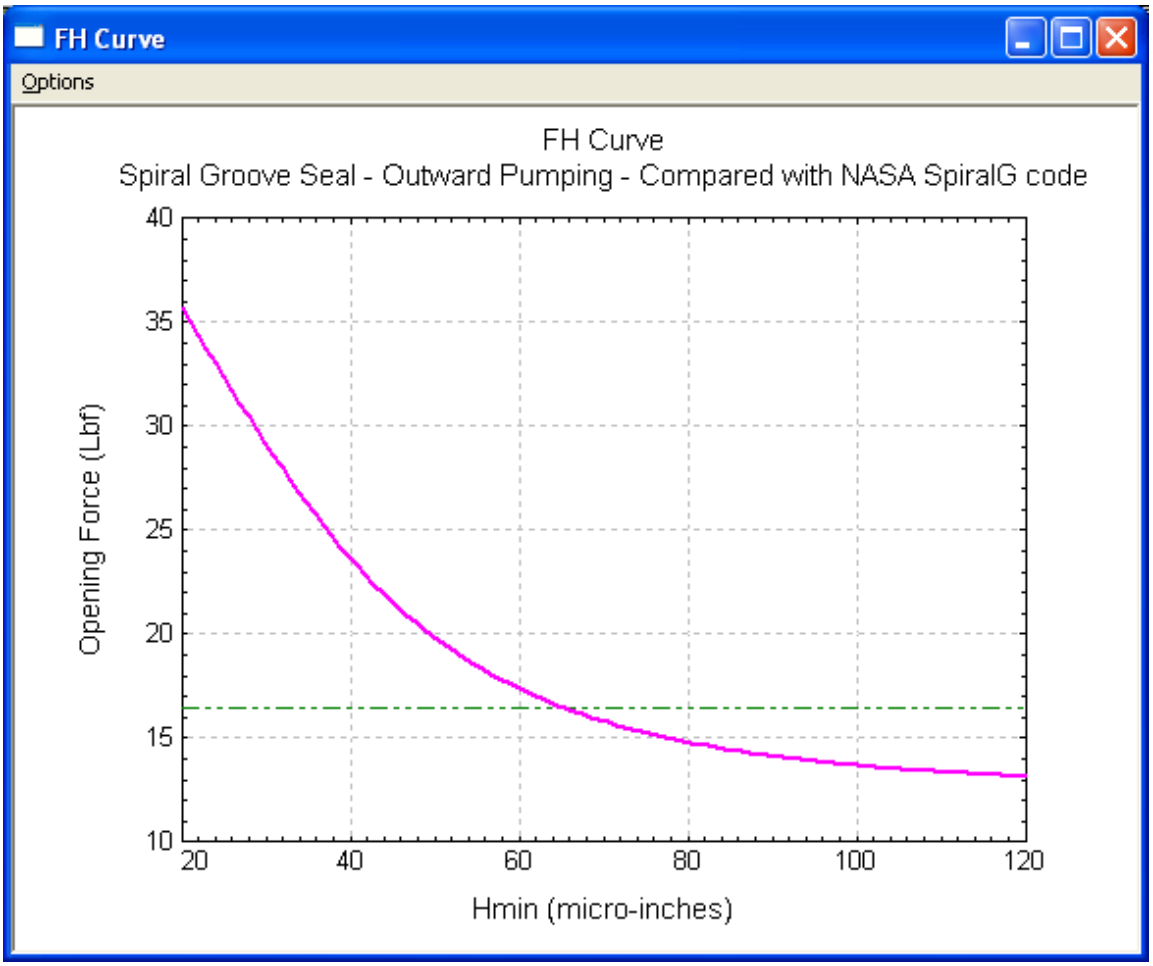

Example_Spiral.OUT - Notepad
File Edit Format View Help
DyRoBeS-SpiralGF Ver 1.0, W. J. Chen, All Rights Reserved.
FileName: C:\Seals\SpiralGF\Example\Example_Spiral.sgf
Comment: Spiral Groove Seal - Outward Pumping
Groove Type: Spiral Groove
Pumping Direction: Outward
No. of Grooves = 16
Seal ID = 1.5000000 in
Seal OD = 1.8000000 in
Coning = 0.0000000 in
L/G Width Ratio = 1.00
Dam Width = 0.0500000 in
Spiral Angle = 9.00 deg.
Groove Depth = 0.0004000 in
Temperature = 300.0 deg F
Gas Viscosity = 0.3484E-08 Reyn
Gas Constant = 0.5334E+02 Ft-Lbf/Lbm-R
Slip Flow Model = 1
Slip Flow ALPHA = 0.890
Pressure at ID = 14.70000 psi
Pressure at OD = 20.00000 psi
Balance Dia. = 1.38200 in
Spring Force = 4.00000 lbf
Closing Force = 20.96649 lbf
Speed = 15000. rpm
Dir. of Rotation of Mating Part: CW
Mesh Size Scale = 1.000
Total No. of Elements = 5840
hmin (in) Opening Force (lbf) Film Stiff (lbf/in) Torque Moment (lbf*in) Power Loss (HP) Leakage at OD (lbm/s) (ft^3/s)
1 0.3000E-04 35.220 512533.4 0.6588E-01 0.1568E-01 0.4803E-06 0.9172E-05
2 0.4000E-04 30.377 452749.2 0.4958E-01 0.1180E-01 0.7542E-06 0.1440E-04
3 0.5000E-04 26.246 368789.6 0.4000E-01 0.9521E-02 0.9680E-06 0.1849E-04
4 0.6000E-04 23.026 277548.7 0.3371E-01 0.8023E-02 0.1101E-05 0.2102E-04
5 0.7000E-04 20.639 203004.0 0.2924E-01 0.6960E-02 0.1164E-05 0.2222E-04
6 0.8000E-04 18.902 147443.1 0.2589E-01 0.6162E-02 0.1173E-05 0.2240E-04
Output at operating point
1 0.6843E-04 20.966 213410.8 0.2986E-01 0.7107E+01 0.1158E-05 0.2211E-04

#$K **Example 1**

This example is used to compare the results with NASA SpiralG code. Due to many assumptions and restrictions used in the NASA code, following seal data is used in the comparison purposes. The results are in good agreement. However, only F-H curve is presented here.



HID_EXAMPLE1
$ Example 1
K Example 1


FH Curve
Options
FH Curve
Spiral Groove Seal - Outward Pumping - Compared with NASA SpiralG code
Opening Force (Lbf)
40
35
30
25
20
15
10
20
40
60
80
100
120
Hmin (micro-inches)