

**DEVELOPING DIMENSIONLESS PI GROUPS  
TO MODEL THE FORCE COEFFICIENTS OF  
POCKET DAMPER SEALS**

**MASTERS' NON-THESIS PROJECT**

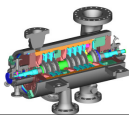


**NIJESH JAYAKAR**

**SPECIAL THANKS**

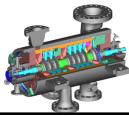
**GRADUATE ADVISORY COMMITTEE:**

- **DR. JOHN M. VANCE., MECHANICAL ENGINEERING  
COMMITTEE CHAIR**
- **DR. SHERIF NOAH., MECHANICAL ENGINEERING**
- **DR. BRETT A. PETERS., INDUSTRIAL ENGINEERING**



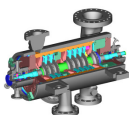
## OUTLINE

- ◆ OBJECTIVE
- ◆ INTRODUCTION
- ◆ IDENTIFICATION OF SIGNIFICANT VARIABLES
- ◆ IDENTIFICATION OF SIGNIFICANT PI GROUPS
- ◆ DESIGN PLOTS WITH SIGNIFICANT PI GROUPS
- ◆ CONCLUSION



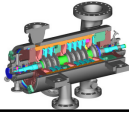
## OBJECTIVE

- ✓ DEVELOP PI GROUPS FOR POCKET DAMPER SEAL (PDS)
- ✓ IDENTIFY SIGNIFICANT PI GROUPS
- ✓ DEVELOP AND ANALYZE DESIGN PLOTS WITH SIGNIFICANT PI GROUPS
- ✓ PROVIDE VIABLE DESIGN TOOL FOR DIFFERENT PDS CONFIGURATIONS



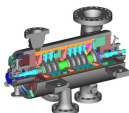
## INTRODUCTION

- **ANNULAR SEALS, THE PRIMARY TASK IS TO RESTRICT LEAKAGE BETWEEN A ROTATING SHAFT AND A STATIONARY HOUSING**
- **CONVENTIONAL LABYRINTH SEALS CONTINUE TO BE A SOURCE OF AERODYNAMIC EXCITATION IN HIGH-PRESSURE COMPRESSORS**
- **A NEW TYPE OF LABYRINTH SEAL, POCKET DAMPER SEAL (PDS) THAT REDUCES CROSS-COUPLED ROTOR FORCES AND PRODUCES A REMARKABLE AMOUNT OF DAMPING WAS INVENTED AT TEXAS A&M UNIVERSITY**
- **DR. VANCE AND HIS STUDENT SCHULTZ DEVELOPED THE POCKET DAMPER SEAL**






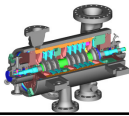
## INTRODUCTION [CONTD..]

- **THE POCKET DAMPER SEAL HAS MUCH HIGHER DAMPING THAN CONVENTIONAL LABYRINTHS, HENCE USED TO ELIMINATE INSTABILITIES IN CENTRIFUGAL COMPRESSORS**
- **PDS PROVIDES DAMPING THAT CAN BE A HUNDRED TIMES HIGHER THAN A STANDARD LABYRINTH SEAL**
- **THE SUB SYNCHRONOUS VIBRATION IS BELIEVED TO BE THE RESULT OF HIGH AERODYNAMIC CROSS COUPLING INTRODUCED BY CONVENTIONAL GROOVED ROTOR AND STATIONARY LABYRINTH CENTER SEALS**
- **THE SEPARATION WALLS IN PDS REDUCE THE FLUID CIRCULATION AND THE CORRESPONDING CROSS-COUPLED STIFFNESS**



## INTRODUCTION [CONTD..]

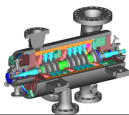
-  **THE INLET TOOTH OF EACH CAVITY HAS A TIGHTER CLEARANCE COMPARED TO THE EXIT TOOTH THUS PRODUCING A DIVERGING CLEARANCE IN THE DIRECTION OF FLOW**
-  **THE DIVERGING CLEARANCE AND THE POCKETED DESIGN ALONG WITH OPTIMIZATION OF THE POCKET VOLUME, PRODUCE HIGH DIRECT DAMPING WHILE REDUCING THE CROSS COUPLED STIFFNESS**
-  **THE CURRENT PROJECT WORK PROVIDES A DESIGN TOOL FOR THE PDS ANALYSIS**



## IDENTIFICATION OF SIGNIFICANT VARIABLES

**NOMENCLATURE OF RELEVANT VARIABLES :**  
**NUMBER OF VARIABLES = 18**

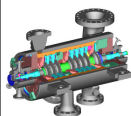
$C_{xx}$	direct damping, lb-s/in
$\omega$	Frequency, rad/s
$CR_i$	radial clearance at the inlet, in
$\Delta P$	pressure drop, psi
$L$	seal length, in
$D$	seal diameter, in





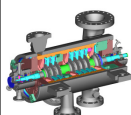
**NOMENCLATURE OF RELEVANT VARIABLES : [CONTD..]**

- $K_{xx}$  direct damping, lb/in
- $\dot{w}$  leakage, lb/s
- $V_a$  acoustic velocity (replaces R, T and k), in/s
- $B$  radial cavity depth, in
- $PR$  pitch ratio, dimensionless
- $g_c$  acceleration of gravity, in/s<sup>2</sup>



**NOMENCLATURE OF RELEVANT VARIABLES : [CONTD..]**

- $N_B$  number of blades (teeth), dimensionless
- $P_i$  pressure at the inlet to the seal, psia
- $R_C$  clearance ratio, dimensionless
- $b_t$  thickness of teeth, in
- $b_w$  thickness of separation walls, in
- $N_W$  number of circumferential pockets,  
dimensionless

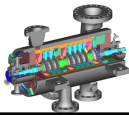


## IDENTIFICATION OF SIGNIFICANT PI GROUPS



### BUCKINGHAM PI THEOREM:

**THE NUMBER OF DIMENSIONLESS AND INDEPENDENT QUANTITIES REQUIRED TO EXPRESS A RELATIONSHIP AMONG THE VARIABLES IN ANY PHENOMENON IS EQUAL TO THE NUMBER OF QUANTITIES INVOLVED, MINUS THE NUMBER OF DIMENSIONS IN WHICH THOSE QUANTITIES MAY BE MEASURED**



### BUCKINGHAM PI THEOREM: [CONTD..]

**IN EQUATION FORM THE PI THEOREM IS,**

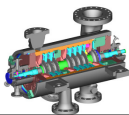
$$S = N - B$$

**WHERE,**

**S IS THE NUMBER OF  $\pi$  TERMS**

**N IS THE TOTAL NUMBER OF QUANTITIES INVOLVED**

**B IS THE NUMBER OF BASIC DIMENSIONS INVOLVED**





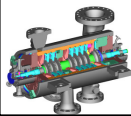
**BUCKINGHAM PI THEOREM: [CONTD..]**

**WE CAN WRITE,**

$$C_{\alpha} C_{XX}^{C1} \omega^{C2} CR_i^{C3} \Delta P^{C4} L^{C5} D^{C6} K_{XX}^{C7} \dot{w}^{C8} \\ V_a^{C9} B^{C10} g_C^{C11} N_B^{C12} PR^{C13} P_i^{C14} R_C^{C15} b_t^{C16} b_w^{C17} N_W^{C18} = 1$$

**THE CORRESPONDING DIMENSIONAL EQUATION IS GIVEN BY,**

$$[FTL^{-1}]^{C1} [T^{-1}]^{C2} [L]^{C3} [FL^{-2}]^{C4} [L]^{C5} [L]^{C6} [FL^{-1}]^{C7} [FT^{-1}]^{C8} \\ [LT^{-1}]^{C9} [L]^{C10} [LT^{-2}]^{C11} [FL^{-2}]^{C14} [L]^{C16} [L]^{C17} = 0$$



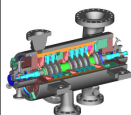
**BUCKINGHAM PI THEOREM: [CONTD..]**

**THREE AUXILIARY EQUATIONS CAN BE WRITTEN,**

$$F: c1 + c4 + c7 + c8 + c14 = 0$$

$$L: -c1 + c3 - 2c4 + c5 + c6 - c7 + c9 + c10 \\ + c11 - 2c14 + c16 + c17 = 0$$

$$T: c1 - c2 - c8 - c9 - 2c11 = 0$$





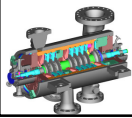
**BUCKINGHAM PI THEOREM: [CONTD..]**

**TOTAL NUMBER OF QUANTITIES [ VARIABLES ] = 18**

**NUMBER OF BASIC DIMENSIONS [ F, L,T]= 3**

**NUMBER OF  $\pi$  GROUPS = 18 - 3**

**= 15  $\pi$  GROUPS**



**BUCKINGHAM PI THEOREM: [CONTD..]**

**WE KNOW THAT,**

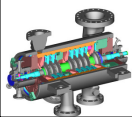
$$\pi_1 = N_B$$

$$\pi_2 = PR$$

$$\pi_3 = R_C$$

$$\pi_4 = N_W$$

**WE HAVE TO FIND THE OTHER PI GROUPS**





**BUCKINGHAM PI THEOREM: [CONTD..]**

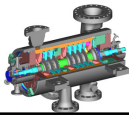
**THE OTHER PI GROUPS ARE IDENTIFIED AS,**

$$\pi_5 = \frac{C_{xx} \cdot g_c}{\dot{w}}$$

$$\pi_6 = \omega \cdot \sqrt{\frac{L}{g_c}}$$

$$\pi_7 = \frac{CR_i}{L}$$

$$\pi_8 = \frac{\Delta P \cdot L^{3/2} \cdot g_c^{1/2}}{\dot{w}}$$



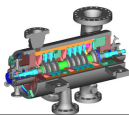
**BUCKINGHAM PI THEOREM: [CONTD..]**

$$\pi_9 = \frac{D}{L}$$

$$\pi_{10} = \frac{K_{xx} \cdot \sqrt{g_c \cdot L}}{\dot{w}}$$

$$\pi_{11} = \frac{V_a}{\sqrt{g_c \cdot L}}$$

$$\pi_{12} = \frac{B}{L}$$

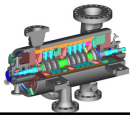


**BUCKINGHAM PI THEOREM: [CONTD..]**

$$\pi_{13} = \frac{P_i \cdot L^{3/2} \cdot g_c^{1/2}}{\dot{w}}$$

$$\pi_{14} = \frac{b_t}{L}$$

$$\pi_{15} = \frac{b_w}{L}$$



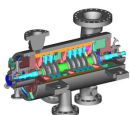
**BUCKINGHAM PI THEOREM: [CONTD..]**

**THE USEFUL PI GROUPS ARE IDENTIFIED AS,**

$$\pi'_1 = \frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = \frac{\pi_5 \cdot \pi_6}{\pi_8}$$

$$\pi'_2 = \frac{K_{xx}}{\Delta P \cdot L} = \frac{\pi_5}{\pi_8}$$

$$\pi'_3 = \frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = \frac{1}{\pi_8 \cdot \pi_7 \cdot \pi_{11}}$$



**BUCKINGHAM PI THEOREM: [CONTD..]**

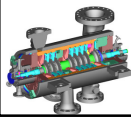
$$\pi'_4 = \frac{\omega^2 \cdot B^2 \cdot L}{V_a^2 \cdot CR_i} = \frac{\pi_6^2 \cdot \pi_{12}^2}{\pi_7 \cdot \pi_{11}^2}$$

$$\pi'_5 = \frac{C_{xx} \cdot g_c}{\dot{w}} = \pi_5$$

$$\pi'_6 = \frac{L}{D} = \frac{1}{\pi_9}$$

$$\pi'_7 = N_B = \pi_1$$

$$\pi'_8 = \frac{CR_i}{D} = \frac{\pi_7}{\pi_9}$$



**BUCKINGHAM PI THEOREM: [CONTD..]**

$$\pi'_9 = PR = \pi_2$$

$$\pi'_{10} = \frac{\Delta P}{P_i} = \frac{\pi_8}{\pi_{13}}$$

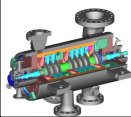
$$\pi'_{11} = R_c = \pi_3$$

$$\pi'_{12} = N_w = \pi_4$$

$$\pi'_{13} = \frac{b_i}{L}$$

$$\pi'_{14} = \frac{b_w}{L}$$

$$\pi'_{15} = \frac{B}{L}$$



### SIGNIFICANT PI GROUPS:

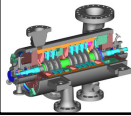
$$\pi'_1 = \frac{C_{xx} \cdot \omega}{\Delta P \cdot L} \quad \text{DAMPING-FREQUENCY PI GROUP}$$

$$\pi'_2 = \frac{K_{xx}}{\Delta P \cdot L} \quad \text{STIFFNESS PI GROUP}$$

$$\pi'_3 = \frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} \quad \text{LEAKAGE PI GROUP}$$

$$\pi'_4 = \frac{\omega^2 \cdot B^2 \cdot L}{V_a^2 \cdot CR_i} \quad \text{HELM-HOLTZ PI GROUP}$$

$$\pi'_5 = \frac{C_{xx} \cdot g_c}{\dot{w}} \quad \text{DAMPING-LEAKAGE PI GROUP}$$



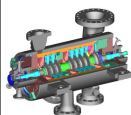
### DESIGN PLOTS WITH SIGNIFICANT PI GROUPS

- ▶ THE DAMPING-FREQUENCY PI GROUP,
- ▶ THE STIFFNESS PI GROUP,
- ▶ THE LEAKAGE PI GROUP,
- ▶ THE HELM-HOLTZ PI GROUP,
- ▶ THE DAMPING-LEAKAGE PI GROUP

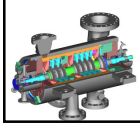
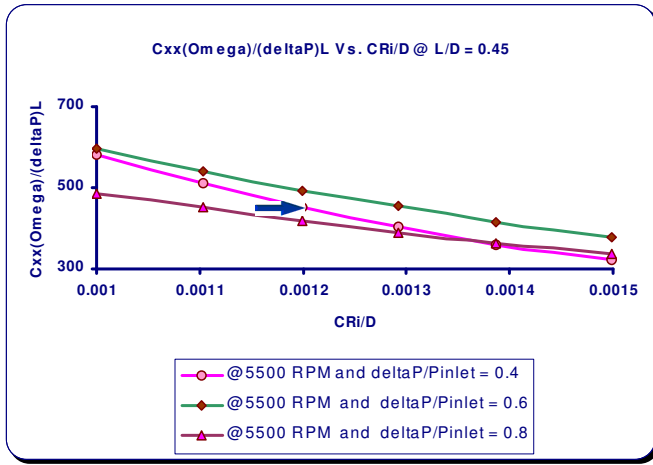
ARE PLOTTED WITH OTHER SIGNIFICANT PI GROUPS VIZ,

- ▶ THE PRESSURE RATIO PI GROUP,
- ▶ THE INLET RADIAL CLEARANCE TO DIAMETER PI GROUP,
- ▶ THE CLEARANCE RATIO PI GROUP AND
- ▶ THE NUMBER OF BLADES PI GROUP

TO OBTAIN THE DESIGN PLOTS FOR  
POCKET DAMPER SEALS.



### DAMPING-FREQUENCY PI GROUP Vs. INLET RADIAL CLEARANCE TO DIAMETER PI GROUP

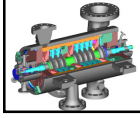


$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 451.7814$$

INPUT	UNITS	DESCRIPTION
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH
Pres_hi	650 psia	UPSTREAM PRESSURE OF SEAL
Pres_lo	390 psia	DOWNSTREAM PRESSURE OF SEAL
CR_inlet	0.0091 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET
CR_exit	0.0136 inches	EXIT RADIAL CLEARANCE TO A POCKET
Seal_length	3.4 inches	SEAL LENGTH (axial)
Dia_inner	7.5556 inches	INNER DIAMETER FOR SEAL (shaft diameter)
Depth	0.3778 inches	DEPTH OF SEAL POCKET
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT

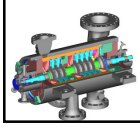
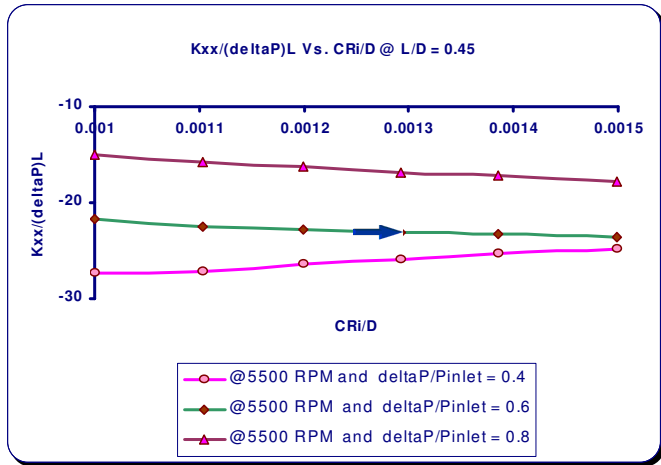
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OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P ratio
Nblade	4 none	1	650	1	0.912947
Dia_outer	8.3112 inches	2	593.4157	2	0.938365
ActvPitch	1.323895 inches(inside)	3	556.8403	3	0.803449
DeadPitch	0.35781 inches(inside)	4	447.3925	4	0.871718
massflow	1.617407 lb/sec	5	390		
Cxx	72.61359 lb-s/in(direct damping)				
Kxx	-23407.11 lb/in(direct stiffness)				



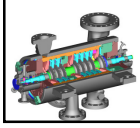
$$C_{xx} = \frac{(451.7814)(260)(3.4)}{5500} = 72.6136 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP Vs. INLET RADIAL CLEARANCE TO DIAMETER PI GROUP



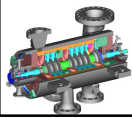
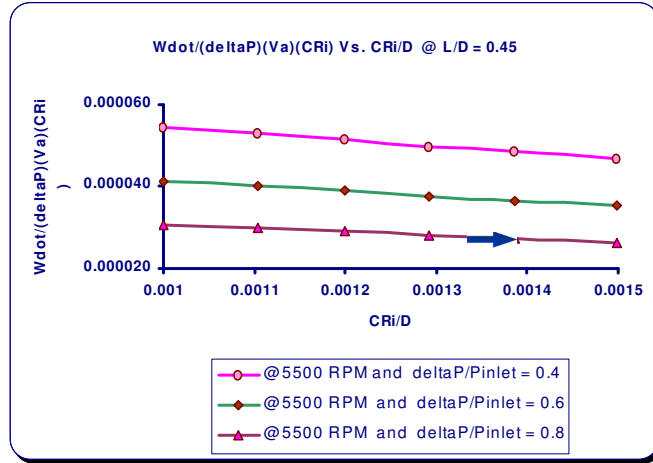
$$\frac{K_{xx}}{\Delta P \cdot L} = -23.1497$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1700 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	680 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0095 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0142 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.3 inches	SEAL LENGTH (axial)				
Dia_inner	7.3333 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3667 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0957 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0957 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
		Always RUN this sheet FIRST	Input only the red numbers			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	1700	1	0.883973
Dia_outer	8.0667 inches		2	1502.753	2	0.912569
ActvPitch	1.284957 inches(inside)		3	1371.367	3	0.689387
DeadPitch	0.347286 inches(inside)		4	945.4029	4	0.71927
massflow	4.862902 lb/sec		5	680		
Cxx	277.6909 lb-s/in(direct damping)					
Kxx	-77921.97 lb/in(direct stiffness)					



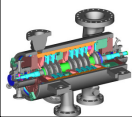
$$K_{xx} = (-23.1497)(1020)(3.3) = -77921.97 \frac{lb}{in}$$

### LEAKAGE PI GROUP VS. INLET RADIAL CLEARANCE TO DIAMETER PI GROUP



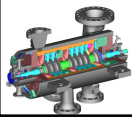
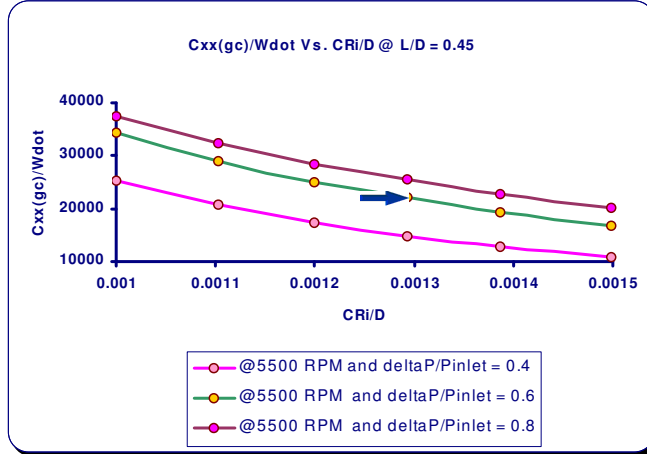
$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 2.73636e - 05$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2500 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	500 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0099 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0148 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.2 inches	SEAL LENGTH (axial)				
Dia_inner	7.1111 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3556 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0928 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0928 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temprtr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	2500	1	0.88527359
Dia_outer	7.8223 inches		2	2213.184	2	0.91382778
ActvPitch	1.246019 inches(inside)		3	2022.469	3	0.695512684
DeadPitch	0.336762 inches(inside)		4	1406.653	4	FLOW CHOKED
massflow	7.191709 lb/sec		5	500		
Cxx	421.7751 lb-s/in(direct damping)					
Kxx	-110205.3 lb/in(direct stiffness)					



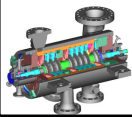
$$\dot{w} = (2.73636 e - 05)(2000)(13333)(0.0099) = 7.1917 \frac{lb}{s}$$

### DAMPING-LEAKAGE PI GROUP Vs. INLET RADIAL CLEARANCE TO DIAMETER PI GROUP



$$\frac{C_{xx} g_c}{\dot{w}} = 22064.9670$$

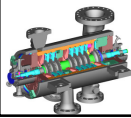
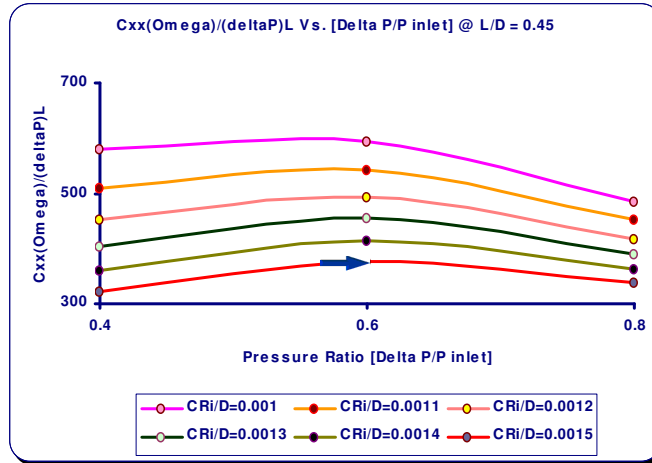
INPUT		UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1700	psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	680	psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0095	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0142	inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.3	inches	SEAL LENGTH (axial)				
Dia_inner	7.3333	inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3667	inches	DEPTH OF SEAL POCKET				
Wallthick	0.0957	inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0957	inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temprr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>				
OUTPUT		UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4	none		1	1700	1	0.88397261
Dia_outer	8.0667	inches		2	1502.753	2	0.912569279
ActvPitch	1.284957	inches(inside)		3	1371.367	3	0.689387394
DeadPitch	0.347286	inches(inside)		4	945.4029	4	0.719270089
massflow	4.862902	lb/sec		5	680		
Cxx	277.6909	lb-s/in(direct damping)					
Kxx	-77921.97	lb/in(direct stiffness)					



$$C_{xx} = \frac{(22064.9670)(4.8629)}{386.4} = 277.6909 \frac{lb-s}{in}$$

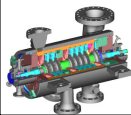


### DAMPING-FREQUENCY PI GROUP VS. PRESSURE RATIO PI GROUP



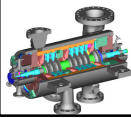
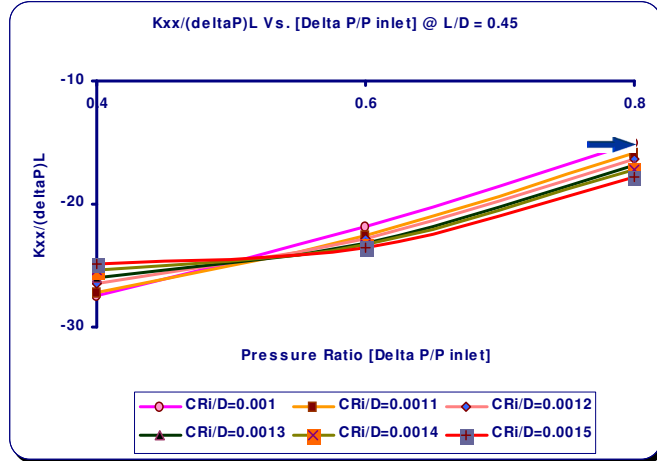
$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 377.1091$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (GPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1500 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	600 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0103 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0155 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.1 inches	SEAL LENGTH (axial)				
Dia_inner	6.8889 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3444 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0899 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0899 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	1500		0.883347
Dia_outer	7.5777 inches		2	1325.021		0.913337
ActvPitch	1.207081 inches(inside)		3	1210.191		0.687824
DeadPitch	0.326238 inches(inside)		4	832.3985		0.720809
massflow	4.380293 lb/sec		5	600		
Cxx	191.2972 lb-s/in(direct damping)					
Kxx	-65722.97 lb/in(direct stiffness)					



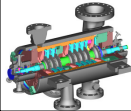
$$C_{xx} = \frac{(377.1091)(900)(3.1)}{5500} = 191.2972 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP Vs. PRESSURE RATIO PI GROUP



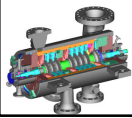
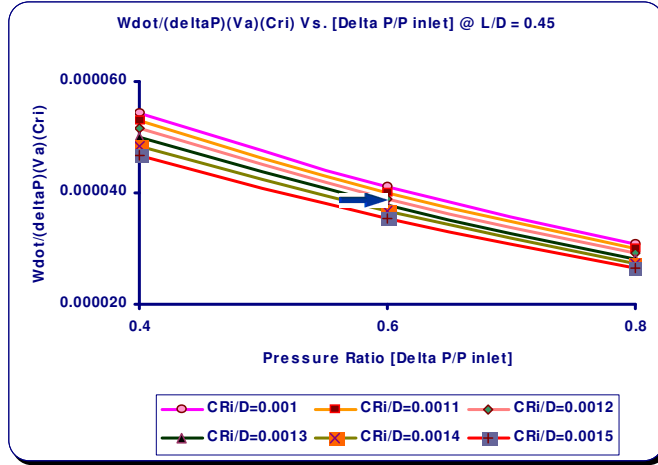
$$\frac{K_{xx}}{\Delta P \cdot L} = -15.0341$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	2000	psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	400	psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.008	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.012	inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.6	inches	SEAL LENGTH (axial)			
Dia_inner	8	inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.4	inches	DEPTH OF SEAL POCKET			
Wallthick	0.1044	inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.1044	inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4	none	1	2000	1	0.884847831
Dia_outer	8.8	inches	2	1769.696	2	0.914098208
ActvPitch	1.401771	inches(inside)	3	1617.676	3	0.694208268
DeadPitch	0.378857	inches(inside)	4	1123.004	4	FLOW CHOKED
massflow	5.238676	lb/sec	5	400		
Cxx	508.2267	lb-s/in(direct damping)				
Kxx	-86596.4	lb/in(direct stiffness)				



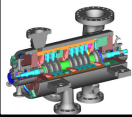
$$K_{xx} = (-15.0341)(1600)(3.6) = -86596.4 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. PRESSURE RATIO PI GROUP



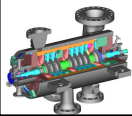
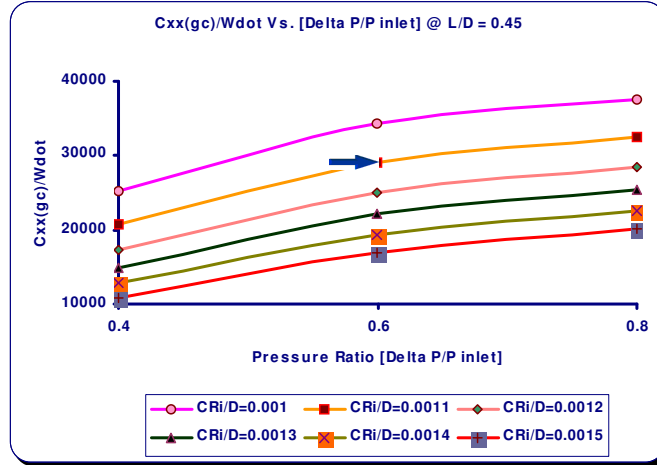
$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 3.89496e - 05$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1800 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	720 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0091 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0136 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.4 inches	SEAL LENGTH (axial)				
Dia_inner	7.5556 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3778 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	1800	1	0.883987002
Dia_outer	8.3112 inches		2	1591.177	2	0.912551619
ActvPitch	1.323895 inches(inside)		3	1452.031	3	0.689423311
DeadPitch	0.35781 inches(inside)		4	1001.064	4	0.719234826
massf	5.081399 lb/sec		5	720		
Cxx	329.6951 lb-s/in(direct damping)					
Kxx	-83815.32 lb/in(direct stiffness)					



$$\dot{w} = (3.89496e - 05)(1080)(13333)(0.0091) = 5.081399 \frac{lb}{s}$$

### DAMPING-LEAKAGE PI GROUP Vs. PRESSURE RATIO PI GROUP

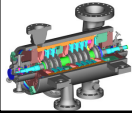


$$\frac{C_{xx} g_c}{\dot{w}} = 29066.3688$$

INPUT		UNITS	DESCRIPTION
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH
Pres_hi	1900	psia	UPSTREAM PRESSURE OF SEAL
Pres_lo	760	psia	DOWNSTREAM PRESSURE OF SEAL
CR_inlet	0.0086	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET
CR_exit	0.0129	inches	EXIT RADIAL CLEARANCE TO A POCKET
Seal_length	3.5	inches	SEAL LENGTH (axial)
Dia_inner	7.7777	inches	INNER DIAMETER FOR SEAL (shaft diameter)
Depth	0.3889	inches	DEPTH OF SEAL POCKET
Wallthick	0.1015	inches	THICKNESS OF SEPARATION WALLS
Bladethick	0.1015	inches	THICKNESS OF THE LABY TEETH
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE
Temptr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT

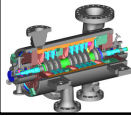
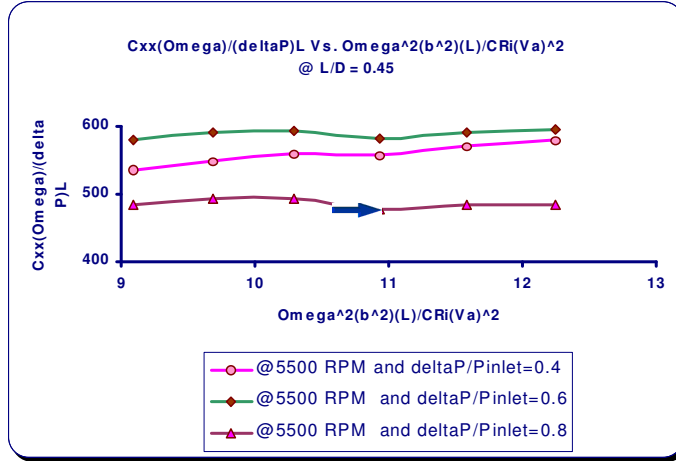
Always RUN this sheet FIRST      Input only the red numbers

OUTPUT		UNITS	cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4	none	1	1900	1	0.88364629
Dia_outer	8.5555	inches	2	1678.928	2	0.912969846
ActvPitch	1.362833	inches(inside)	3	1532.811	3	0.688572368
DeadPitch	0.368333	inches(inside)	4	1055.451	4	0.720071311
massflow	5.224563	lb/sec	5	760		
Cxx	393.01	lb-s/in(direct damping)				
Kxx	-89999.82	lb/in(direct stiffness)				



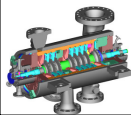
$$C_{xx} = \frac{(29066.3688)(5.224563)}{386.4} = 393.01 \frac{lb-s}{in}$$

### DAMPING-FREQUENCY PI GROUP Vs. HELM-HOLTZ PI GROUP



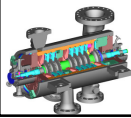
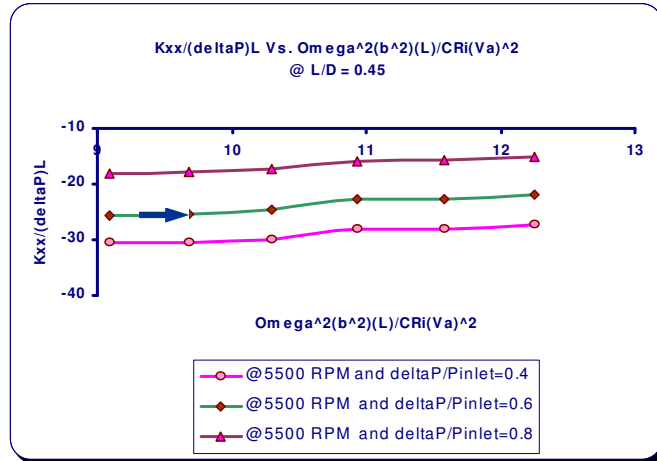
$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 477.9453$$

INPUT		UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2250	psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	450	psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0076	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0113	inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.4	inches	SEAL LENGTH (axial)				
Dia_inner	7.5556	inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3778	inches	DEPTH OF SEAL POCKET				
Wallthick	0.0986	inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0986	inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temprtr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
			<i>Always RUN this sheet FIRST</i>	<i>Input only the red numbers</i>			
OUTPUT		UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4	none		1	2250	1	0.885960642
Dia_outer	8.3112	inches		2	1993.411	2	0.913391982
ActvPitch	1.323895	inches(inside)		3	1820.766	3	0.697610371
DeadPitch	0.35781	inches(inside)		4	1270.185	4	FLOW CHOKED
massflow	5.265783	lb/sec		5	450		
Cxx	531.8228	lb-s/in(direct damping)					
Kxx	-97276.17	lb/in(direct stiffness)					



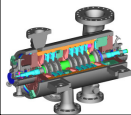
$$C_{xx} = \frac{(477.9453)(1800)(3.4)}{5500} = 531.8228 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP VS. HELM-HOLTZ PI GROUP



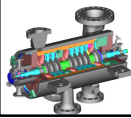
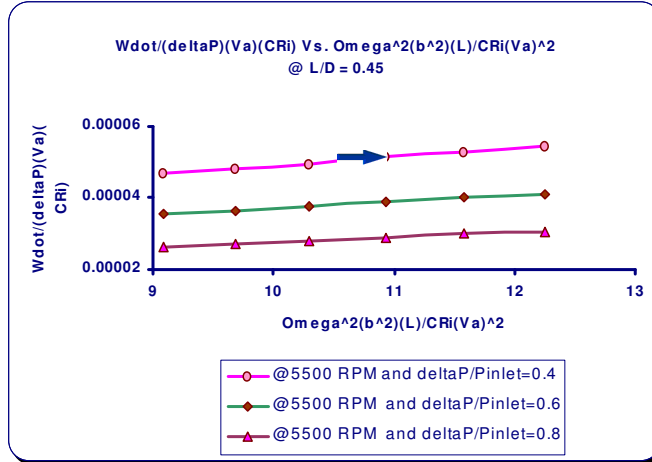
$$\frac{K_{xx}}{\Delta P \cdot L} = -25.4681$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	1600 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	640 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0071 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0107 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.2 inches	SEAL LENGTH (axial)			
Dia_inner	7.1111 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3556 inches	DEPTH OF SEAL POCKET			
Wallthick	0.0928 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0928 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>		<i>Input only the red numbers</i>			
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none	1	1600	1	0.883212881
Dia_outer	7.8223 inches	2	1413.141	2	0.91350225
ActvPitch	1.246019 inches(inside)	3	1290.907	3	0.687488065
DeadPitch	0.336762 inches(inside)	4	887.4832	4	0.721140377
massflow	3.326243 lb/sec	5	640		
Cxx	329.623 lb-s/in(direct damping)				
Kxx	-78238.07 lb/in(direct stiffness)				



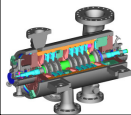
$$K_{xx} = (-25.4681)(960)(3.2) = -78238.07 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. HELM-HOLTZ PI GROUP



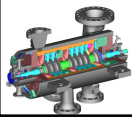
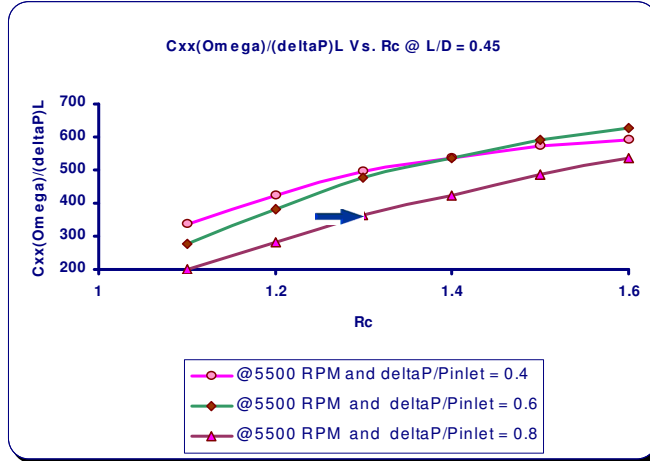
$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 5.14972e - 05$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	650 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	390 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0076 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0113 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.4 inches	SEAL LENGTH (axial)			
Dia_inner	7.5556 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3778 inches	DEPTH OF SEAL POCKET			
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>					
<i>Input only the red numbers</i>					
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none	1	650	1	0.91330069
Dia_outer	8.3112 inches	2	593.6454	2	0.937936646
ActvPitch	1.323895 inches(inside)	3	556.8018	3	0.804155644
DeadPitch	0.35781 inches(inside)	4	447.7553	4	0.871011414
massfl	1.348338 lb/sec	5	390		
Cxx	89.75526 lb-s/in(direct damping)				
Kxx	-24876.1 lb/in(direct stiffness)				



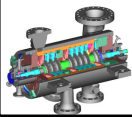
$$\dot{w} = (5.14972e - 05)(260)(13333)(0.0076) = 1.348338 \frac{lb}{s}$$

### DAMPING-FREQUENCY PI GROUP VS. CLEARANCE RATIO PI GROUP



$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 361.9795$$

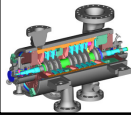
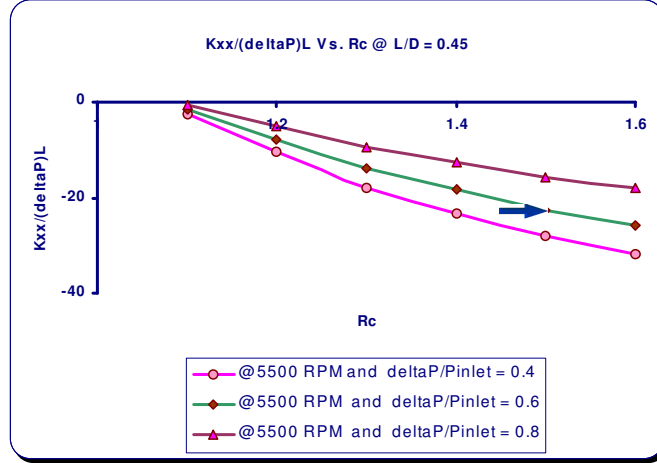
INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2375 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	475 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0073 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0095 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.3 inches	SEAL LENGTH (axial)				
Dia_inner	7.3333 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3667 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0957 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0957 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	2375	1	0.902927254
Dia_outer	8.0667 inches		2	2144.452	2	0.902886333
ActvPitch	1.284957 inches(inside)		3	1936.197	3	0.746786282
DeadPitch	0.347286 inches(inside)		4	1445.925	4	FLOW CHOKED
massflow	4.830072 lb/sec		5	475		
Cxx	412.6566 lb-s/in(direct damping)					
Kxx	-58816.49 lb/in(direct stiffness)					



$$C_{xx} = \frac{(361.9795)(1900)(3.3)}{5500} = 412.6566 \frac{lb-s}{in}$$

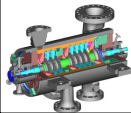


### STIFFNESS PI GROUP Vs. CLEARANCE RATIO PI GROUP



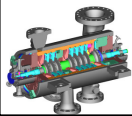
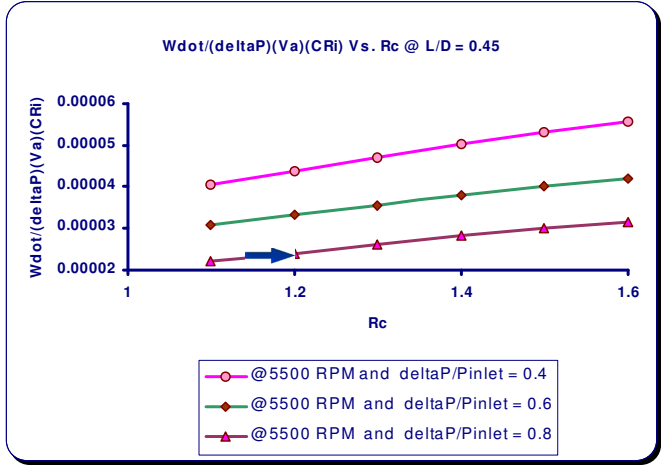
$$\frac{K_{xx}}{\Delta P \cdot L} = -22.5964$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	1900 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	760 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0078 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0117 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.5 inches	SEAL LENGTH (axial)			
Dia_inner	7.7777 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3889 inches	DEPTH OF SEAL POCKET			
Wallthick	0.1015 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.1015 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>		<i>Input only the red numbers</i>			
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none	1	1900	1	0.88364629
Dia_outer	8.5555 inches	2	1678.928	2	0.912969846
ActvPitch	1.362833 inches(inside)	3	1532.811	3	0.688572368
DeadPitch	0.368333 inches(inside)	4	1055.451	4	0.720071311
massflow	4.738557 lb/sec	5	760		
Cxx	429.2118 lb-s/in(direct damping)				
Kxx	-90159.57 lb/in(direct stiffness)				



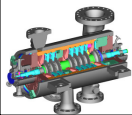
$$K_{xx} = (-22.5964)(1140)(3.5) = -90159.57 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. CLEARANCE RATIO PI GROUP



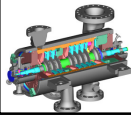
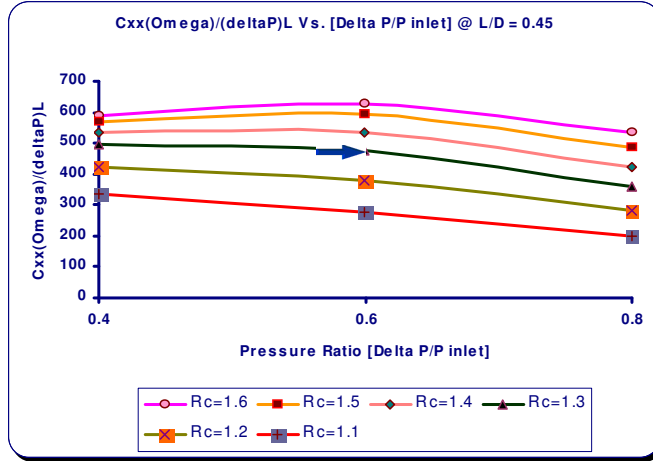
$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 2.4026e - 05$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2500 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	500 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0071 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0085 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.2 inches	SEAL LENGTH (axial)				
Dia_inner	7.1111 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3556 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0928 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0928 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none		1	2500	1	0.913461841
Dia_outer	7.8223 inches		2	2283.655	2	0.896493819
ActvPitch	1.246019 inches(inside)		3	2047.282	3	0.77493568
DeadPitch	0.336762 inches(inside)		4	1586.512	4	FLOW CHOKED
massf	4.555912 lb/sec		5	500		
Cxx	327.3755 lb-s/in(direct damping)					
Kxx	-32935.72 lb/in(direct stiffness)					



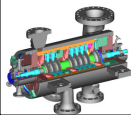
$$\dot{w} = (2.4026e - 05)(2000)(13333)(0.0071) = 4.5559 \frac{lb}{s}$$

### DAMPING-FREQUENCY PI GROUP Vs. PRESSURE RATIO PI GROUP



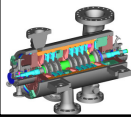
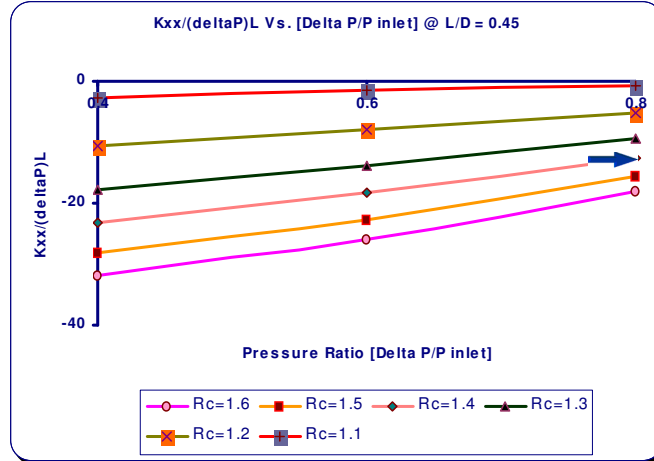
$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 475.0014$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	1700 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	680 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0073 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0095 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.3 inches	SEAL LENGTH (axial)			
Dia_inner	7.3333 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3667 inches	DEPTH OF SEAL POCKET			
Wallthick	0.0957 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0957 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>					
<i>Input only the red numbers</i>					
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P ratio
Nblade	4 none	1	1700	1	0.897514665
Dia_outer	8.0667 inches	2	1525.775	2	0.896159159
ActvPitch	1.284957 inches(inside)	3	1367.337	3	0.72232928
DeadPitch	0.347286 inches(inside)	4	987.5359	4	0.688582538
massflow	3.540885 lb/sec	5	680		
Cxx	290.7009 lb-s/in(direct damping)				
Kxx	-46638.45 lb/in(direct stiffness)				



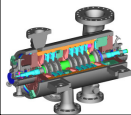
$$C_{xx} = \frac{(475.0014)(1020)(3.3)}{5500} = 290.7009 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP Vs. PRESSURE RATIO PI GROUP



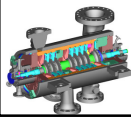
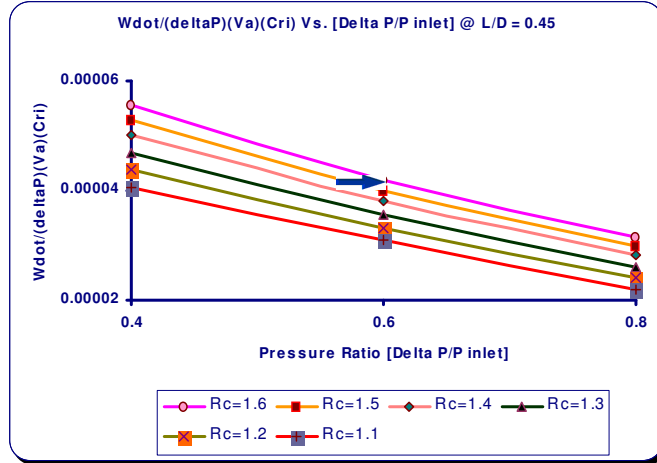
$$\frac{K_{xx}}{\Delta P \cdot L} = -12.6004$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	2250 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	450 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0076 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0106 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.4 inches	SEAL LENGTH (axial)			
Dia_inner	7.5556 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3778 inches	DEPTH OF SEAL POCKET			
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>		
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4 none	1	2250	1	0.89408037
Dia_outer	8.3112 inches	2	2011.681	2	0.90829582
ActvPitch	1.323895 inches(inside)	3	1827.201	3	0.721746255
DeadPitch	0.35781 inches(inside)	4	1318.776	4	FLOW CHOKED
massflow	5.099927 lb/sec	5	450		
Cxx	470.1801 lb-s/in(direct damping)				
Kxx	-77114.36 lb/in(direct stiffness)				



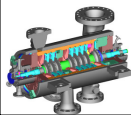
$$K_{xx} = (-12.6004)(1800)(3.4) = -77114.36 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. PRESSURE RATIO PI GROUP



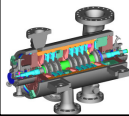
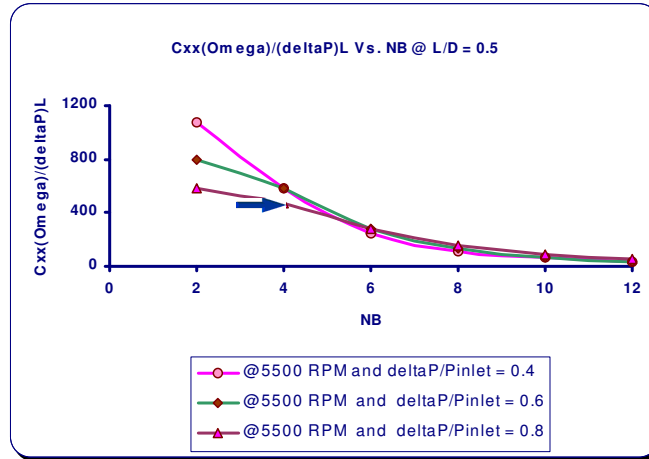
$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 4.1977e - 05$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2000 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	800 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.008 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0128 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.6 inches	SEAL LENGTH (axial)				
Dia_inner	8 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.4 inches	DEPTH OF SEAL POCKET				
Wallthick	0.1044 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.1044 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P ratio
Nblade	4 none		1	2000	1	0.877822138
Dia_outer	8.8 inches		2	1755.644	2	0.920161251
ActvPitch	1.401771 inches(inside)		3	1615.476	3	0.673824212
DeadPitch	0.378857 inches(inside)		4	1088.547	4	0.734924811
massflo	5.37292 lb/sec		5	800		
Cxx	494.0448 lb-s/in(direct damping)					
Kxx	-111846.3 lb/in(direct stiffness)					



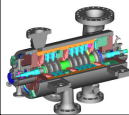
$$\dot{w} = (4.1977e - 05)(1200)(13333)(0.008) = 5.37292 \frac{lb}{s}$$

### DAMPING-FREQUENCY PI GROUP VS. NUMBER OF BLADES PI GROUP



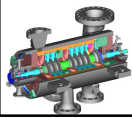
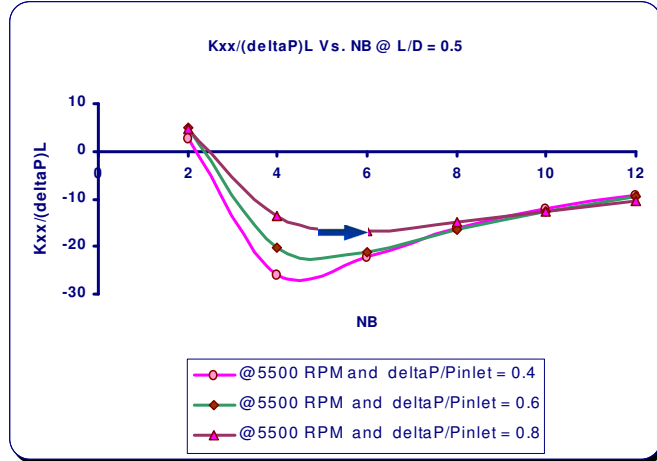
$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 470.5358$$

INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	2125	psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	425	psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.007	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0105	inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.5	inches	SEAL LENGTH (axial)			
Dia_inner	7	inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3889	inches	DEPTH OF SEAL POCKET			
Wallthick	0.1015	inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.1015	inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	4	none	1	2125	1	0.884847831
Dia_outer	7.7778	inches	2	1880.302	2	0.914098208
ActvPitch	1.362833	inches(inside)	3	1718.78	3	0.694208268
DeadPitch	0.368333	inches(inside)	4	1193.192	4	FLOW CHOKED
massflow	4.26154	lb/sec	5	425		
Cxx	509.0342	lb-s/in(direct damping)				
Kxx	-81854.33	lb/in(direct stiffness)				



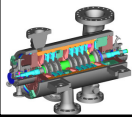
$$C_{xx} = \frac{(470.5358)(1700)(3.5)}{5500} = 509.0342 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP Vs. NUMBER OF BLADES PI GROUP



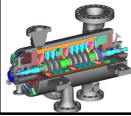
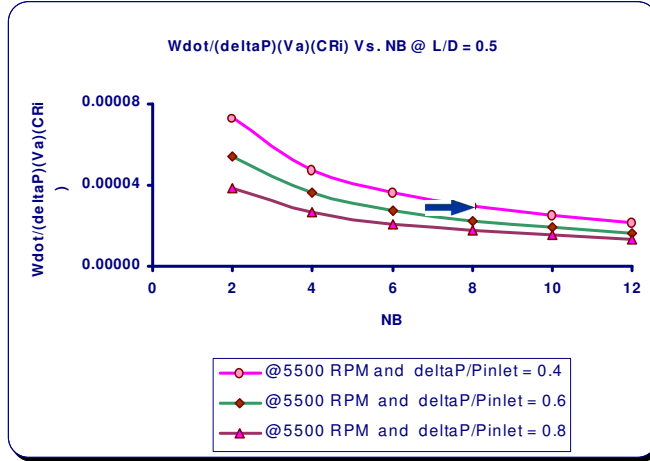
$$\frac{K_{xx}}{\Delta P \cdot L} = -16.715$$

INPUT	UNITS	DESCRIPTION			
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	3 none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	2250 psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	450 psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0068 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0102 inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.4 inches	SEAL LENGTH (axial)			
Dia_inner	6.8 inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3778 inches	DEPTH OF SEAL POCKET			
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>		
OUTPUT	UNITS	cavity no.	PRESSURES	blade no.	P ratio
Nblade	6 none	1	2250	1	0.9290251
Dia_outer	7.5556 inches	2	2090.306	2	0.951793101
ActvPitch	0.793212 inches(inside)	3	1989.539	3	0.85238207
DeadPitch	0.214382 inches(inside)	4	1695.848	4	0.908894711
massflow	3.431964 lb/sec	5	1541.347	5	0.699423141
Cxx	306.8051 lb-s/in(direct damping)	6	1078.054	6	FLOW CHOKED
Kxx	-102296 lb/in(direct stiffness)	7	450		



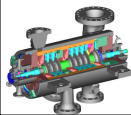
$$K_{xx} = (-16.715)(1800)(3.4) = -102296 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. NUMBER OF BLADES PI GROUP



$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 2.95191e-05$$

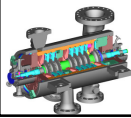
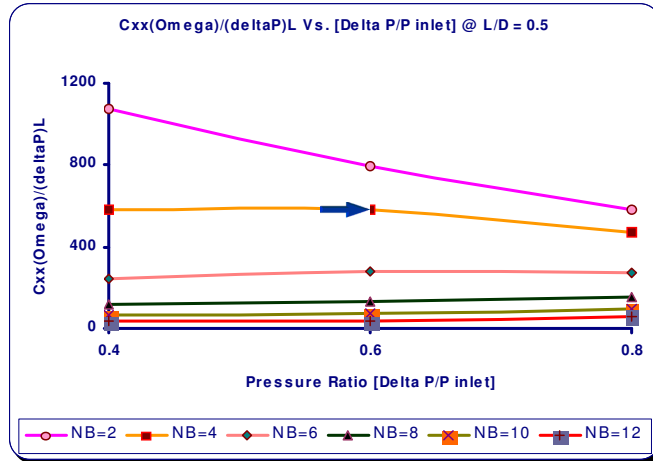
INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)			
Npair	4	none	NUMBER OF PAIRS OF LABYRINTH TEETH			
Pres_hi	600	psia	UPSTREAM PRESSURE OF SEAL			
Pres_lo	360	psia	DOWNSTREAM PRESSURE OF SEAL			
CR_inlet	0.0066	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET			
CR_exit	0.0099	inches	EXIT RADIAL CLEARANCE TO A POCKET			
Seal_length	3.3	inches	SEAL LENGTH (axial)			
Dia_inner	6.6	inches	INNER DIAMETER FOR SEAL (shaft diameter)			
Depth	0.3667	inches	DEPTH OF SEAL POCKET			
Wallthick	0.0957	inches	THICKNESS OF SEPARATION WALLS			
Bladethick	0.0957	inches	THICKNESS OF THE LABY TEETH			
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH			
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE			
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE			
Temptr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT			
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P_ratio
Nblade	8	none	1	600	1	0.964348201
Dia_outer	7.3334	inches	2	578.6089	2	0.977411346
ActvPitch	0.526813	inches(inside)	3	565.5389	3	0.93643145
DeadPitch	0.142382	inches(inside)	4	529.5884	4	0.96702328
massflow	0.623427	lb/sec	5	512.1243	5	0.91197213
Cxx	16.86619	lb-s/in(direct damping)	6	467.0431	6	0.952810411
Kxx	-12902.21	lb/in(direct stiffness)	7	445.0036	7	0.871767674
			8	387.9397	8	0.927979235
			9	360		



$$\dot{w} = (2.95191e-05)(240)(13333)(0.0066) = 0.623427 \frac{lb}{s}$$

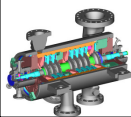


### DAMPING-FREQUENCY PI GROUP Vs. PRESSURE RATIO PI GROUP



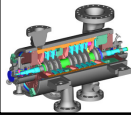
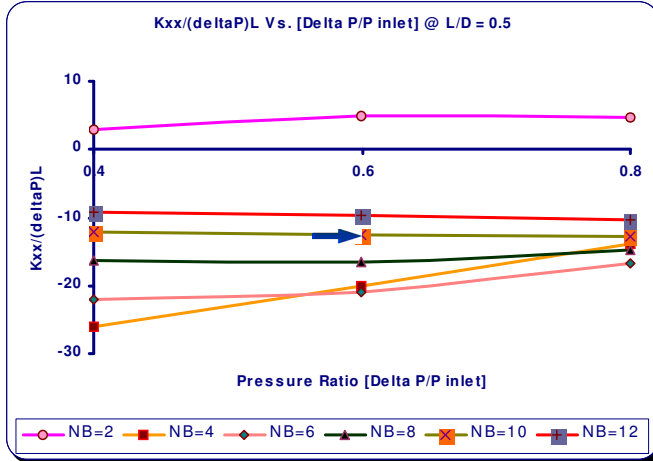
$$\frac{C_{xx} \cdot \omega}{\Delta P \cdot L} = 582.5370$$

INPUT		UNITS	DESCRIPTION				
Vibe_freq	5500	cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	2	none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1900	psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	760	psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.007	inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0105	inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.5	inches	SEAL LENGTH (axial)				
Dia_inner	7	inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3889	inches	DEPTH OF SEAL POCKET				
Wallthick	0.1015	inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.1015	inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7	none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29	none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4	none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259	deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
			<i>Always RUN this sheet FIRST</i>	<i>Input only the red numbers</i>			
OUTPUT		UNITS		cavity no.	PRESSURES	blade no.	P ratio
Nblade	4	none		1	1900	1	0.88364629
Dia_outer	7.7778	inches		2	1678.928	2	0.912969846
ActvPitch	1.362833	inches(inside)		3	1532.811	3	0.688572368
DeadPitch	0.368333	inches(inside)		4	1055.451	4	0.720071311
massflow	3.827334	lb/sec		5	760		
Cxx	422.6041	lb-s/in(direct damping)					
Kxx	-80170.89	lb/in(direct stiffness)					



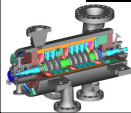
$$C_{xx} = \frac{(582.5370)(1140)(3.5)}{5500} = 422.6041 \frac{lb-s}{in}$$

### STIFFNESS PI GROUP VS. PRESSURE RATIO PI GROUP



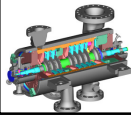
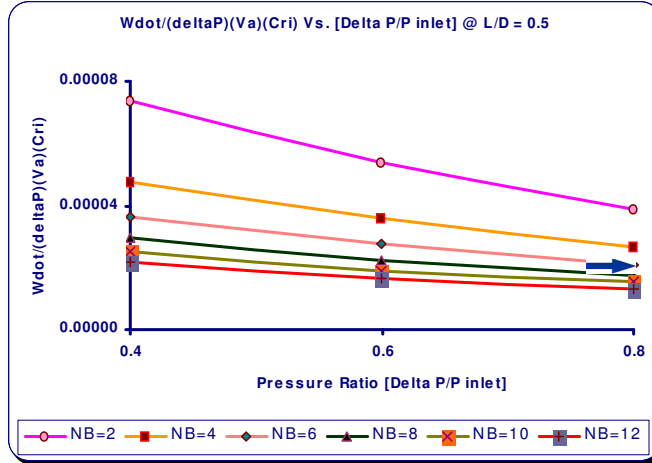
$$\frac{K_{xx}}{\Delta P \cdot L} = -12.5625$$

INPUT	UNITS	DESCRIPTION				
Vibe freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	5 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	1600 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	640 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0064 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0096 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal length	3.2 inches	SEAL LENGTH (axial)				
Dia_inner	6.4 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3556 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0928 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0928 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temptr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P ratio
Nblade	10 none		1	1600	1	0.964459353
Dia_outer	7.1112 inches		2	1543.135	2	0.977486543
ActvPitch	0.373618 inches(inside)		3	1508.394	3	0.936657811
DeadPitch	0.100978 inches(inside)		4	1412.849	4	0.967154947
massflow	1.560902 lb/sec		5	1366.444	5	0.912359353
Cxx	39.24941 lb-s/in(direct damping)		6	1246.688	6	0.953054217
Kxx	→ -38592.02 lb/in(direct stiffness)		7	1188.161	7	0.872531551
			8	1036.708	8	0.926377054
			9	960.3824	9	0.783664836
			10	752.6179	10	0.85036511
			11	640		



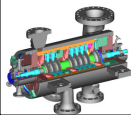
$$K_{xx} = (-12.5625)(960)(3.2) = -38592.02 \frac{lb}{in}$$

### LEAKAGE PI GROUP Vs. PRESSURE RATIO PI GROUP



$$\frac{\dot{w}}{\Delta P \cdot V_a \cdot CR_i} = 2.10297e-05$$

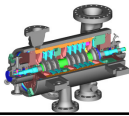
INPUT	UNITS	DESCRIPTION				
Vibe_freq	5500 cpm	VIBRATION OR WHIRL FREQUENCY (CPM)				
Npair	3 none	NUMBER OF PAIRS OF LABYRINTH TEETH				
Pres_hi	2250 psia	UPSTREAM PRESSURE OF SEAL				
Pres_lo	450 psia	DOWNSTREAM PRESSURE OF SEAL				
CR_inlet	0.0068 inches	INLET RADIAL CLEARANCE TO A SEAL POCKET				
CR_exit	0.0102 inches	EXIT RADIAL CLEARANCE TO A POCKET				
Seal_length	3.4 inches	SEAL LENGTH (axial)				
Dia_inner	6.8 inches	INNER DIAMETER FOR SEAL (shaft diameter)				
Depth	0.3778 inches	DEPTH OF SEAL POCKET				
Wallthick	0.0986 inches	THICKNESS OF SEPARATION WALLS				
Bladethick	0.0986 inches	THICKNESS OF THE LABY TEETH				
Pitch_R	3.7 none	RATIO OF ACTIVE/INACTIVE PITCH				
Mole_wt	29 none	29 FOR AIR, 16 FOR METHANE				
Gamma	1.4 none	RATIO OF SPECIFIC HEAT, 1.4 FOR AIR, 1.3 FOR METHANE				
Temprr	259 deg F	TEMPERATURE OF GAS IN FAHRENHEIT				
<i>Always RUN this sheet FIRST</i>			<i>Input only the red numbers</i>			
OUTPUT	UNITS		cavity no.	PRESSURES	blade no.	P ratio
Nblade	6 none		1	2250	1	0.9290251
Dia_outer	7.5556 inches		2	2090.306	2	0.951793101
ActvPitch	0.793212 inches(inside)		3	1989.539	3	0.85238207
DeadPitch	0.214382 inches(inside)		4	1695.848	4	0.908894711
mass	3.431964 lb/sec		5	1541.347	5	0.699423141
Cxx	306.8051 lb-s/in(direct damping)		6	1078.054	6	FLOW CHOKED
Kxx	-102296 lb/in(direct stiffness)		7	450		



$$\dot{w} = (2.10297e-05)(1800)(13333)(0.0068) = 3.431964 \frac{lb}{s}$$

## CONCLUSION

- ☑ **PI GROUPS FOR POCKET DAMPER SEAL (PDS) ARE DEVELOPED**
- ☑ **SIGNIFICANT PI GROUPS ARE IDENTIFIED**
- ☑ **DESIGN PLOTS WITH SIGNIFICANT PI GROUPS ARE DEVELOPED AND ANALYZED**
- ☑ **VIABLE DESIGN TOOL FOR DIFFERENT PDS CONFIGURATIONS IS PROVIDED**
- ☑ **FURTHER STUDY BASED ON THIS PROJECT WORK COULD BE PERFORMED BY INCORPORATING MORE VARIABLES THAT COULD AFFECT SIGNIFICANTLY THE OPERATION OF POCKET DAMPER SEALS AS THE RESEARCH PROGRESSES.**



## QUESTIONS !

