Case – 19 Centrifugal Gas Compression Calculation

Thomas T.S. Wan
（温到祥)
Dec. 28, 2012

Case Background:

See Case-18 Gas Analysis for calculating gas properties for mixture gas.

Practically all hydrocarbon gases are usable for as refrigerant in refrigeration system. Gas compression calculation is for compressor selection which is used for gas other than halocarbon refrigerants. The compressor can also be used for the application such as mixed hydrocarbon gas compression or transmission.

The case is to demonstrate how to handle the application which is involved with gas compression.

If the Gas compression is for gas pumping for special gases such as Hydrogen, Oxygen, HCl, H_2S, Cl_2, Helium and etc, these requires special compressor and are not in the scope of this case cogitation. A standard hydrocarbon compressor only can accept small amount of special gas mixed with main hydrocarbon gas flow.

The purpose of this case is only to provide an understanding to the basic knowledge of some requirements to the approach of gas compression application. It shall be always ask the compressor manufacturer to make compressor selection or to confirm any validity and feasibility of gas compression application.

The operating conditions for gas compressor selection are not the same as for refrigeration application. The conditions which are required for gas compressor selection are:

Inlet Pressure at suction of the compressor.
Inlet temperature at the suction of the compressor.
Compressor discharge pressure requirement.
Gas flow rate. (Flow rate shall be weight flow or SCFM)
Gas composition in mole percent or weight percent.

The necessary charts and curves are shown in the Related Technical Data and Engineering Information for the Case.

Related Technical Data and Engineering Information for the Case:

Table 19-1 Compressor Impeller Diameter-Inches and $(Dia.)^2$

CASING SIZE	DIA.	$(DIA.)^2$
26B	12.2	149
26A	14.8	219
38B	18.0	324
38A	21.9	480
55B	26.7	713
55A	31.5	993

Table 19-2 Maximum Allowable HP Per 1,000 RPM

CASING SIZE	SHAFT OR COUPLING	EACH IMPELLER
26	356	91
38	1,360	295
55	2,650	877

Table 19-3 Maximum Allowable Compressor Speed and CFM Flow

CASING SIZE	MAXIMUM	
	RPM	CFM*
26B	15,950	3,690
26A	13,150	5,450
38B	10,800	8,050
38A	8,900	11,900
55B	7,300	17,700
55A	6,180	24,600

*Note:
Maximum CFM may be less than shown depending on head requirements and mol. wt. of gas being pumped.

Table 19-4 Approximate Compressor First Critical Speed - RPM

Comp. Model	Impeller Material All Aluminum	Impeller Material All Steel	Comp. Model	Impeller Material All Aluminum	Impeller Material All Steel
226B	61,200	48,700	526B	14,400	11,400
226A	55,700	41,500	526A	13,100	9,600
238B	41,000	32,700	538B	9,700	7,600
238A	37,300	27,800	538A	8,800	6,500
255B	28,100	22,400	555B	6,600	5,200
255A	25,600	19,100	555A	6,000	4,400
326B	31,900	25,400	626B	11,100	8,700
326A	29,200	21,500	626A	10,000	7,400
338B	21,400	17,000	638B	7,400	5,800
338A	19,600	14,500	638A	6,700	4,900
355B	14,700	11,700	655B	5,100	4,000
355A	13,400	10,000	655A	4,600	3,400
426B	20,300	16,100	726B	8,900	7,000
426A	18,400	13,600	726A	8,000	5,900
438B	13,600	10,800	738B	6,000	4,700
438A	12,300	9,200	738A	5,400	3,900
455B	9,300	7,400	755B	4,100	3,200
455A	8,400	6,300	755A	3,700	2,700

Note: The first number refers to number of stages.
The operating compressor speed of the compressor shall not exceed 80% of the first critical speed.

Table 19-5 Maximum Temperature Limitation for Impellers

Aluminum FPS	Aluminum °F	Stainless Steel
900	283	520°F at Any Speed
850	300	
800	317	** Temp. with "P.R.V. closed," i.e., Design Temp. Rise Times 1.3 Plus Suction Temp.
750	334	
700	351	
650	368	
600	384	
550 & Less	400	

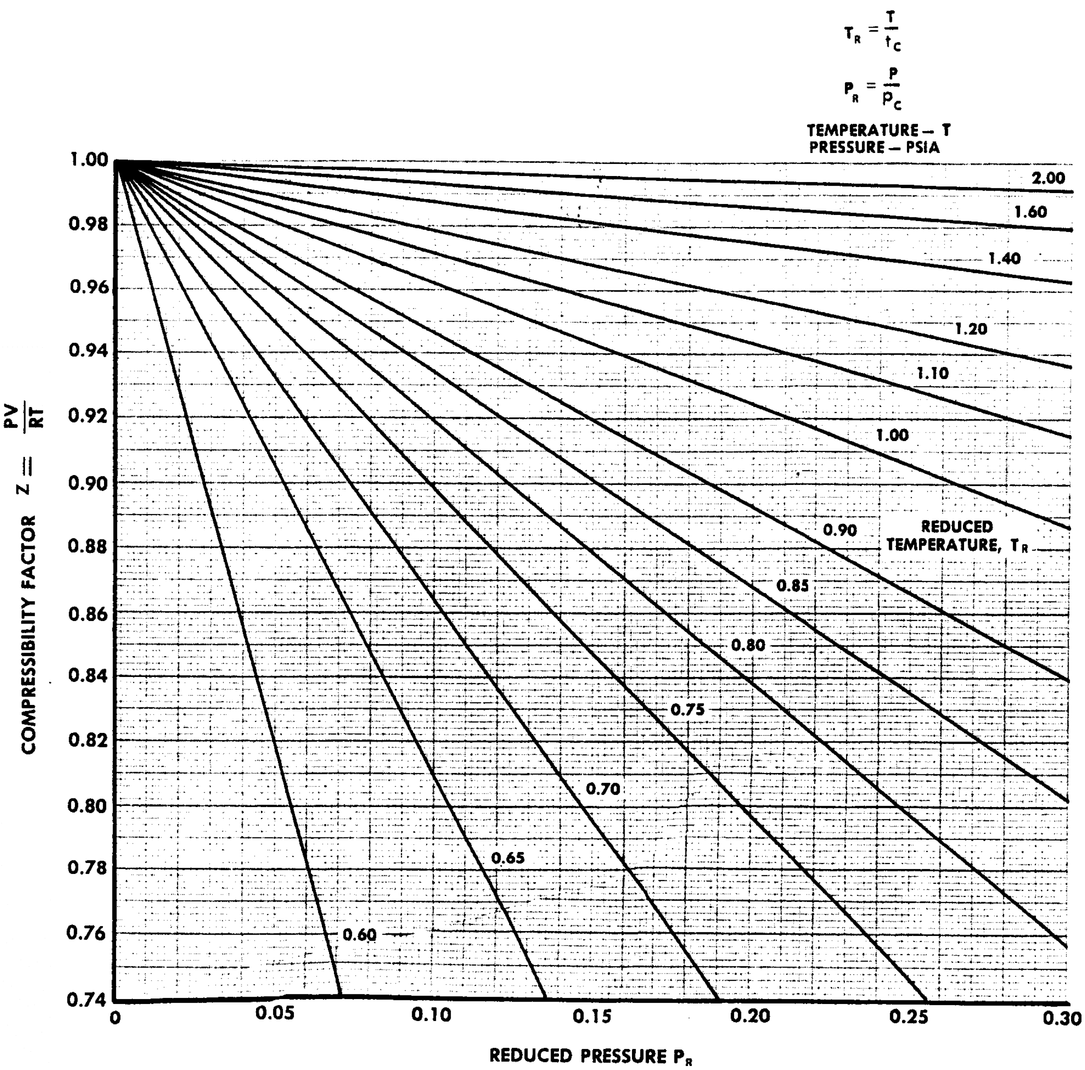


Figure 19-1 Compressibility Z Factor

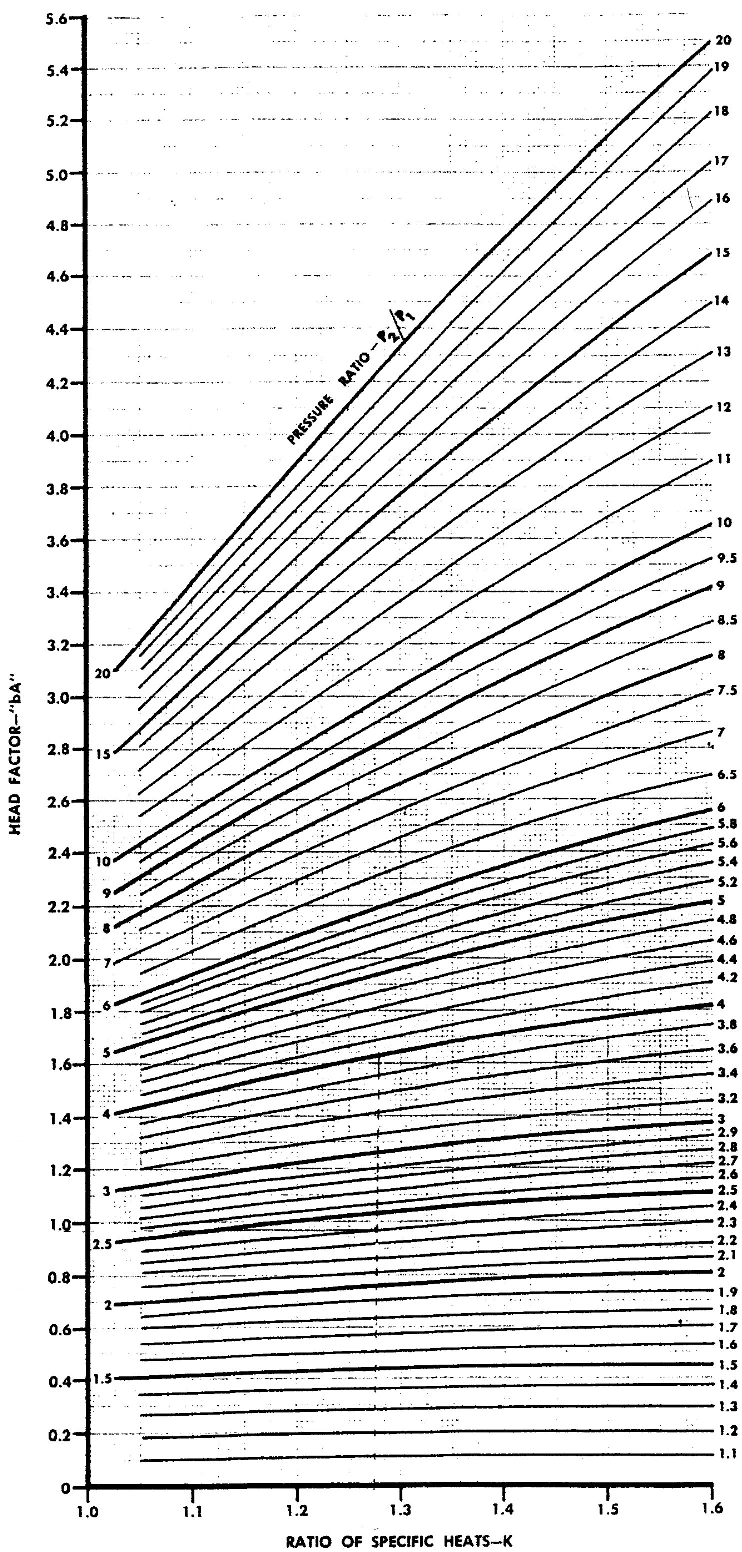


Figure 19-2   Compression Head Factor - Ba

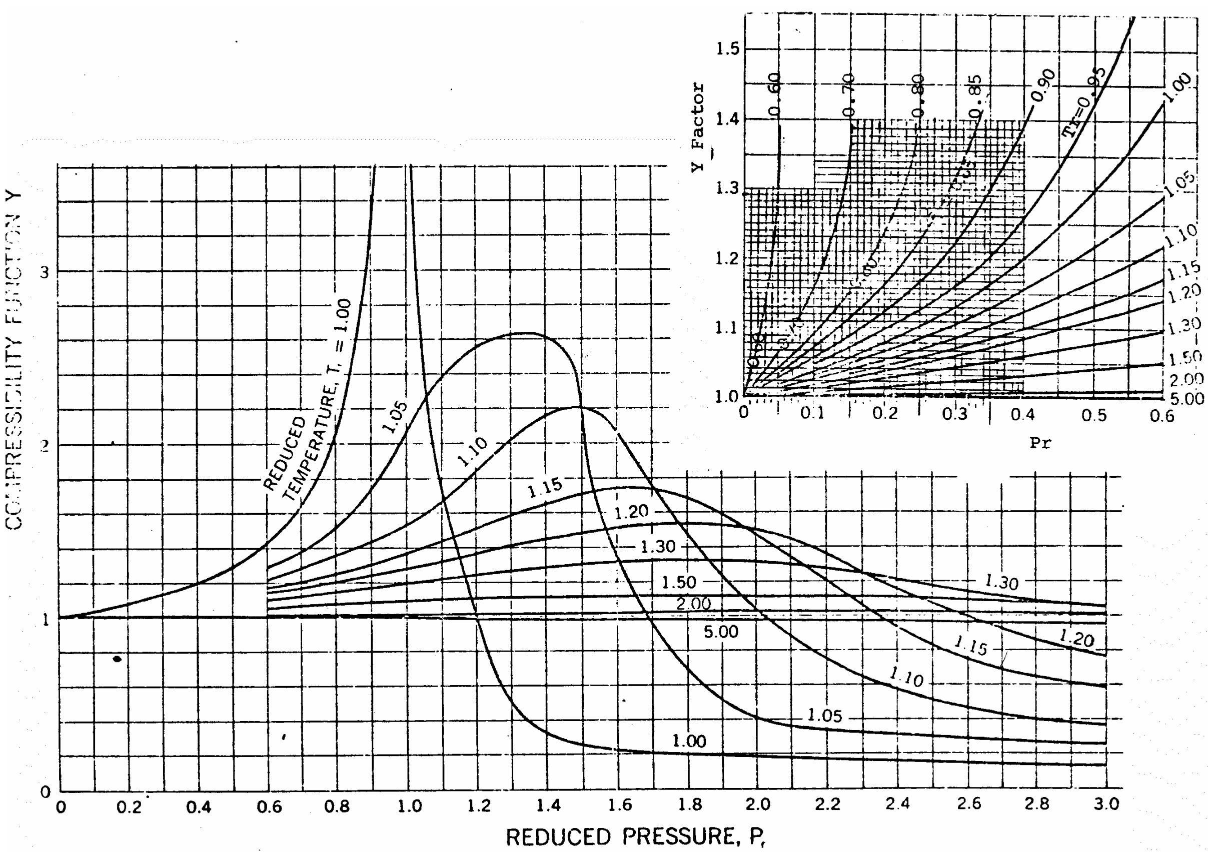


Figure 19-3 Compressibility Y Factor

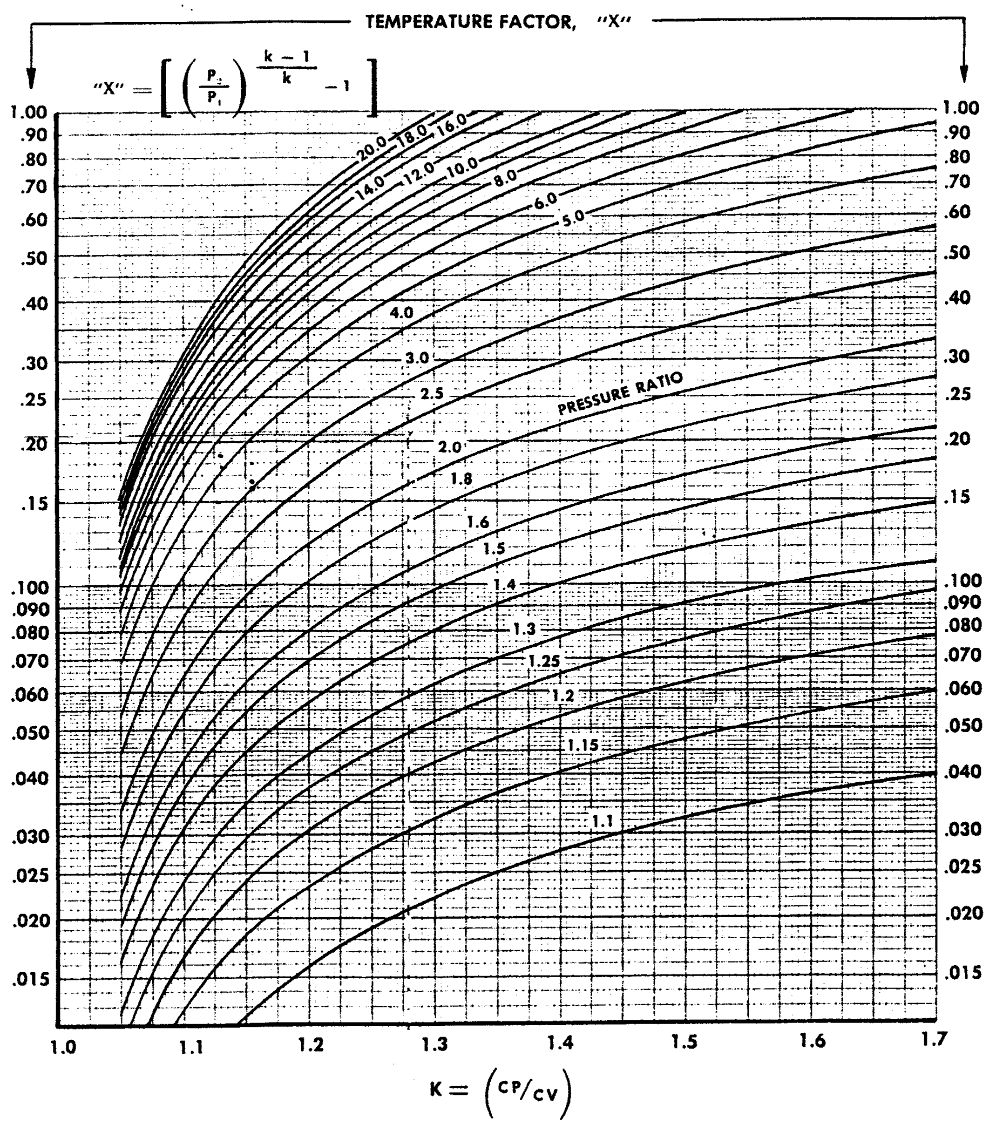


Figure 19-4   Temperature X Factor

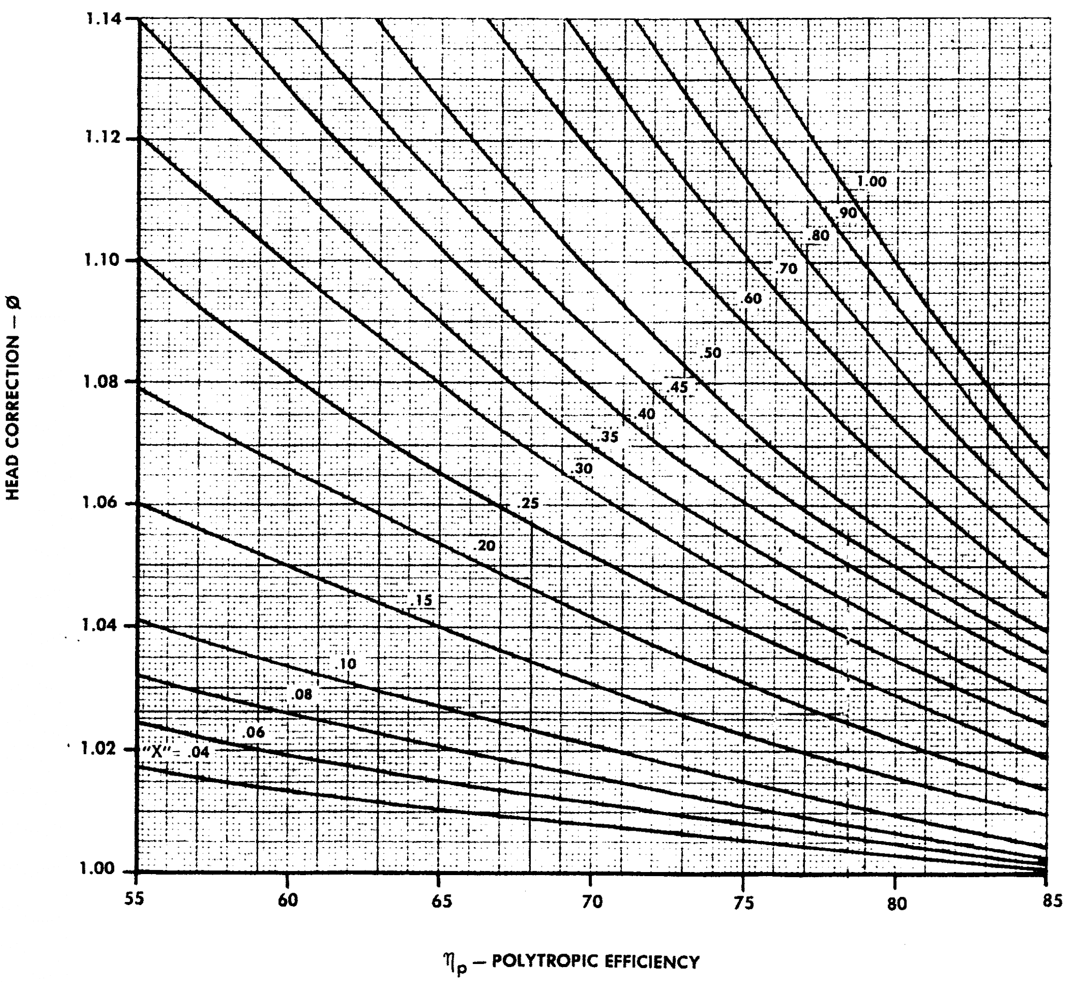


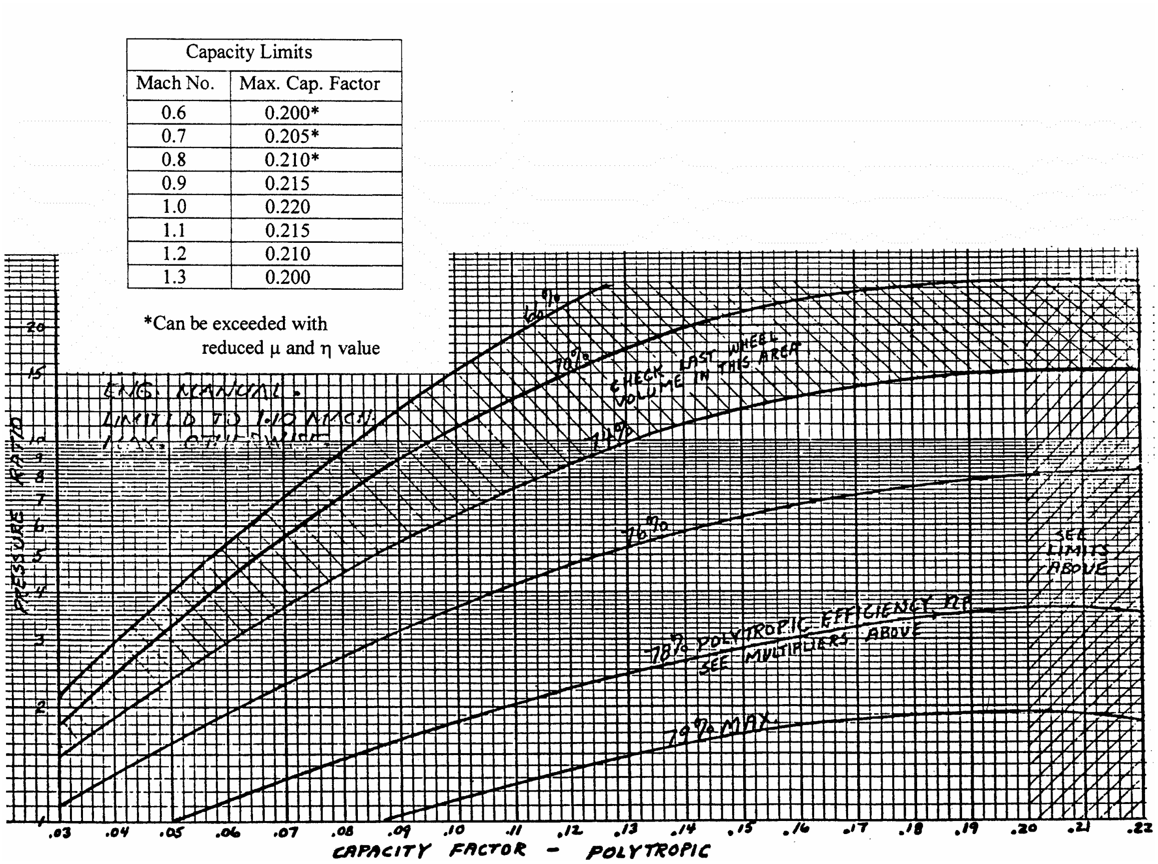
Figure 19-5 Compression Head Correction Factor Ø

Table 19-6 Compressor Efficiency Multiplier

EFFICIENCY MULTIPLIERS					
COMPRESSOR SIZE	MULT.	STAGES	MACH NO		
			UP TO 1.10	1.20	1.30
26"	1.00	1	1.00	0.98	0.96
38"	1.01	2	1.00	0.98	0.96
55"	1.02	3	1.00	0.97	0.94
		4	1.00	0.97	0.92
		5	1.00	0.96	0.90

Table 19-7 Polytropic Head Coefficiency

POLYTROPIC HEAD COEF μ								
CAP FACTOR	MACH NUMBER							
	UP TO 0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.17	0.51	0.51	0.51	0.51	0.51	0.51	0.50	0.49
0.18	0.50	0.51	0.51	0.51	0.51	0.51	0.50	0.49
0.19	0.49	0.50	0.51	0.51	0.51	0.51	0.50	0.49
0.20	0.48	0.49	0.50	0.51	0.51	0.51	0.50	
0.21	0.46	0.48	0.49	0.50	0.51	0.51		
0.22			0.48	0.49	0.50			



Capacity Limits	
Mach No.	Max. Cap. Factor
0.6	0.200*
0.7	0.205*
0.8	0.210*
0.9	0.215
1.0	0.220
1.1	0.215
1.2	0.210
1.3	0.200

*Can be exceeded with reduced μ and η value

Figure 19-6 Compressor Polytropic Capacity Factor

Note: Compressor efficiency and part load performance can be improved by changing the impeller profile design. Ask the compressor manufacturer for a better energy consumption selection for energy conservation application.

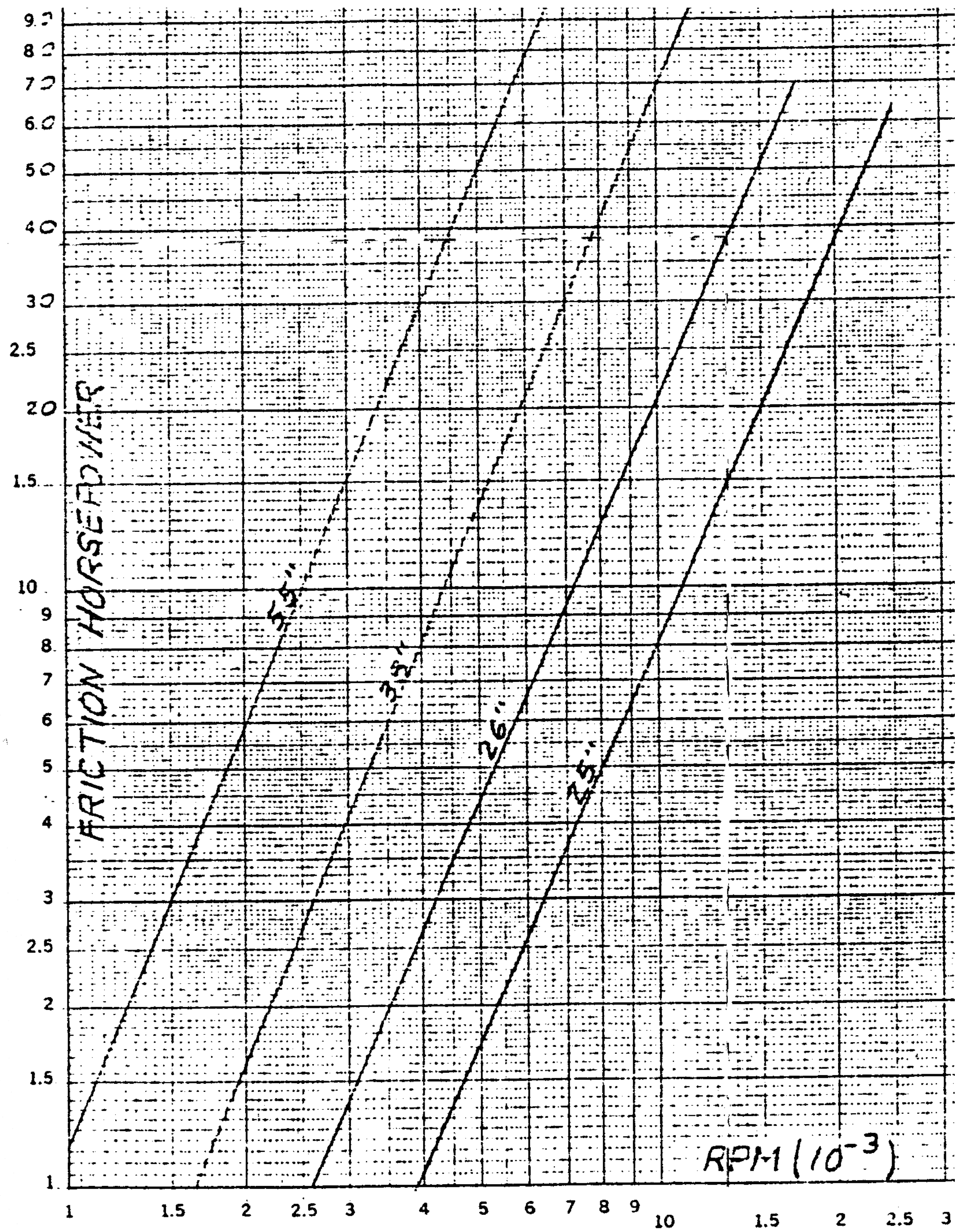


Figure 19-2 Friction HP for Multistage Centrifugal Compressor

Cogitation

This case is a compressor selection illustration for natural gas pumping application.

Outline operating conditions for the compressor:

Gas Flow:	15 MMSCFD
Inlet pressure:	40 Psia
Inlet temperature:	80°F
Outlet pressure:	96 Psia

Gas compositions:

Methane	89% Mole
Ethane	4%
Propane	5%
Carbon Dioxide	2%

Properties of the mixture gas:

Componet	Formula	M.W.	Mol %	Pseudo M.W.	Critical Press.	Critical Temp.	MWcp	Component Pseudo Press.	Component Pseudo Temp.	Component Pseudo MWcp
Methane	C1	16.0	89%	14.24	668	343	8.54	595	305	7.600
Ethane	C2	30.1	4%	1.20	708	550	12.60	28	22	0.504
Propane	C3	44.1	5%	2.21	616	666	17.6	31	33	0.880
Carb.Dioxide	CO2	44.0	2%	0.88	1071	548	8.89	21	11	0.178
Mixture Gas			100%	18.53				675	371	9.162

Therefore, the properties of the gas mixture:

MW =	18.53
Critical Pressure =	675 Psia
Critical Temperature =	371°R
MWcp =	9.162

Gas Constant of the Gas Mixture:

Gas Constant: $$R = \frac{1545}{MW} = \frac{1545}{18.53} = 83.5$$

Gas Constant for the Gas Mixture R = 83.5

Calculate the Gas Flow:

Mixture Gas Flow 15 MMSFD

$$= 15{,}000{,}000 \text{ SFD}$$

$$= \frac{15{,}000{,}000}{24 \times 60} = 10{,}416.7 \text{ SCFM}$$

Calculate the Weight Flow of the Gas at Standard Conditions:

Standard Condition is usually at 14.7 Psia and 60°F (520°R)

Gas Mixture Pc = 675 Psia
Gas Mixture Tc = 371°R

$$P_R = \frac{14.7}{675} = 0.0218$$

$$T_R = \frac{520}{371} = 1.4$$

Z = 0.997 at Standard Conditions
(Obtain from Figure 19-1 at $P_R = 0.0218$ and $T_R = 1.4$)

$$V_g = \frac{R \times (°F + 460) \times Z}{144 \times P}$$

$$V_g = \frac{83.5 \times (60 + 460) \times 0.997}{144 \times 14.7} = 20.4 \text{ Cu.Ft/\#}$$

$$\text{Weight Flow} = \frac{\text{SCFM}}{V_g}$$

$$= \frac{10{,}416.7}{20.4} = 510.6 \text{ Lbs/Min}$$

Suction and Discharge Pressure Drops:

Assume Compressor Suction Inlet PD = 0.5 Psi
Assume Compressor Discharge Outlet PD = 4.0 Psi

Actual Compressor Suction and Discharge Pressure :

Actual Compressor Suction Pressure = 40 – 0.5 = 39.5 Psia

Actual Compressor Discharge Pressure = 96 + 4.0 = 100 Psia

Compressor Actual Suction Conditions:

Compressor Suction pressure = 39.5 Psia
Suction temperature = 80°F
Gas Mixture Pc = 675 Psia
Gas Mixture Tc = 371°R

$$P_R = \frac{39.5}{675} = 0.0585$$

$$T_R = \frac{(460 + 80)}{371} = \frac{540}{371} = 1.45$$

Z factor at actual suction conditions:

Z = 0.993 (From Figure 19-1 at P_R = 0.0585 and T_R = 1.45)

Gas Specific Volume at Suction Conditions:

$$V_g = \frac{R \times (°F + 460) \times Z}{144 \times P}$$

$$= \frac{83.5 \times (80 + 460) \times 0.993}{144 \times 39.5} = 7.87 \text{ Cu.Ft/\#}$$

Suction Actual CFM = 510.6 x 7.87

= 4,019.30 ACFM

Compressor Selection Calculation:

k factor of the gas at suction conditions:

$$k = \frac{C_p}{C_v} = \frac{MW_{cp}}{MW_{cp} - 1.99 \times Z}$$

$$= \frac{9.162}{9.162 - 1.99 \times 0.993} = \frac{9.162}{7.1859}$$

$$= 1.275 \qquad \text{Use} \quad k = 1.28$$

Adiabatic Head:

$$H_{ad} = 83.5 \times (80 + 460) \times 0.993 \times \frac{1.28}{1.28 - 1} \left\{ \left[\frac{100}{39.5} \right]^{\frac{1.28 - 1}{1.28}} - 1 \right\}$$

$$= 46{,}116 \text{ Ft.}$$

Check & Compare Head using B_a factor from Figure 19-2:

$$\text{Let } B_a = \frac{k}{k - 1} \left\{ \left[\frac{P_2}{P_1} \right]^{\frac{k - 1}{k}} - 1 \right\}$$

$$= \frac{1.28}{1.28 - 1} \left\{ \left[\frac{100}{39.5} \right]^{\frac{1.28 - 1}{1.28}} - 1 \right\}$$

$$= 1.03 \quad (B_a \text{ Calculated})$$

$$CR = \frac{P_2}{P_1} = \frac{100}{39.5} = 2.532$$

At CR = 2.532 and k = 1.28

B_a = 1.035 (From Figure 19-2)

$H_{ad} = R \times T \times Z \times B_a$

$= 83.5 \times (80 + 460) \times 0.993 \times 1.035$

= 46,341 Ft.

y factor

y = 1.005 (From Figure 19-3 at P_R = 0.0585 and T_R = 1.45)

Acoustic Velocity at suction conditions:

$$Va = \sqrt{\frac{k \times g \times R \times (460 + °F) \times Z}{y}}$$

$$Va = \sqrt{\frac{1.28 \times 32.2 \times 83.5 \times (460 + 80) \times 0.993}{1.005}} = 1356 \text{ Ft/Sec}$$

Trial No. 1, Assume Eff_p = 68%

Head Factor [ϕ] for Polytropic Function

Temperature Factor [X]

X = 0.225 (From Figure 19-4 at k = 1.28 CR = 2.532)

ϕ = 1.0515 (From Figure 19-5 at Eff_p = 68% X = 0.225)

<u>Polytropic Head</u>:

$Hp = H_{ad} \times \phi$

= 46,341 x 1.0515

= 48,728 Ft.

Maximum tip speed for the impeller is 900 fps. Assume $\mu_p = 0.5$
Estimate 4-stage

$$T_s = \sqrt{\frac{32.2 \times Hp}{N \times \mu_p}}$$

$$= \sqrt{\frac{32.2 \times 48728}{4 \times 0.5}} = 885.7 \text{ fps}$$

Too close to the 900 fps limit, change to 5 stages

$$T_s = \sqrt{\frac{32.2 \times 48728}{5 \times 0.5}} = 784.4 \text{ fps}$$

Assume using 26A compressor casing:

$$\text{Capacity Factor} = Q/ND^3 = \frac{7.54 \times CFM}{T_s \times D^2}$$

ACFM = 4,019.3
T_s = 784.4 fps
D = 14.8”
D^2 = 219

$$\text{Capacity Factor} = Q/ND^3 = \frac{7.54 \times 4019.3}{784.4 \times 219} = 0.1763$$

$Eff_p = \eta_p = 78.5\%$

(From Efficiency Figure 19-6 at CR = 2.532, $Q/ND^3 = 0.1763$)

The Trial #1 is no good, the original Eff_p assumed was 68%

Trial No. 2, Assume Eff_p = 78.5%

X = 0.225 (From Figure 19-4 at k = 1.28 CR = 2.532)

ϕ = 1.0285 (From Figure 19-5 at Eff_p = 78.5% X = 0.225)

$Hp = H_{ad} \times \phi$

$= 46{,}341 \times 1.0285$

$= 47{,}662$ Ft.

Assume $\mu_p = 0.50$
Estimate compressor is with 5-stage

$$T_s = \sqrt{\frac{32.2 \times Hp}{N \times \mu_p}}$$

$$= \sqrt{\frac{32.2 \times 47{,}662}{5 \times 0.5}} = 783.5 \text{ fps}$$

Assume using 26A compressor casing:

$$\text{Capacity Factor} = Q/ND^3 = \frac{7.54 \times CFM}{T_s \times D^2}$$

ACFM = 4,019.3
T_s = 783.5 fps
D = 14.8"
D^2 = 219

$$\text{Capacity Factor} = Q/ND^3 = \frac{7.54 \times 4019.3}{783.5 \times 219} = 0.1766$$

$Eff_p = \eta_p = 78.5\%$

(Obtain from Efficiency Figure 19-6 at CR = 2.532 and Q/ND^3 = 0.1766)

The Trial #2 is good, the original Eff_p assumed was 78.5%

$$M_o = \frac{T_s}{V_a}$$

$$= \frac{783.5}{1355} = 0.578$$ OK it is below 1.3 limit

Re-check μ_p factor. (See Table 19-7)

The μ_p should be 0.503 at $M_o = 0.578$ and $Q/ND^3 = 0.1766$ instead of assumed 0.5

FINAL CORRECTION:

Let $\mu_p = 0.503$

5-stage Rotor Assembly
26A size casing
M526A Compressor

$$T_s = \sqrt{\frac{32.2 \text{ x } Hp}{N \text{ x } \mu_p}}$$

$$= \sqrt{\frac{32.2 \text{ x } 47{,}662}{5 \text{x } 0.503}} = 781.2 \text{ fps}$$

$$\text{Capacity Factor } = Q/ND^3 = \frac{7.54 \text{ x CFM}}{T_s \text{ x } D^2}$$

ACFM = 4,019.3
T_s = 781.2 fps
D = 14.8"
D^2 = 219

$$\text{Capacity Factor } = Q/ND^3 = \frac{7.54 \text{ x } 4019.3}{781.2 \text{ x } 219} = 0.177$$

From Efficiency Figure 19-6 at CR = 2.532 $Q/ND^3 = 0.177$

Efficiency correction factors: Casing correction = 1.0 for 5-stage, $M_o < 1.10$
Mach No. correction = 1.0 (See Table 19-6)

Corrected Eff_p = 78.5% x 1.0 x 1.0
= 78.5%

Gas HP Calculation:

$$GHP = \frac{W \times H_p}{33000 \times Eff_p}$$

$$GHP = \frac{510.6 \times 47{,}662}{33000 \times 0.785} = 939.4 \text{ HP}$$

Compressor Speed Calculation:

$$Rpm = \frac{229 \times T_s}{D}$$

$$= \frac{229 \times 781.2}{14.8}$$

= 12,087 RPM

Compressor Friction HP:

FHP = 33 HP (From Figure 19-2 at 12,087 RPM for 26" compressor)

Compressor Shaft HP:

SHP = GHP + FHP = 939.4 + 33

= 1,005.4

Add Safety Factor 3%

SHP = 1,005.4 x 1.03 = 1,035.6

Say compressor power consumption **SHP = 1,036 BHP**

Compressor Coupling Size 1-1/4" from information given by maker.

Driving HP with the external gear loss:

= 1,036 x 1.03 = 1,067 BHP

Check Compressor Suction Pressure Drop:

M426A suction connection is 10" given by the maker.

$$FPS = \frac{CFM}{60 \times FT^2}$$

$CFM = 4{,}019.3$
$FT^2 = 0.548$

= 122.24

$$FVH = \frac{(FPS)^2 \times k}{64.4}$$

k = 1.5 for suction

= 348.05

$$PD\ Psi = \frac{FVH}{144 \times V_g}$$

$V_g = 7.87$

= 0.307 Psi

Suction Inlet PD = 0.307 Psi <0.5 Psi assumed, Ok.

(Need to reduce the PD if the power consumption is tight)

Compressor Discharge Temperature:

$$t_{out} = \text{Discharge temp.} = t_1 + \frac{(460 + t_1) \times X \times \phi}{\eta_p}$$

$\phi = 1.0285$
$X = 0.225$
$\eta_p = 0.785$

$$t_{out} = 80 + \frac{(460 + 80) \times 0.225 \times 1.0285}{0.785} = 80 + 159.2 = 239.2°F \text{ (Ok)}$$

Temperature Rise with Inlet Guide Vane Closed:

Tdisch = 80 + 159.2 x 1.3 = 286.96°F with inlet guide vane closed (Ok)

Impeller Material:

Tdisch = 287°F when inlet guide vane closed.

Max. Temperature limit is 323°F when Ts = 781.2 fps, all aluminum impeller Ok. (See Table 19-5)

Check Compressor Discharge Outlet Pressure Drop:

Discharge pressure = 100 Psia
Discharge temperature = 239.2°F

$$P_R = \frac{100}{675} = 0.148$$

$$T_R = \frac{(460 + 239.2)}{371} = 1.885$$

Z factor at discharge: 0.995 (From Figure 19-1)

$$V_g = \frac{83.5 \text{ x } (460 + 239.2) \text{ x } 0.995}{144 \text{ x } 100} = 4.034$$

$$\Delta P = \frac{W^2 \text{ x } V_g}{C} + 0.25$$

W = Compressor discharge flow, Lbs/Min
= 510.6

V_g = Specific volume of the gas, Ft^3/Lb
= 4.034

C = 309,000 for M526A

$$\Delta P = \frac{(510.6)^2 \text{ x } 4.034}{309{,}000} + 0.25 = 3.62 \text{ Psi}$$

ΔP = 3.62 Psi

Discharge PD = 3.62 Psi < 4.0 Psi assumed. Ok.

Check Critical Speed:

The first critical speed of all Aluminum wheel of M526A compressor is 13,100 RPM (See Table 19-4); the compressor speed is 12,087 RPM. The critical speed is above the operation speed, it is within the 20% range. Therefore, critical speed correction is needed by the manufacturer by changing the rotor assembly design.

Check Last Wheel Capacity Factor Q/ND^3:

Calculate the last wheel inlet pressure = P_x

Overall B_a = 1.035

On equal head theory, each impeller carries B_a = 0.207

B_a at the 5th wheel inlet is 0.207 x 4 = 0.828
From B_a Chart, CR = 2.13 at k = 1.28 and B_a = 0.828

P_x = 39.5 x 2.13 = 84.14 Psia

Calculate the last wheel inlet temperature = t_x

From X Chart, X = 0.178 at CR = 2.13 and k = 1.28

$$t_x = \text{Discharge temp.} = t_1 + \frac{(460 + t_1) \times X \times \phi}{\eta_p}$$

ϕ = 1.0285
X = 0.178
η_p = 0.785

$$t_x = 80 + \frac{(460 + 80) \times 0.178 \times 1.0285}{0.785}$$

= 206°F

5th wheel inlet pressure = 84.14 Psia
5th wheel inlet temperature = 206°F

$$P_R = \frac{84.14}{675} = 0.1247$$

$$T_R = \frac{(460 + 206)}{371} = 1.795$$

Z factor at discharge: 0.996

$$V_g = \frac{83.5 \times (460 + 206) \times 0.996}{144 \times 84.18} = 4.569$$

5th wheel flow = 510.6 x 4.569 = 2,333 CFM

T_s = 781.2 ft/sec.

$$Q/ND^3 = \frac{7.54 \times 2{,}333}{781.2 \times 219} = 0.103$$

Last wheel Q/ND^3 = 0.103 > Minimum 0.02 Limit, Ok

Check Driving Coupling:

SHP = 1,036 BHP
Compressor Speed = 12,087 RPM

Maximum HP limit 93.4 HP per 1000 RPM (As advised by the maker)

$$\text{Maximum coupling HP} = 93.4 \times \frac{12{,}087 \text{ RPM}}{1{,}000} = 1{,}128 \text{ HP} \qquad \text{Ok.}$$

Check Impeller Fasten:

$$\text{Each impeller carries } \frac{1{,}036}{5} = 207.2 \text{ HP}$$

$$\text{Maximum impeller fasten limit} = 120 \times \frac{12{,}087}{1{,}000} = 1{,}450 \text{ HP} \qquad \text{Ok.}$$

Oil Cooling:

FHP = 33 HP

Oil cooler = FHP + F x (Tdisch. – 275)

TDisch. = 287°F
F = 0.08 for 25” casing compressor

Oil Cooling = 33 + 0.08 x (287 – 275) = 33.96 HP

Therefore, Oil cooling = 34 FHP

External Gear:

The compressor speed is 12,087 RPM and a 2-pole motor speed is 3,540 RPM for 60 Hz power supply; or 2,950 RPM for 50 Hz power supply. An external gear is required to step up the motor input speed to compressor operating speed.

Conclusion:

Compressor Selected:	M26A with 5 stages
Compressor Casing:	Cast Iron
DWP, Casing:	300 Psig Standard
Shaft HP:	1,036 BHP
Compressor Speed:	12,087 rpm
Compressor Coupling:	1-1/4”ϕ
Oil Cooler:	34 HP
Driving HP:	1,067 BHP with estimated gear loss of 3%.

Important Notes:

(A) The compressor selection shown above is just for preliminary study and information only. The final and official selection must be either made or confirmed by the compressor manufacturer.

(B) Different impeller design results in different compressor efficiency and different partial load characteristics, check with the compressor manufacturer for details.