TABLE OF CONTENT

RECIPROCATING COMPRESSOR

I. PURPOSE

To be used for selection, application into the system, power and cooling water estimation. This manual does not for designing reciprocating compressor and the related parts.

II. SYMBOLS AND UNIT

Designation	Symbol	Unit
Pressure	p	bar A
Pressure ratio	r	-
Temperature	t	C
Absolute Temperature	T	K
Capacity (volume flow)	Q	m^3 / hr
Piston displacement volume	V_P	m^3
Volumetric efficiency	η_V	-
Mechanical Efficiency	η_M	-
Power	P	kW
Brake horse power	BHP	kW
Gas horse power	GHP	kW
Speed	N	RPM
Head	H	m
Gas Constant	R	kJ/kg.K
Molecular Mass	MW	kg/kg_{mole} $(=lb/lb_{mole})$
Mole	MM	kgmole (kgmole/h or kmol/h)
Density	DS	kg/m^3
Specific Gravity	SG	
Specific volume	v	m^3/kg
Specific Heat	Cp	kJ/kg.K
Mass Flowrate	G	kg / hr
Adiabatic Exponent	k	-
Polytropic Exponent	n	-
Isentropic exponent	m	-
Compressibility Factor	Z (capital)	-
Gravity	g	m/s^2 (9.81)
Heat Capacity	MCp	kJ/kgmole
Enthalpy	h	kJ/kg
Enthalpy different	Δh	kJ/kg
Entropy	s	kJ/kg.K
Piston diameter	D	mm
Piston speed	U	m/s
No. of stage	i	Integer number
No. of throw	z	Integer number
Power loss	P_{LOSS}	kW

Subkrip (Subscript)

cr atau CR	Critical	a	Adiabatic process
red atau R	Reduced	p	Polytropic
s atau S	Suction	1, 2 etc.	Position
d atau D	Discharge	I, II etc.	Stage No.
G	Gas/GHP	N	Normal condition (0 °C , 1.013 bar A)
V	Volumetric	MAX, max	Maximum
STG	Stage, throw		

III. UNIT CONVERSION

Designation	Unit to be converted	Factor	Unit to be used
Length	ft	304.8	mm
	inch	25.4	mm
Pressure	psi	0.06897	bar
	kg/cm^2 (at.)	0.981	bar
	atm.	1.013	bar
	Pa (Pascal)	10^{-5}	bar
Temperature	F (Fahrenheit)	(t-32) x (5/9)	C
	K (Kelvin)	T - 273	C
	R (Rankin)	(5/9)	K
Velocity	ft/s	0.3048	m/s
	ft/min (fpm)	0.00508	m/s
Volume flow	GPM (US)	0.227	m^3/hr
	Cfm	1.699	m^3/hr
Mass	lbm	0.4536	kg
Power	HP	0.7457	kW
Head	ft	0.3048	m
Enthalpy	kcal/kg	4.1868	kJ/kg
	BTU/lbm	2.326	kJ/kg
Gas constant	kcal/kg.K	4.1868	kJ/kg.K
Specific heat & Entropy	BTU/lbm.R	4.1868	kJ/kg.K
Specific mass or density	lbm/ft^3	16.0185	kg/m^3
Specific volume	ft^3 /lbm	0.06243	m^3/kg
Viscosity	$N.s/m^2$	1000	cP
	$lbf.s/ft^2$	47880.3	cP

Note : American Standard State at 1.013 bar A and 15.5 C. In volume common written as SCF.
Normal condition at 1.0132 bar A and 0 C. In volume common written as Nm^3

IV. MAIN COMPONENT OF RECIPROCATING COMPRESSOR

Figure 1 and figure 2 show components of reciprocating compressor.

1. Crankshaft
2. Connecting rod
3. Crosshead
4. Piston rod

5. Piston and their rings
6. Packing rings or seal rings
7. Check valves
8. Suction unloader and clearance pocket
9. Distance pieces

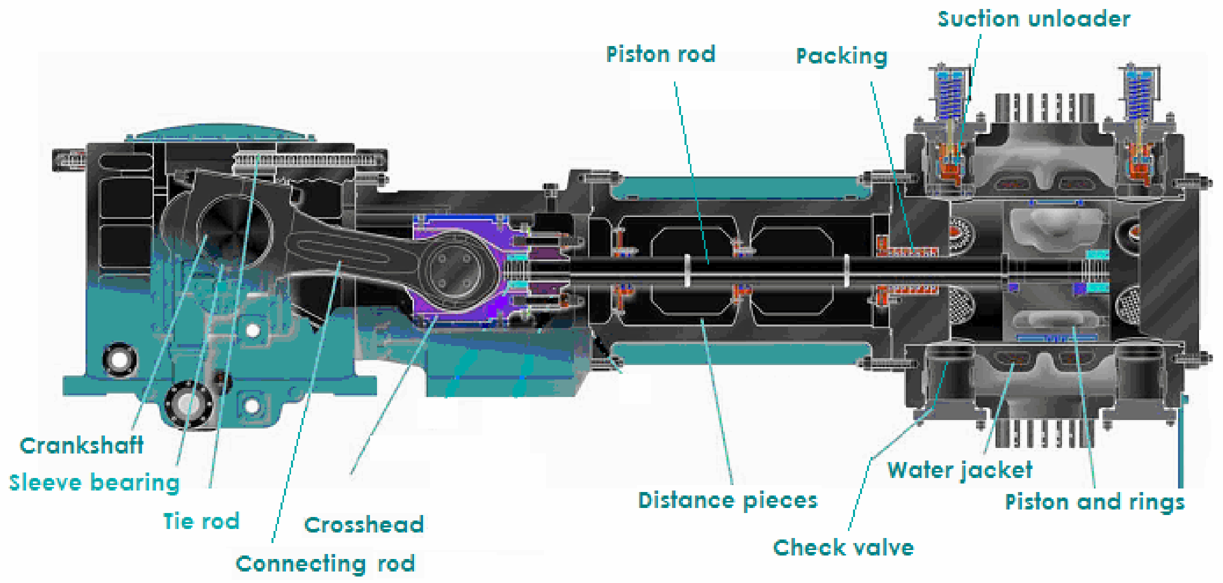


Figure 1. Cross Section of Typical Reciprocating Compressor

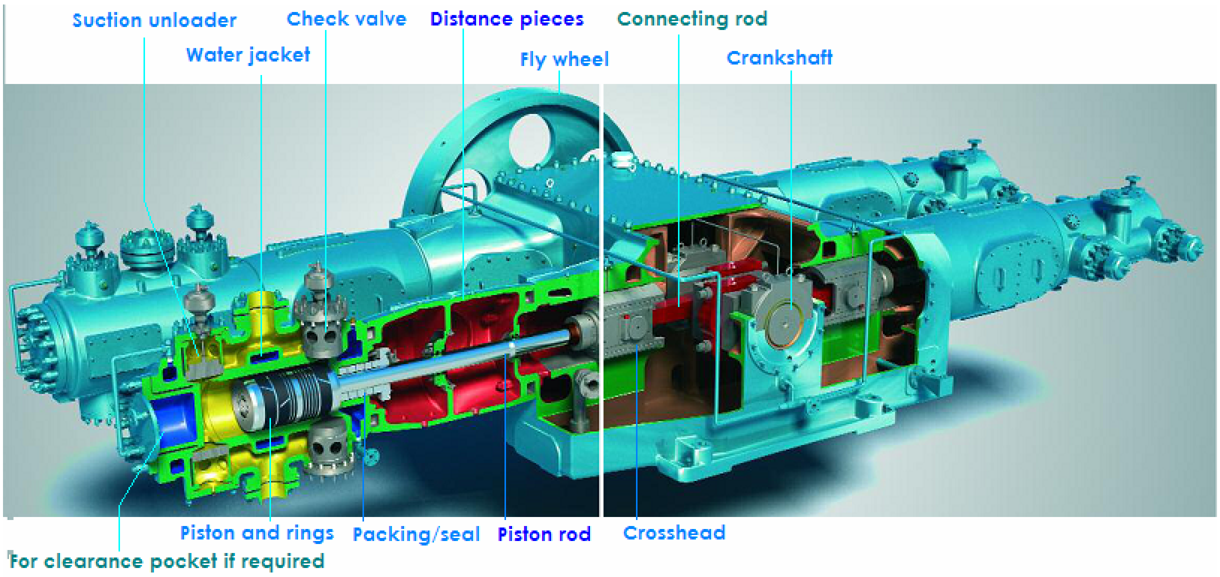


Figure 2. Cross Section of Typical Reciprocating Compressor

V. OPERATING RANGE OF RECIPROCATING COMPRESSOR

Figure 3 shows operating range of reciprocating compressor base on suction volume flow against speed (RPM). Comparing to the other compressor types, reciprocating compressor has lowest operating speed where below 1000 RPM.

Compression ratio of reciprocating compressor is up to more than 500 where is highest compression ratio compared to the other compressor types.

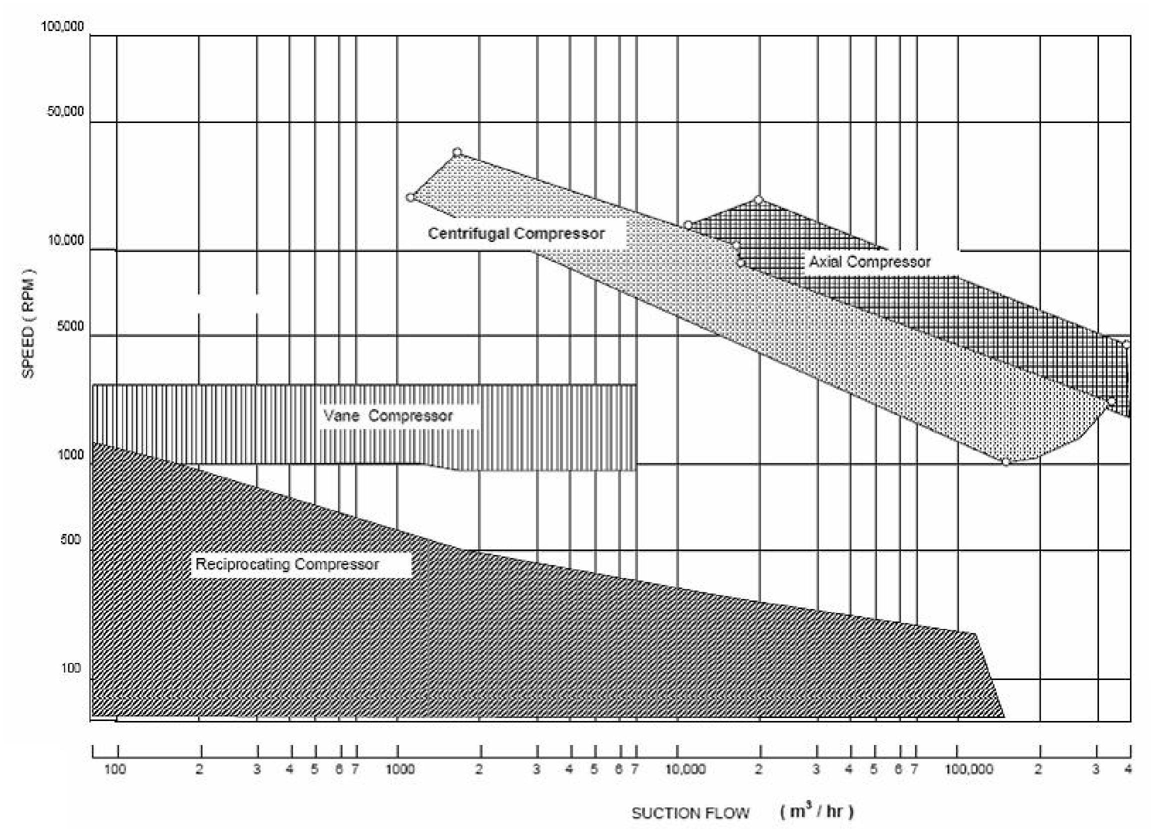


Figure 3. Operating Range of Reciprocating Compressor.

VI. GAS COMPRESSION

Gases to be handled by compressor are both single component (pure gas) and mixed gas. This manual also describes physical properties of mixed gas. In the next equations and calculations, gas is assumed as ideal gas but then corrected by correction factors and so ever is assumed equal to actual physical properties of the gas.

Figure 4 shows typical gas flow diagram in reciprocating compressor. Due to the discontinuity of gas flow of reciprocating compressor, gas pulsation will occur if excitation frequency is near or equal to natural frequency of gas column in the system. Pulsation dampener is made from pressure vessel and orifice. Pulsation dampeners usually can be designed and supplied by compressor manufacturer.

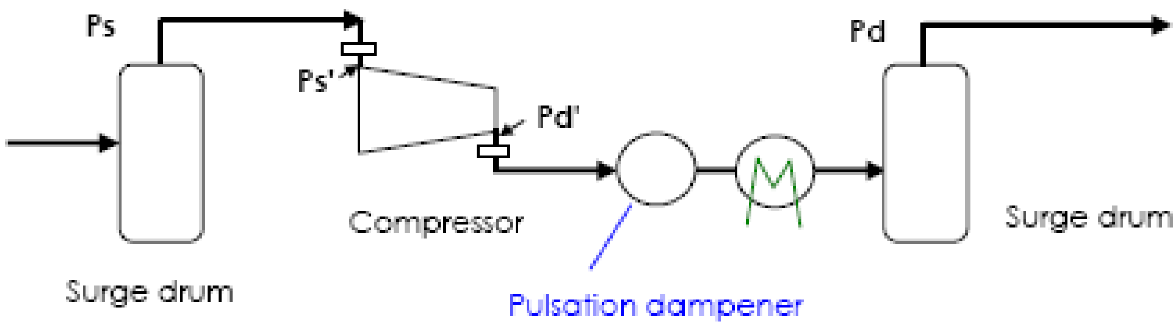


Figure 4. Flow Diagram of Gas at around Reciprocating Compressor

There is pressure drop at suction side and discharge side of reciprocating compressor due to inlet / outlet and check valve constructions. Ps is system suction pressure, Ps' is intake pressure of compressor cylinder, Pd' is outlet pressure of compressor cylinder and Pd is discharge pressure to the system.

Gas compression process in reciprocating compressor can be expressed such in figure 5. In the way back from point 1 to point 3, gas flows or gas induced to cylinder is only from point 2 to 3, because from point 1 to 2 there is only gas expansion of residual gas in clearance space. Ratio of effective stroke (Le) by physical stroke (Lp) named volumetric efficiency.

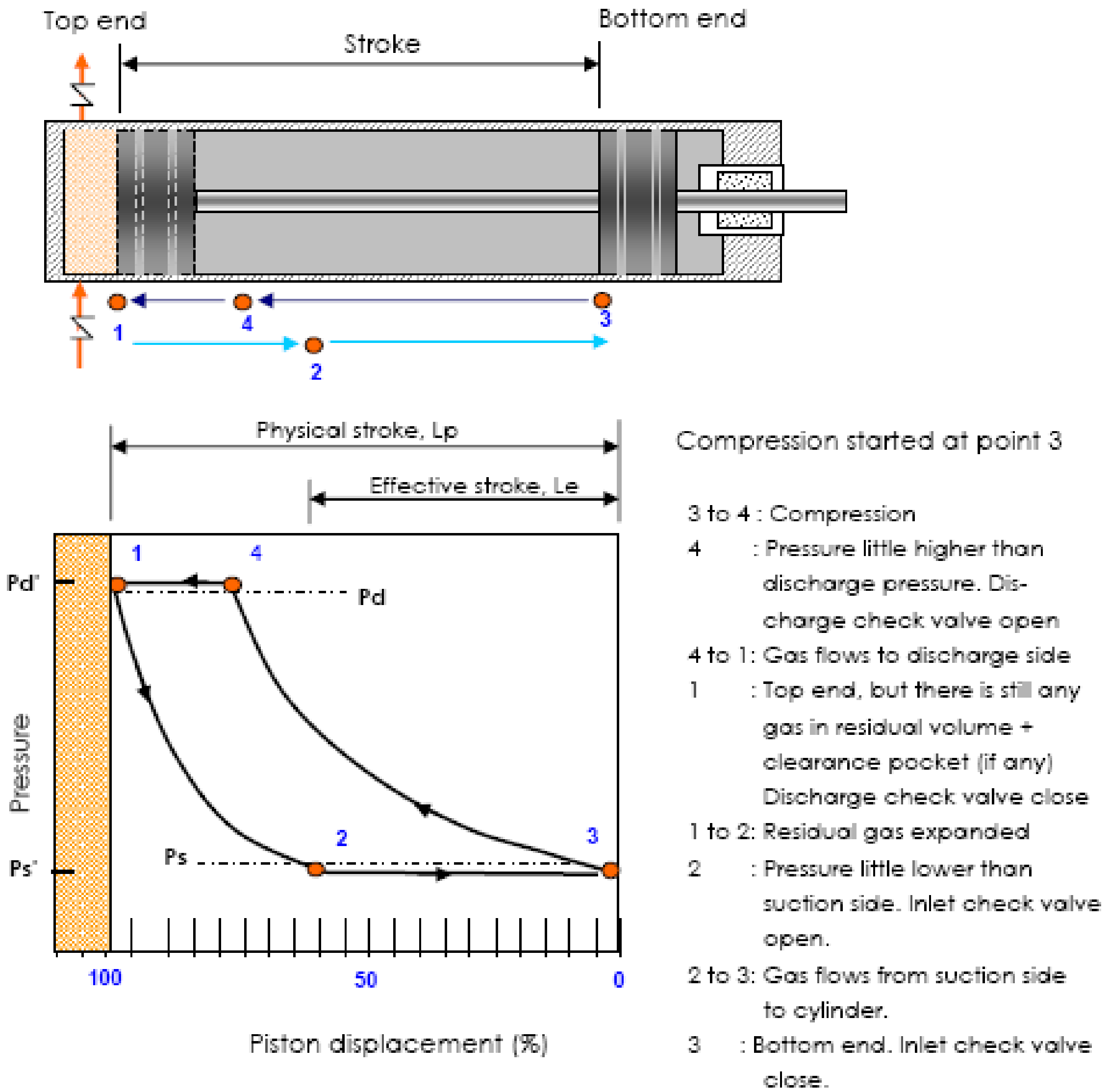


Figure 5. Idealized Gas compression Process in Piston Displacement and Pressure

VII. INTERCOOLER AND AFTERCOOLER

Intercooler is required when compressed gas temperature to the next compression will higher than permitted temperature during or after compression. Permitted gas temperature during compression is depending to the weakest of constructed components, cooling media or gas compressed properties itself. The following are typical permitted temperature in reciprocating compressor.

Designation	Permitted temperature (C)
Oil lubricated air compressor	160 for multi stage
	200 for single stage
Pure oxygen and pure chlorine	120
Dry cylinder with Teflon seals	200

Other typical standard give maximum temperature 150 C for any gas based on adiabatic process calculation.

If intercooler is cooling water media type, differential temperature between inlet cooling water and exhaust gas from intercooler shall be not so close, i.e. higher than 5 °C or 8 to 10 °C is most used.

Aftercooler is required when discharge system temperature of compressor is limited or to be cooled due to process requirements.

VIII. COMPRESSOR CONTROL

There are some ways to control reciprocating compressor capacity such as speed for turbine driver, suction valve unloader or clearance pocket or bypass control or combination of these controls for constant speed driver (i.e. electric motor). See also Appendix C.

Figure 6 shows gas process in clearance pocket control. When residual gas space is larger, intake volume will decrease. Figure 7 shows gas process in suction valve unloader. Suction valve unloader controls pressure drop between suction pressure and cylinder suction pressure (ΔPs') and by itself, volume flow is also controlled because given energy by driver is constant or equal.

Figure 8 shows gas process in bypass control system. Effective volume will reduced when bypass volume is become parts of total volume.

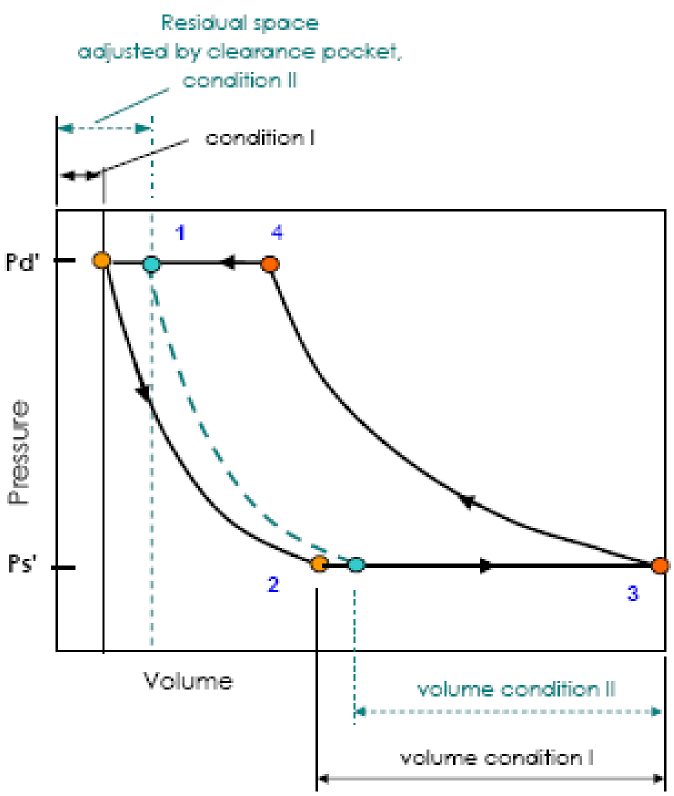


Figure 6. Volume Control by Clearance Pocket

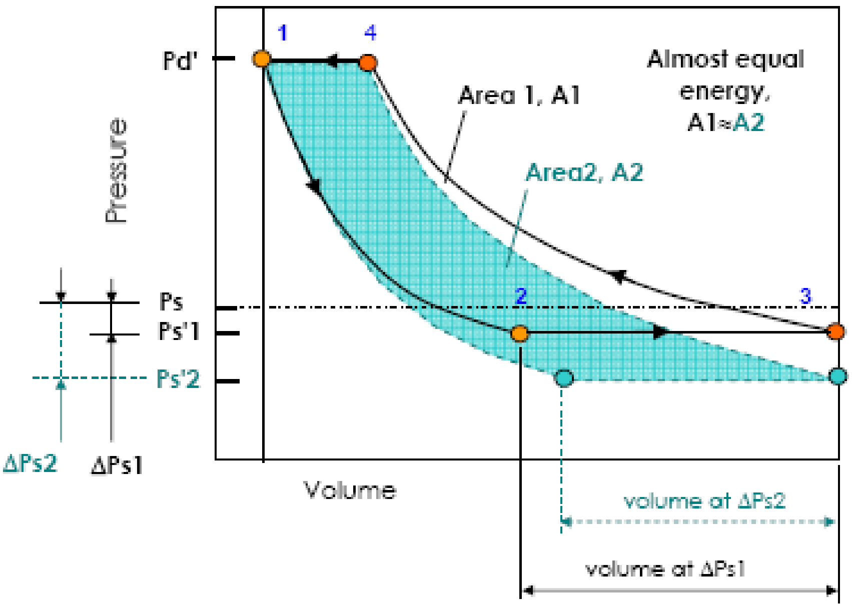
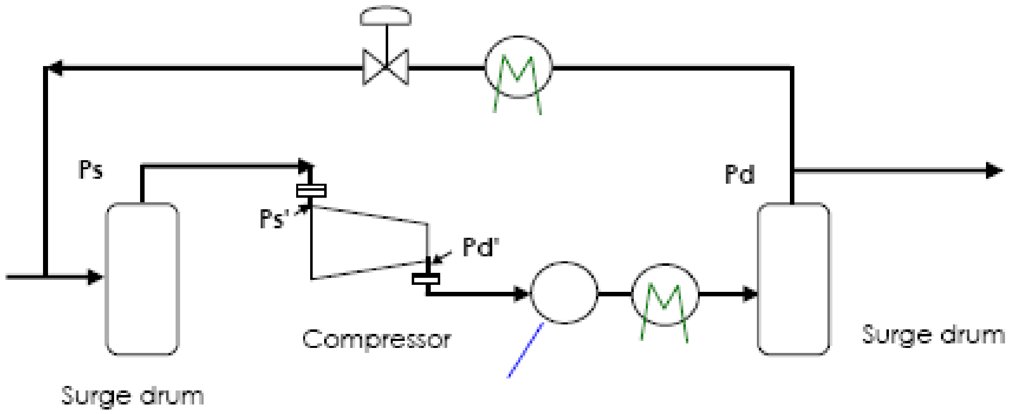


Figure 7. Volume Control by Suction Valve Unloader



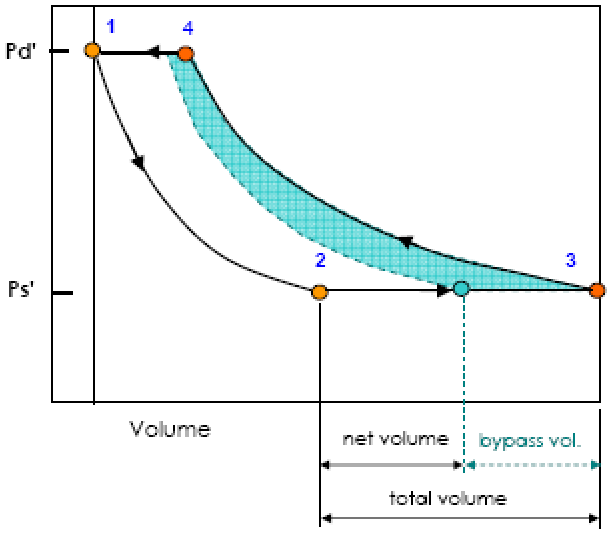


Figure 8. Gas Process in Bypass Controller.

IX. CALCULATION FORMULA

All following calculation formula are related to required power, required cooling water, number of stage and gas condition for each stage of gas in reciprocating compressor.

Brake **horse power**,

BHP = GHP/η_M (kW) (1)

where η_M is mechanical efficiency, see Appendix A.

Gas horse power

GHP = $\dfrac{G.H.g.10^{-6}}{3.6(\eta_V)}$ (kW) (2)

where G is induced mass flow and η_V is volumetric efficiency, see Appendix A.

G = DS_S . Qs (kg/h) (3)

DS_S is density of gas in kg/m3 and Qs is induced volume flow in m3/hr

For **perfect gas**,

Qs = $\dfrac{Ts.Qn}{269.69(ps)}$ and Qd = $\dfrac{Td.Qn}{269.69(pd)}$ (m^3/hr) (4)

Where Qn is volume flow at normal condition (0 C and 1.013 bar A)

DS_S = $\dfrac{100(ps)}{Rs.Ts}$, DS_N = $\dfrac{101.3}{273(R)}$ and DS_D = $\dfrac{DSs.Ts.pd}{Td.ps}$ (m^3 /hr) (5)

For **actual gas** with compressibility correction,

Qs = $\dfrac{Ts.Qn.Zs}{269.69(ps)}$ and Qd = $\dfrac{Td.Qn.Zd}{269.69(pd)}$ (m^3/hr) where $Z_N \approx 1$ (6)

DS_S = $\dfrac{100(ps)}{Rs.Ts.Zs}$, and DS_D = $\dfrac{DSs.Ts.pd.Zs}{Td.Zd}$ (m^3 /hr) (7)

Hydrodynamic **head** in adiabatic process,

H = $\dfrac{1000(Zs)(R)(Ts)}{g}\{\dfrac{k}{k-1}\}\{(\dfrac{pd'}{ps'})^{(\frac{k-1}{k})}-1\}$ (m) (8)

With substitution, GHP can be rewritten as the following equation,

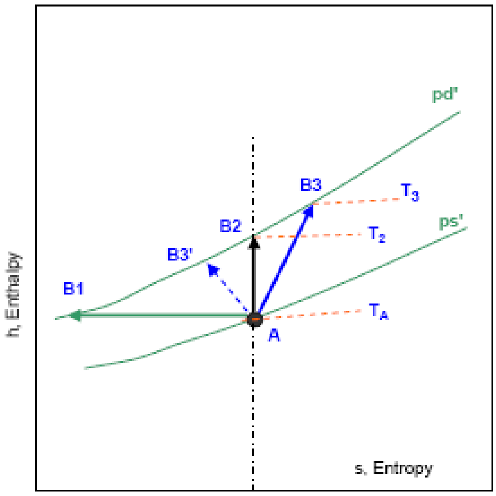
GHP = $\dfrac{0.02778\,x\,ps'\,x\,Qs}{\eta_V\,(\lambda/\eta_V)}\left\{\dfrac{k}{k-1}\right\}\left\{\left(\dfrac{pd'}{ps'}\right)^{\left(\frac{k-1}{k}\right)}-1\right\}$ (9)

Where (pd'/ps' = r') is compression ratio. pd' and ps' are in absolute pressure (bar A) and k is adiabatic exponent. Following figure 9 shows relation between compression process and the exponents.

Isothermal compression is where gas always in constant temperature during compression.

Adiabatic compression is where gas always in constant entropy during compression. There is no heat loss or heat addition and no friction that potentially produce heat.

Polytropic compression is where during gas compression there is heat loss and friction as an actual compression process.



A - B1	Isothermal compression	p.V = C	Exponent = 1
A - B2	Adiabatic compression	$p.V^k = C$	k = adiabatic exponent
A - B3	Polytropic compression	$p.V^n = C$	n = polytropic exponent

Polytropic exponent n > k : with friction and heat transfer to gas
n < k : with cooling process

Figure 9. Gas Compression Process and Their Exponents

Practically, n is almost equal with k for reciprocating compressor without special cooling process.

R = Ro / MW (kJ/kg.K)

Ro = 8.314 (kJ/kgmole.K)

See **Appendix B** for R, MW, k and Z for several gas.

Discharge Temperature

$$Td = Ts \cdot \left(\frac{pd'}{ps'}\right)^{\left(\frac{k-1}{k}\right)} \quad (10)$$

If discharge temperature is limited at Tdmax, then maximum pressure ratio become

$$\left(\frac{pd'}{ps'}\right)_{MAX} = \left(\frac{Td\max}{Ts}\right)^{\left(\frac{k}{k-1}\right)} \quad (11)$$

Average **piston speed** (also piston rod and crosshead),

$$U = \frac{0.002\, x\, L\, x\, N}{60} \quad m/s \quad (12)$$

Where L is piston stroke in mm, N crankshaft speed in RPM. Several data shows U is in the range of 2 up to 6 m/s.

APPENDIX A. SIZE, EFFICIENCY, LOSSES AND MAXIMUM FRAME BHP

A.1. VOLUMETRIC EFFICIENCY

Piston displacement volume,

$V_P = 7.8675 \times 10^{-10} \times D^2$ (m^3) (A.1)

Piston displacement volume flow / acting,

$Q_P = 4.7205 \times 10^{-8} \times D^2 \times N$ (m^3/hr) (A.2)

Adiabatic volumetric efficiency,

$\eta_{VO} = 1 - \left(r'^{\frac{1}{k}} - 1 \right) x\,(0.01\,c)$ and $c < \dfrac{100(1-\eta_{v0-EXP})}{(r'^{\frac{1}{k}} - 1)}$, $\eta_{VO\text{-}EXP}$, c >2 % (A.3)

k is adiabatic exponent, r is pressure ratio (pd/ps) and c is clearance volume divided by total volume of cylinder in %. $\eta_{VO\text{-}EXP}$ is expected efficiency but c must be approximately > 2 %.

Correction factors due to the actual compression process are given such as the following equations,

$\eta_V = 0.96 \times \eta_{VO}$ or $\eta_V = \eta_{VO} - 0.05$. In this manual, η_V is taken as :

$\eta_V = 0.95 \times \eta_{VO}$ (A.4)

During compression there is heating effect during suction stroke, gas leak through valves, piston rings and piston rod seals. Actual delivered of gas become smaller than induced gas at intake. Defined "Supply efficiency", λ .

$\lambda = \eta_V \,.\, (\lambda / \eta_V)$

Typical of λ/η_V is given in the following equation,

$\lambda/\eta_V = 1.03 - 0.03116\,r + 0.001\,r^2$, r within the range of 1 up to 5 (A.5)

Required piston capacity,

$Qp = Qs / \lambda$ (m^3/hr) (A.6)

or

$Qp = \dfrac{Qs}{(\lambda/\eta_V).\eta_V}$ (m^3/hr) (A.7)

A.2. INTAKE AND EXHAUST LOSSES

Pressure drop at intake and exhaust is (see also figure 4),

0.08 x p at low pressure stage and 0.03 x p for other stage

ps' = 0.92 x ps for low pressure and ps' = 0.97 x ps for high pressure (A.8)

pd' = 1.08 x pd for low pressure and pd' = 1.03 x pd for high pressure

A.3. HEAD AT EACH STAGE

When temperature is limited during compression, maximum head for each stage is

$$H_{STG\text{-}MAX} = \frac{1000(Zs)(R)(Ts)}{g}\left\{\frac{k}{k-1}\right\}\left\{\left(\frac{pd'}{ps'}\right)_{max}^{\left(\frac{k-1}{k}\right)} - 1\right\} \qquad (A.9)$$

where $(pd'/ps')_{max} = r'_{STG\text{-}MAX\text{-}T} = \left(\frac{Td\max}{Ts}\right)^{\left(\frac{k}{k-1}\right)}$ or $pd_{STG\text{-}MAX\text{-}T} = ps\left(\frac{Td\max}{Ts}\right)^{\left(\frac{k}{k-1}\right)}$ bar A (A.10)

r' is also limited by maximum frame power of compressor.
Substitute equation 1, 2 and A.9,

$$H_{STG\text{-}MAX} = \frac{3.6\,BHP_{frame}\,\eta_m\,\eta_V\,.10^6}{g.G.z} \text{ and } r'_{STG\text{-}MAX\text{-}P} = \left\{\frac{H.g.\left(\frac{k-1}{k}\right)}{1000.Z.R.Ts}+1\right\}^{\left(\frac{k}{k-1}\right)} \qquad (A.11)$$

If so, maximum r' is selected whichever is lower.

A.4. PISTON CAPACITY, PISTON SPEED, STROKE LENGTH AND MAXIMUM FRAME BHP

In this article, **maximum piston speed is defined at 6 m/s**. Figure A.1 shows relation between N (RPM), stroke length L (mm) at several average piston speed, U based on equation (12). When there is no data for frame BHP, **maximum frame BHP is defined at 0.11 Qp1. z kW**, where **Qp1** is piston displacement capacity for each stroke in **m^3/hr** (**$4.721.10^{-8}.D^2.L.N$** where D is maximum diameter in mm, L in mm and N in RPM) and z is number of throw.

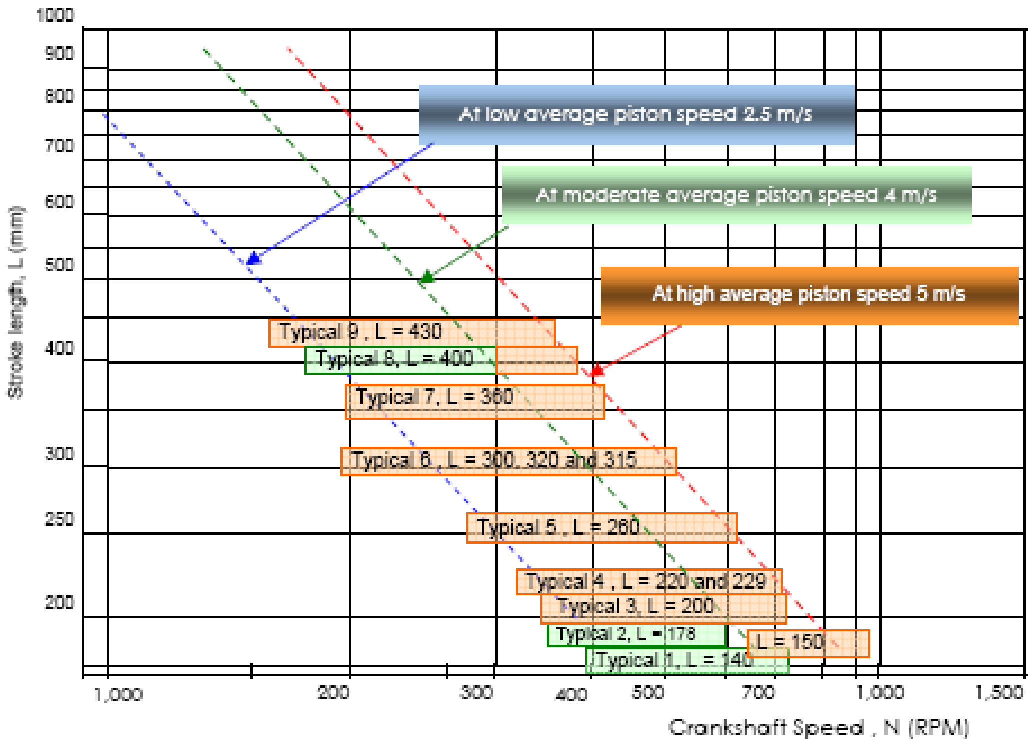


Figure A.1. Typical Stroke Length for Reciprocating Compressor

Available maximum diameter in this manual is decided at 1130 mm based on manufacturer's data. Figure A.2 and A.3 show relation between stroke length L and piston volume flow at defined L/D = 0.4 for varies number of throw. Manufacturers are available to produce reciprocating compressor with number of throw, z up to 12 at one casing. In general, stroke length 430 mm and shorter are available. Figure A.2 for single acting and figure A.3 for double acting compression.

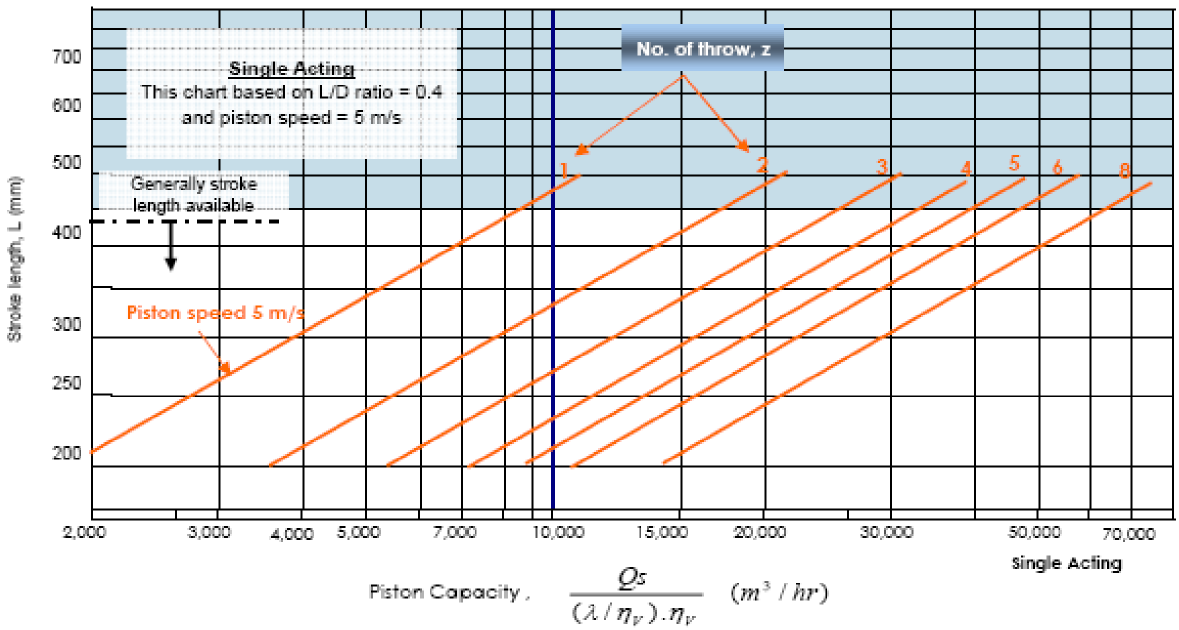


Figure A.2. Stroke length Against Piston Capacity Chart for Single Acting Compression

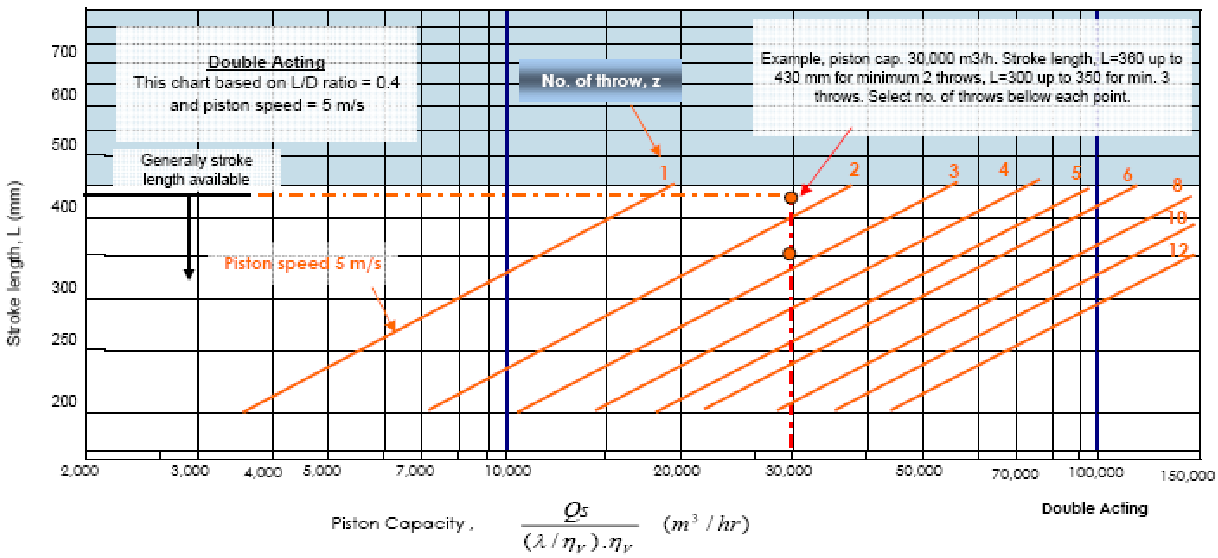


Figure A.3. Stroke length Against Piston Capacity Chart for Double Acting Compression

A.5. MECHANICAL EFFICIENCY

The following figure shows mechanical efficiency, η_m

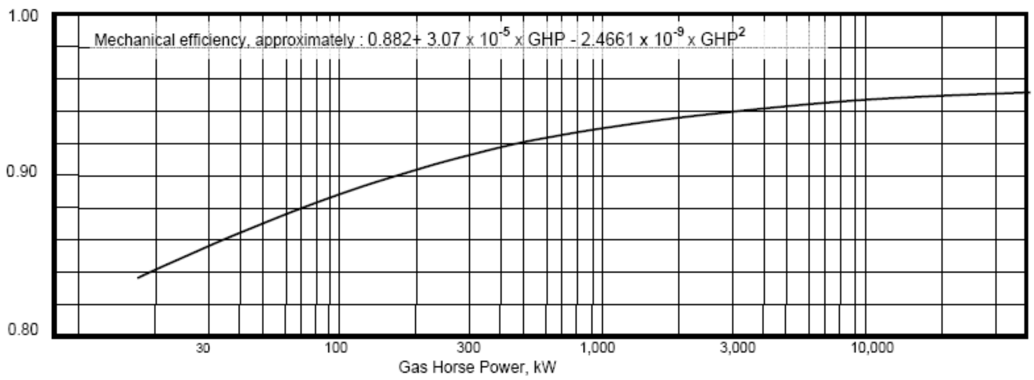


Figure A.4. Mechanical Efficiency of Reciprocating Compressor

APPENDIX B. GAS PROPERTIES

B.1. SINGLE GAS

The following table presents single gas properties. There are MW (molecular weight), k (adiabatic exponent), pcr (critical pressure), Tcr (critical temperature) and MCp (=MW x Cp).

Table 1. Pure Gas Properties

Gas or Vapor Name	Hydrocar - bon Refer. Symbols	Chemical formula	MW (kg/kgmol)	k at 15.5 °C	Critical condition		MCp (kJ/kgmol.°K)		
					p_{CR} (bar A)	T_{CR} (°K)	at 0 °C	at 100 °C	at 197 °C
Acetylene	C_2 =	C_2H_2	26.04	1.24	62.4	309.4	42.16	48.16	53.17
Air (dry)		N_2+O_2	28.97	1.4	37.7	132.8	29.05	29.32	-
Ammonia		NH_3	17.03	1.31	112.8	406.1	34.65	37.93	-
Argon		Ar	39.94	1.66	48.6	151.1	20.79	20.79	20.79
Benzene		C_6H_6	78.11	1.12	49.2	562.8	74.18	103.52	-
Iso-Butane	iC_4	C_4H_{10}	58.12	1.1	36.5	408.3	89.75	116.89	141.88
n-Butane	nC_4	C_4H_{10}	58.12	1.09	38	425.6	93.03	117.92	141.04
Iso-Butylene	iC_4 _	C_4H_8	56.1	1.1	40	418.3	83.36	104.96	124.87
Butylene	nC_4 _	C_4H_8	56.1	1.11	40.2	420	83.4	105.06	-
Carbon Dioxide		CO_2	44.01	1.3	74	304.4	36.04	40.08	43.7
Carbon Monoxide		CO	28.01	1.4	35.2	134.4	29.1	29.31	29.63
Chlorine		Cl_2	70.91	1.36	77.2	417.2	35.29	35.53	35.9
Coke Oven Gas [1)]		-	10.71	1.35	28.1	109.4	31.95	34.21	-
n-Decane	nC_{10}	$C_{10}H_{22}$	142.28	1.03	22.1	619.4	218.35	280.41	-
Ethane	C_2	C_2H_6	30.07	1.19	48.8	305.6	49.49	62.14	74.37
Ethyl Alcohol		C_2H_5OH	46.07	1.13	63.9	516.7	69.92	81.97	-
Ethyl chloride		C_2H_4Cl	64.52	1.19	52.7	460.6	59.61	70.16	-
Ethylene	C_2 _	C_2H_4	28.05	1.24	51.2	283.3	40.9	51.11	60.55
Flue Gas [1)]		-	30	1.38	38.8	146.7	30.17	30.98	-
Helium		He	4	1.66	2.3	5	20.79	20.79	20.79
n-Heptane	nC_7	C_7H_{16}	100.2	1.05	27.4	540.6	161.2	202.74	239.8
n-Hexane	nC_6	C_6H_{14}	86.17	1.06	30.3	508.3	138.09	174.27	206.88
Hydrogen		H_2	2.02	1.41	13	33.3	28.67	29.03	29.25
Hydrogen Sulfide		H_2S	34.08	1.32	90	373.9	33.71	35.07	36.88
Methane	C_1	CH_4	16.04	1.31	46.4	191.1	34.5	40.13	44.64
Methyl Alcohol		CH_3OH	32.04	1.2	79.8	513.3	42.67	55.32	-
Methyl Chloride		CH_3Cl	50.49	1.2	66.7	416.7	45.6	49.82	-
Natural Gas [1)]		-	18.82	1.27	46.5	210.6	34.66	39.54	-
Nitrogen		N_2	28.02	1.4	33.9	126.7	29.1	29.31	29.46
n-Nonane	nC_9	C_9H_{20}	128.25	1.04	23.8	596.1	197.07	253.1	-
Iso-Pentane	iC_5	C_5H_{12}	72.15	1.08	33.3	461.1	112.09	145.56	-
n-Pentane	nC_5	C_5H_{12}	72.15	1.07	33.7	470.6	115.21	145.94	173.96
Pentylene	C_5 _	C_5H_{10}	70.13	1.08	40.4	474.4	102.11	130.37	-
n-Octane	nC_8	C_8H_{18}	114.22	1.05	25	569.4	176.17	226.17	-
Oxygen		O_2	32	1.4	50.3	154.4	29.17	29.92	30.78
Propane	C_3	C_3H_8	44.09	1.13	42.5	370	68.34	88.68	107.71
Propylene	C_3 ..	C_3H_6	42.08	1.15	46.1	365.6	60.16	75.7	90.54
Blast Furnace Gas [1)]		-	29.6	1.39	-	-	29.97	30.64	-
Cat Cracker Gas [1)]		-	28.83	1.2	46.5	286.1	46.16	57.31	-
Sulphur Dioxide		SO_2	64.06	1.24	78.7	430.6	38.05	40	45.7
Water Vapor		H_2O	18.02	1.33	221.2	647.8	33.31	34.07	34.9

Note : For MCp, use linier interpolation to determine MCp at other temperature.

Gas constant (R), specific heat (Cp) and k

$$\text{Gas constant } R = \frac{8.314}{MW} \qquad \text{(B.1)}$$

Specific heat $Cp = \frac{R.k}{k-1}$ (B.2)

Value of k is constant for dry gas, see table above.

Compressibility factor (Z)

Z determined by gas compressibility chart using reduction temperature (Tred) and pressure (pred) as the variables. Tred = T/Tcr and pred = p/pcr. See following figure A.1

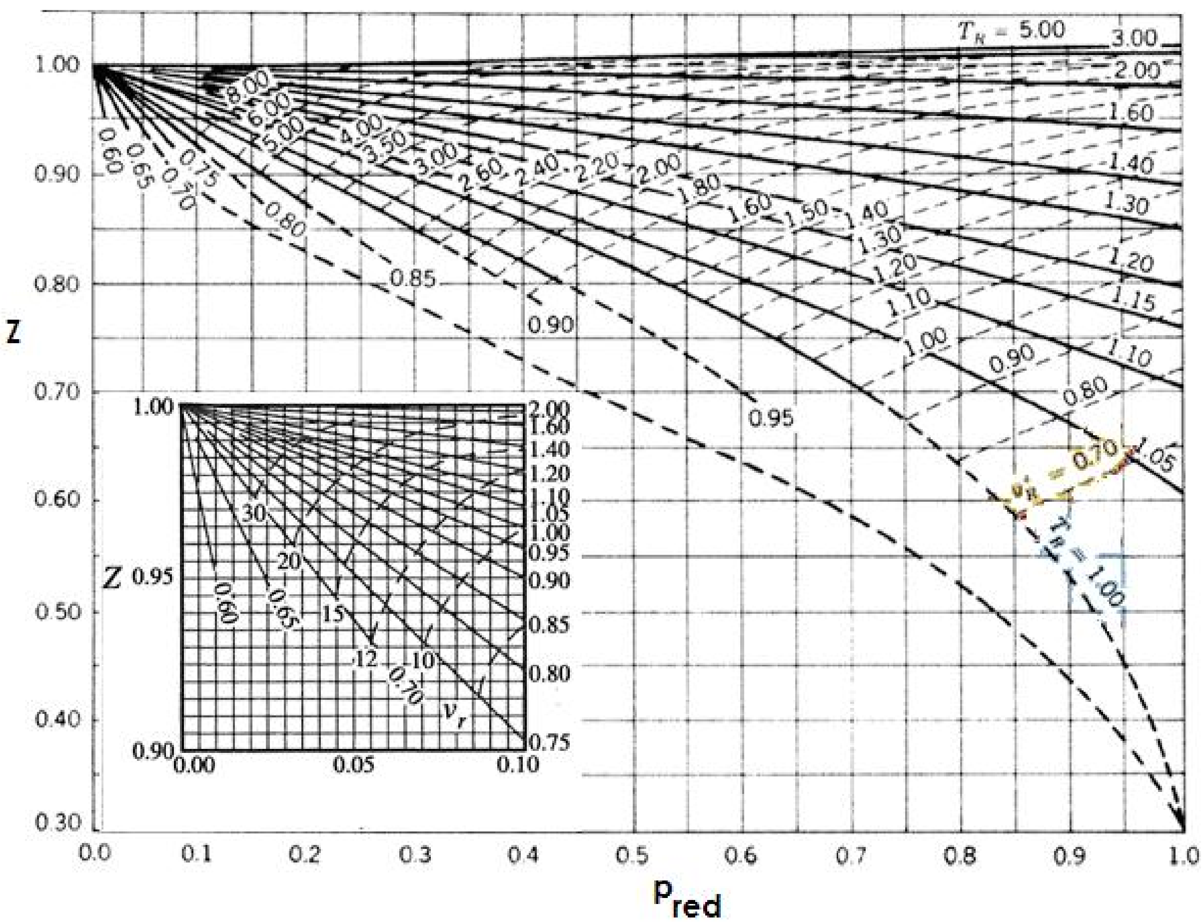


Figure B.1. Gas compressibility chart for pred < 1

Figure B.1 presents Z factor for pred = 1 and lower. For pred higher than 1 see figure B.2.

Density of gas,

$$DS = \frac{100(p)}{R.T.Z} \quad (B.3)$$

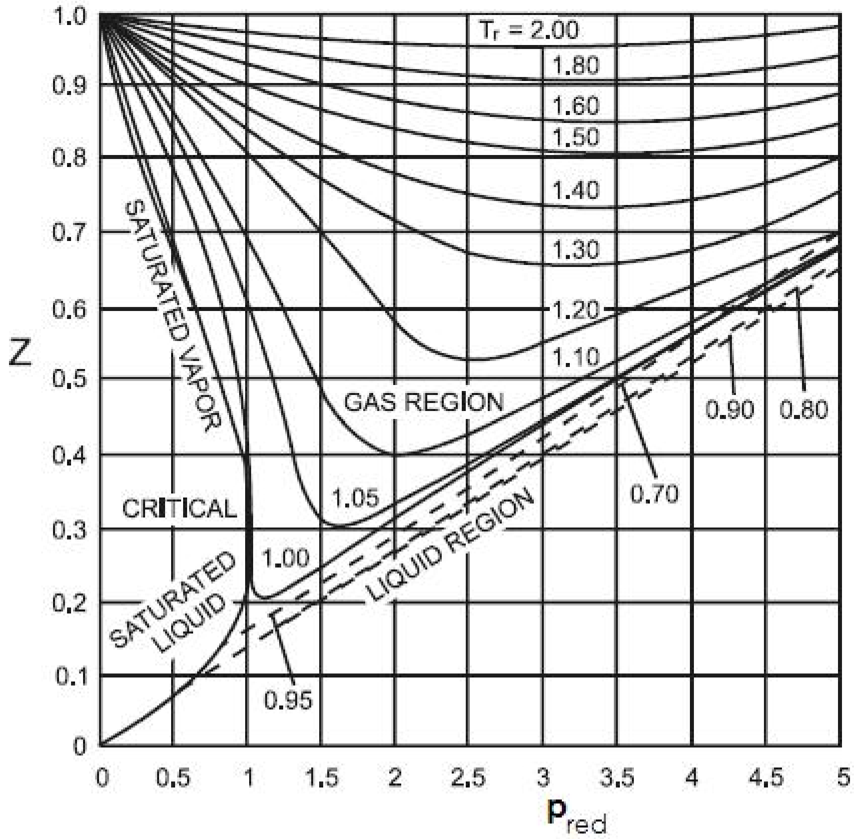


Figure B.2. Gas compressibility chart for pred higher than 1.

B.2. MIXED GAS

Gas constant (R), specific heat (Cp) and k of mixed gas

Subscript (i) indicates partial of pure gas.

MW = $\sum^{i}\{0.01(\%Mi)(MWi)\}$ (B.4)

Where %Mi is partial mole of each individual gas in %

% Mi = $\dfrac{100(MMi)}{\sum MMi}$ (B.5)

Where MMi is molal mass of each gas in kgmole or mols

MMi = $\dfrac{Mgi}{MWi}$ (B.6)

Where Mgi is mass of each gas in kg

k = $\dfrac{\sum 0.01(MCpi)(\%Mi)}{\sum 0.01(MCpi)(\%Mi) - 8.314}$ (B.7)

Gas constant R = $\dfrac{8.314}{MW}$

Specific heat $Cp = \frac{R.k}{k-1}$

Compressibility factor (Z)

pcr = $\sum 0.01(\%Mi)(pcri)$ (B.8)

Tcr = $\sum 0.01(\%Mi)(Tcri)$ (B.9)

Z factor determined using figure A.1 and A.2.

Density of mixed gas,

DS = $\frac{100(p)}{R.T.Z}$ (B.10)

B.3. WET GAS

Gas shall be dry in centrifugal compressor to prevent internal parts and impeller from erosion due to liquid particles. Gas condition shall be kept at little far from wet condition. Following table presents vapor pressure for some gases.

$p_{VAPOR} = A \times T^B$ bar A, and T at K

Gas name	A	B
Ethylene	1.64E-15	6.739
Ethane	1.02E-16	7.137
Propane	6.36E-19	7.702
Isobutane	2.42E-23	9.324
n-Butane	3.59E-25	9.984
n-Pentane	6.68E-30	11.647
n-Hexane	3.72E-35	13.568
n-Heptane	4.03E-31	11.794
n-Octane	5.85E-35	13.149
n-Decane	9.13E-42	15.533

Gas name	A	B
Carbon Dioxide	4.95E-19	8.141
HCl	4.26E-19	8.117
H_2S	1.29E-18	7.716
NH_3	1.23E-23	9.6
Cl_2	6.73E-22	8.86
SO_2	4.58E-27	10.816
Water	6.71E-28	10.578
(diatas 1 bar A)		

B.4. WET AIR

Following steps describes how to determine properties of wet air.

1. Relative humidity RH in %
2. Dry bulb temperature tdb in C and then Tdb = 273 + tdb in K
3. Atmospheric pressure patm at bar A
4. From psychometric chart, determine wet bulb temperature twb and Twb = 273 + twb
5. From H2O saturated pressure table, determine saturated pressure at twb, pg
6. Partial pressure of H2O — pw = 0.01 (%RH)(pg)
7. Partial pressure of dry air — pa = patm – pg
8. Mole fraction of dry air — Xa = pa / patm
9. Mole fraction of H2O — Xw = pw / patm
10. Molal mass of wet air — MW = (MWdry air)(Xa) + (MW_{H2O})(Xw)
11. MCp of wet air — MCp = (MCp dry air)(Xa) + (MCp H2O)(Xw)
12. Gas constant — R = 8.314 / MW
13. k — k = MCp / (MCp-8.314)
14. Density — DS = 100.patm / (R.Tdb)

Table 2. Saturated pressure of H2O

Temperature (C)	15	20	25	30	35	40	45	50
Sat.press. (barA)	0.01704	0.02337	0.03166	0.04241	0.05622	0.07375	0.0958	0.1233

Temperature (C)	55	60	65	70	75	80	90	100
Sat.press. (barA)	0.1574	0.1992	0.2501	0.3116	0.3855	0.4736	0.7011	1.0133

From % RH and tdb determine twb from following typical psychometric chart

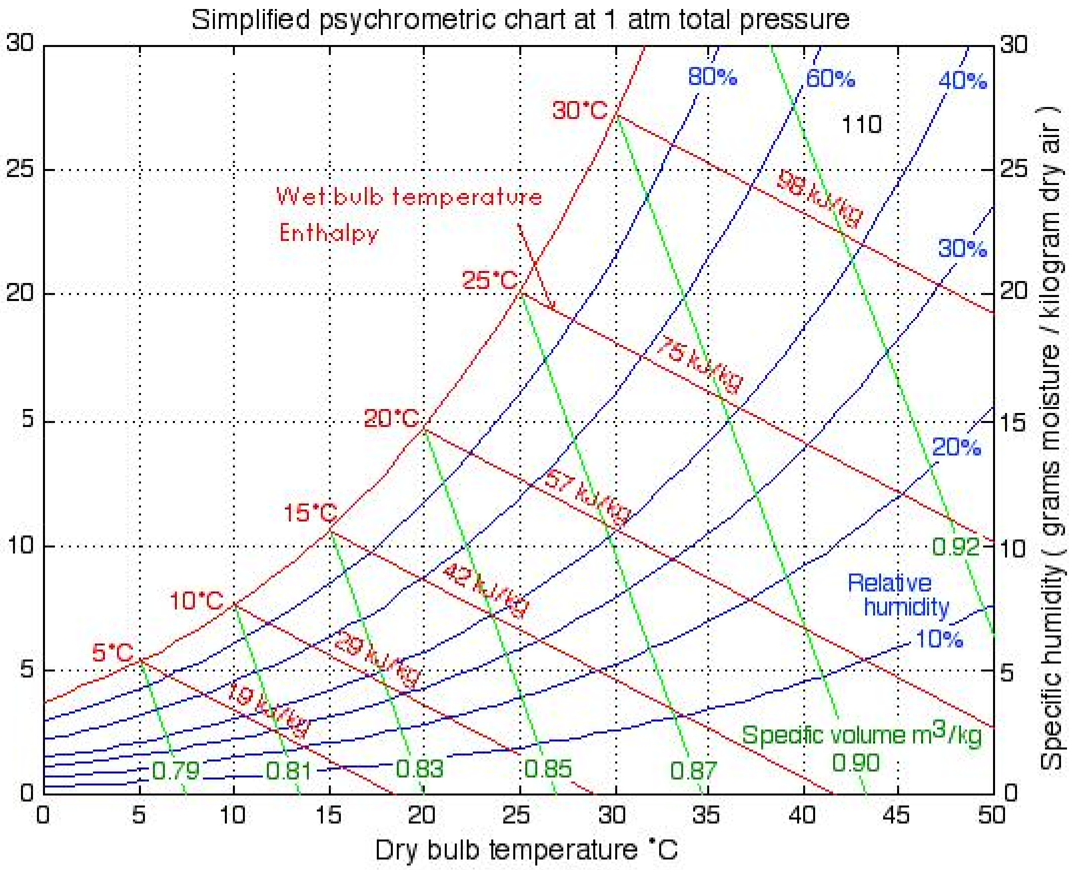


Figure B.3. Psychometric chart for air at 1 atm.

APPENDIX C. COMPRESSOR CONROL

The following figures are typical reciprocating controller diagram and capacity charts. Figure C.1 up to C.3 for constant speed driver and C.4 for variable speed driver.

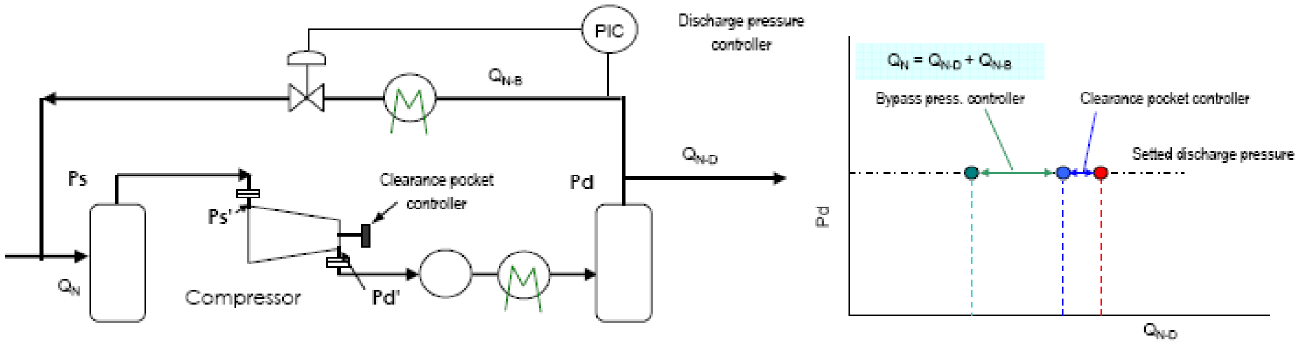


Figure C.1. Bypass Pressure Controller and Clearance Pocket Controller for Constant Speed

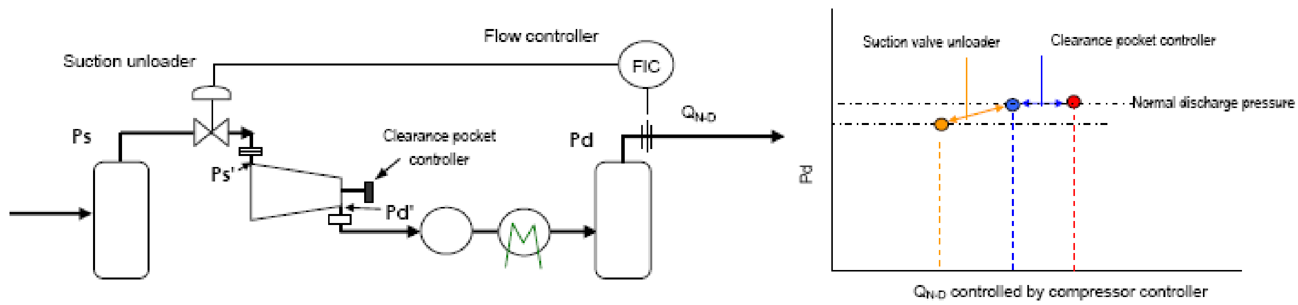


Figure C.2. Suction Valve Unloader and Clearance Pocket Controller

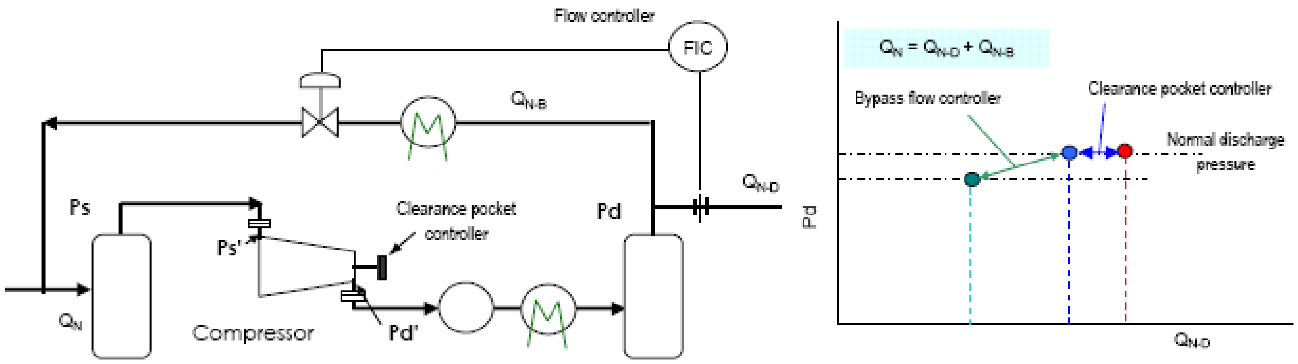


Figure C.3. Bypass Capacity Controller and Clearance Pocket Controller

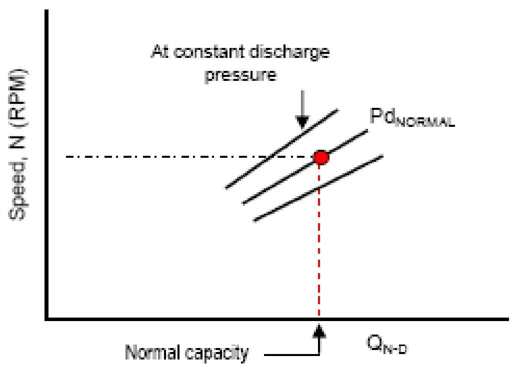


Figure C.4. Variable Speed Controller