

## I. MANUAL PURPOSE

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

## II. MAIN COMPONENTS OF IN-LINE CENTRIFUGAL COMPRESSOR

Following figure (Fig.1) shows components of in-line centrifugal compressor.

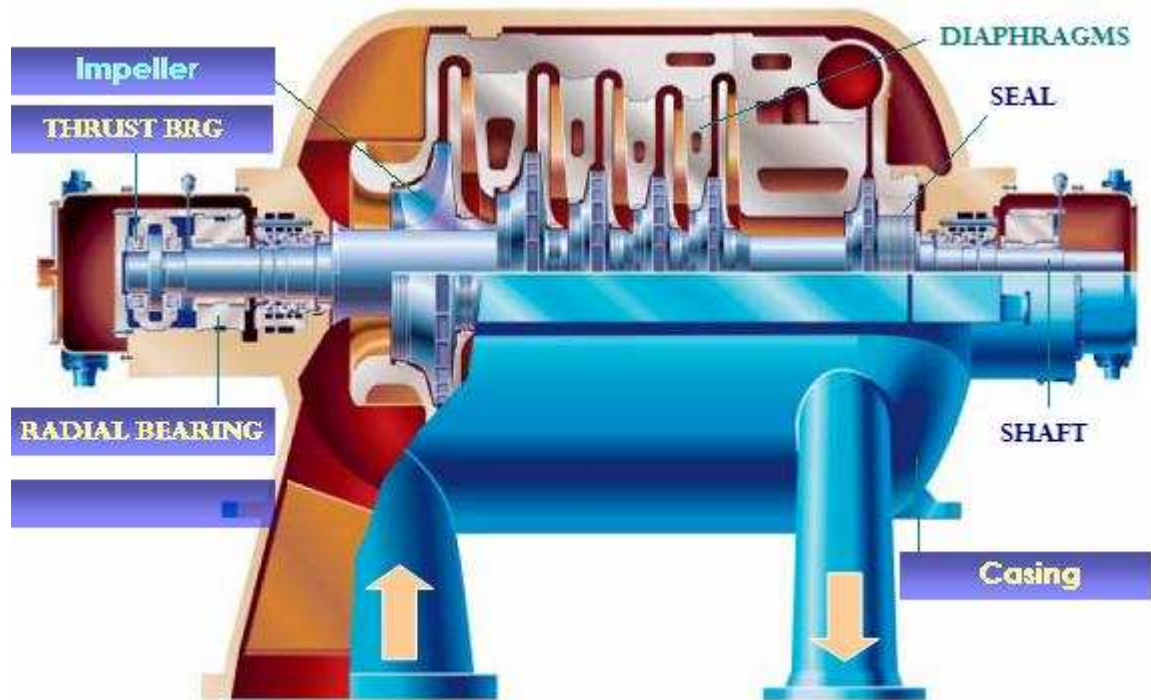


Fig.1. Typical horizontal split centrifugal compressor

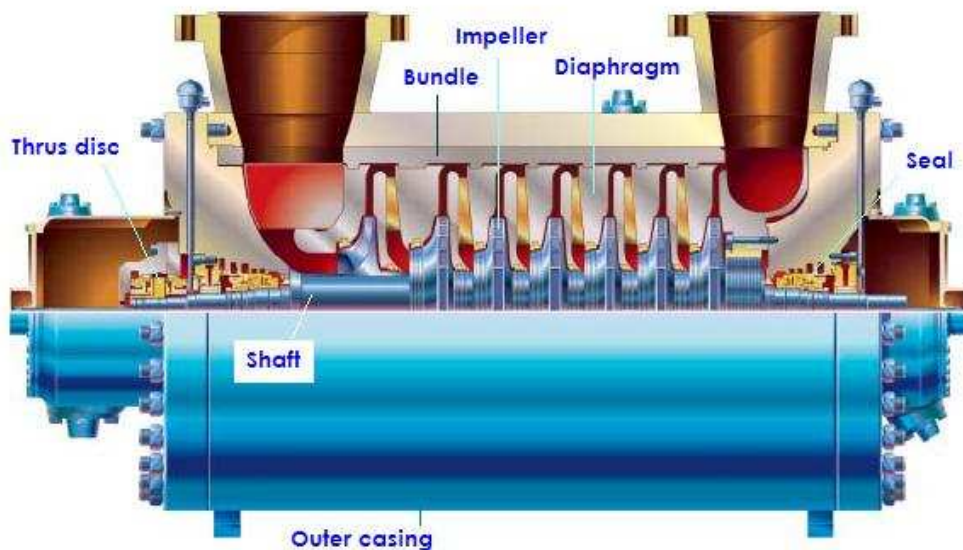


Fig. 2. Typical vertically split centrifugal compressor

Main components of centrifugal compressor are Casing, Shaft, Impellers, Bearings, Diaphragms and Seals.

## II. SYMBOLS AND UNIT

| <u>Designation</u>     | <u>Symbol</u>     | <u>Unit</u>                                     |                                            |
|------------------------|-------------------|-------------------------------------------------|--------------------------------------------|
| Pressure               | p                 | bar A                                           |                                            |
| Temperature            | t                 | C                                               |                                            |
| Absolute Temperature   | T                 | K                                               |                                            |
| Capacity (volume flow) | Q                 | m <sup>3</sup> / hr                             |                                            |
| Power                  | P                 | kW                                              |                                            |
| Brake horse power      | BHP               | kW                                              |                                            |
| Gas horse power        | GHP               | kW                                              |                                            |
| Speed                  | N                 | RPM                                             |                                            |
| Head (polytropic)      | H                 | m                                               |                                            |
| Gas Constant           | R                 | kJ/kg.K                                         |                                            |
| Molecular Mass         | MW                | kg/kg <sub>mole</sub> (=lb/lb <sub>mole</sub> ) |                                            |
| Mole                   | MM                | kgmole ( kgmole/h or kmol/h )                   |                                            |
| Density                | DS                | kg/m <sup>3</sup>                               |                                            |
| Specific Gravity       | SG                |                                                 |                                            |
| Specific volume        | v                 | m <sup>3</sup> /kg                              |                                            |
| Specific Heat          | Cp                | kJ/kg.K                                         |                                            |
| Mass Flowrate          | G                 | kg / hr                                         |                                            |
| Adiabatic Exponent     | k                 | -                                               |                                            |
| Polytropic Exponent    | n                 | -                                               |                                            |
| Compressibility Factor | Z                 | -                                               |                                            |
| Efficiency             | E                 | -                                               |                                            |
| Gravity                | g                 | m/s <sup>2</sup> (9.81)                         |                                            |
| Heat Capacity          | MCp               | kJ/kgmole                                       |                                            |
| Enthalpy               | h                 | kJ/kg                                           |                                            |
| Enthalpy different     | dh                | kJ/kg                                           |                                            |
| Entropy                | s                 | kJ/kg.K                                         |                                            |
| Impeller Diameter      | D                 | mm                                              |                                            |
| Tip speed (tangential) | U                 | m/s                                             |                                            |
| Number of impeller     | i                 | -                                               |                                            |
| Mach Number            | Ma                |                                                 |                                            |
| Flow Coefficient       | CQ                | -                                               |                                            |
| Head Coefficient       | Y                 | -                                               |                                            |
| Mechanical power loss  | Pml               | kW                                              |                                            |
| <b>Subscript</b>       |                   |                                                 |                                            |
| cr                     | Critical          | i                                               | Partial for gas, per impeller for impeller |
| red                    | Reduced           | p                                               | Polytropic                                 |
| s                      | Suction           | 1, 2 etc.                                       | Position                                   |
| d                      | Discharge         | I, II etc.                                      | Stage or step                              |
| g                      | Gas (Horse Power) | n                                               | Normal condition ( 0 C , 1.013 bar A )     |
| STG                    | Stage or 1 casing |                                                 |                                            |

### III. UNIT CONVERSION

| <u>Designation</u>          | <u>Unit to be converted</u> | <u>Factor</u>    | <u>Unit to be used</u> |
|-----------------------------|-----------------------------|------------------|------------------------|
| Length                      | ft                          | 304.8            | mm                     |
|                             | inch                        | 25.4             | mm                     |
| Pressure                    | psi                         | 0.06897          | bar                    |
|                             | kg/cm <sup>2</sup> (at.)    | 0.981            | bar                    |
|                             | atm.                        | 1.013            | bar                    |
|                             | Pa (Pascal)                 | 10 <sup>-5</sup> | 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 <sup>3</sup> /hr     |
|                             | Cfm                         | 1.699            | m <sup>3</sup> /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<br>& Entropy  | BTU/lbm.R                   | 4.1868           | kJ/kg.K                |
| Specific mass<br>or density | lbm/ft <sup>3</sup>         | 16.0185          | kg/m <sup>3</sup>      |
| Specific volume             | ft <sup>3</sup> /lbm        | 0.06243          | m <sup>3</sup> /kg     |
| Viscosity                   | N.s/m <sup>2</sup>          | 1000             | cP                     |
|                             | lbf.s/ft <sup>2</sup>       | 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<sup>3</sup>

## IV. OPERATING RANGE OF CENTRIFUGAL COMPRESSOR

Fig.3 presents operating range of Centrifugal Compressor based on suction flow and discharge pressure and fig. 4 presents operating range of centrifugal compressor compare with other type of compressor based on suction volume flow and speed.

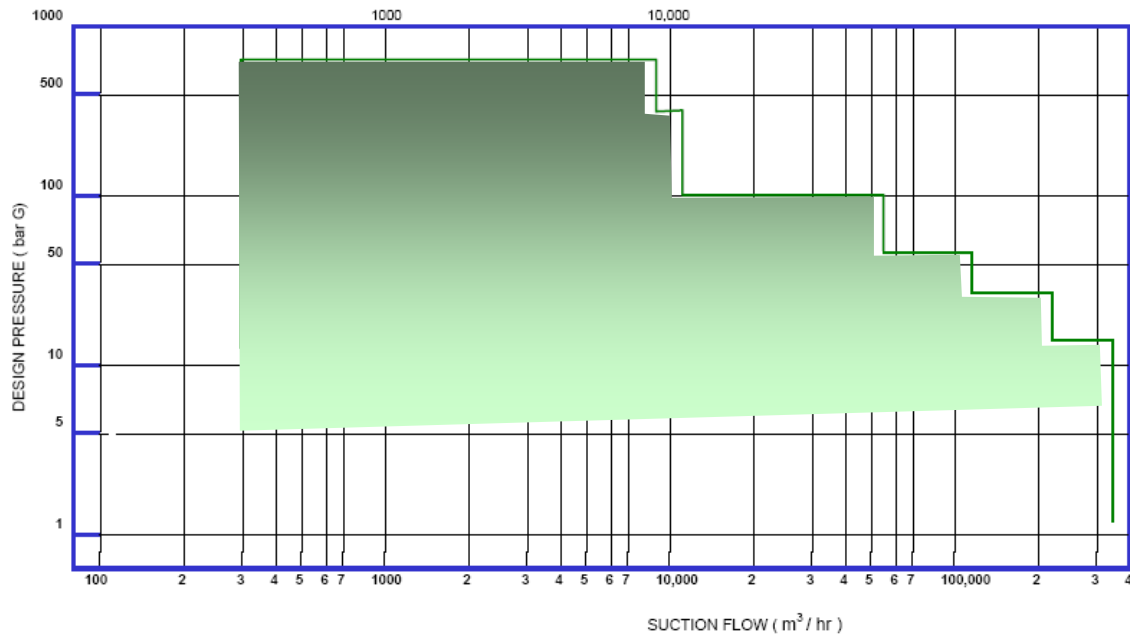


Fig. 3. Operating range of centrifugal compressor

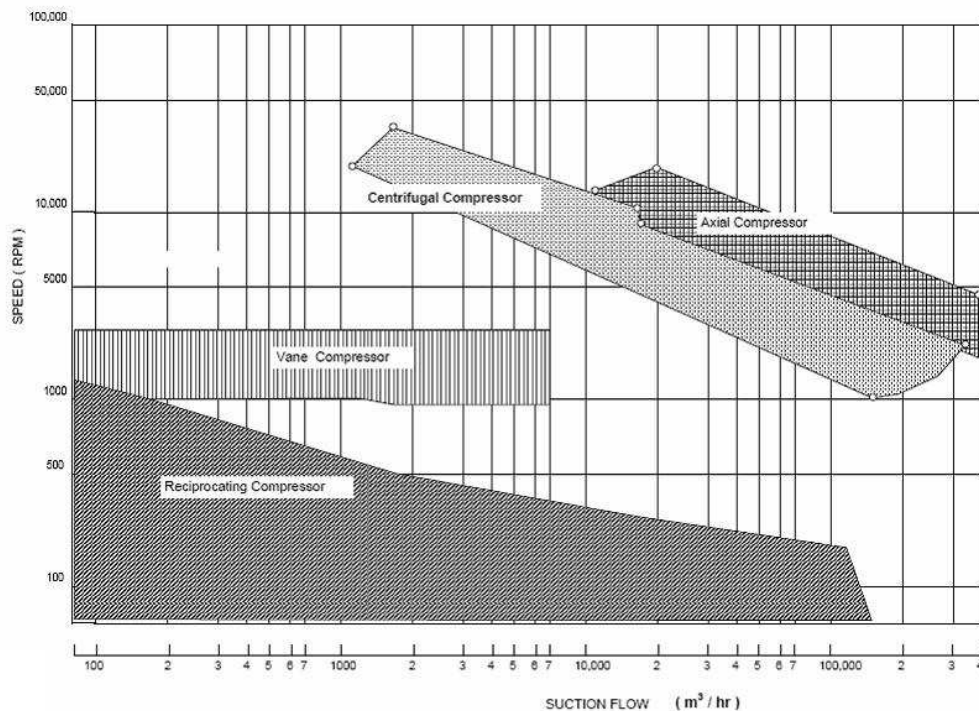


Fig. 4. Operating range of centrifugal compressor compared with other types of compressors

## V. 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. By any reason, for some cases, compressed gas is also assumed as non ideal gas.

Compression process of gas in centrifugal compressor describes with Fig. 5.

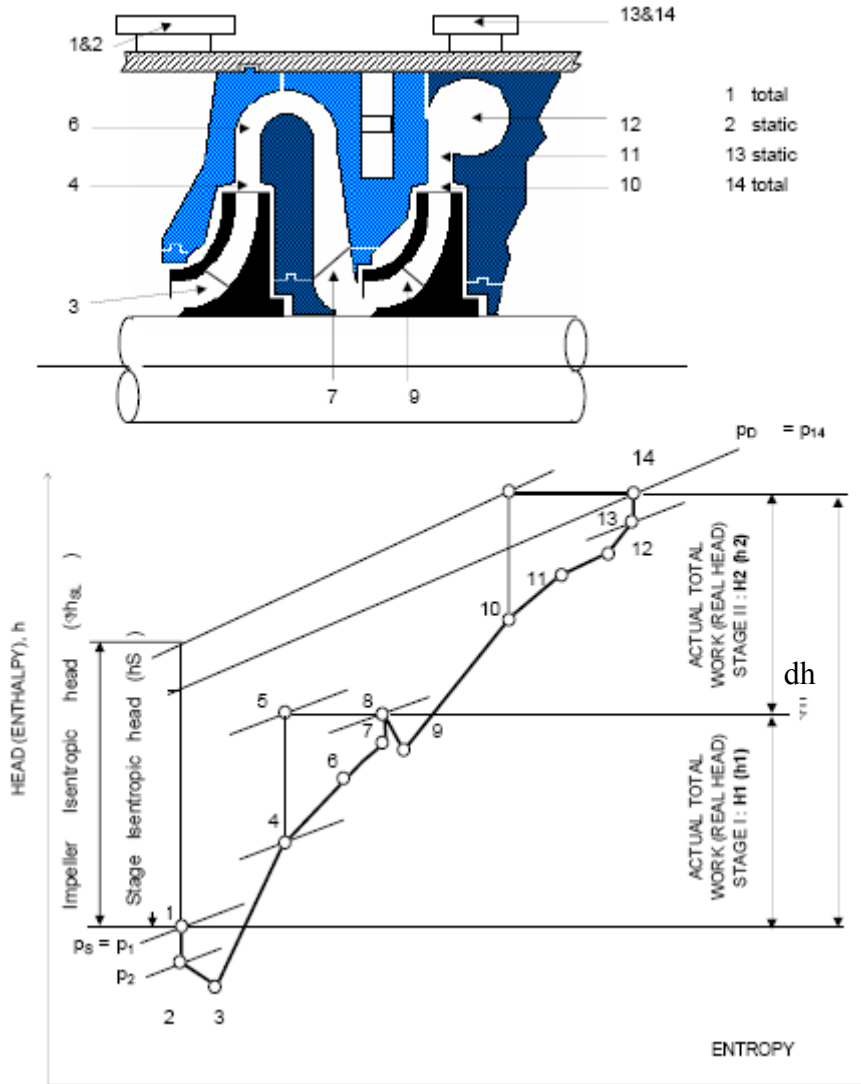
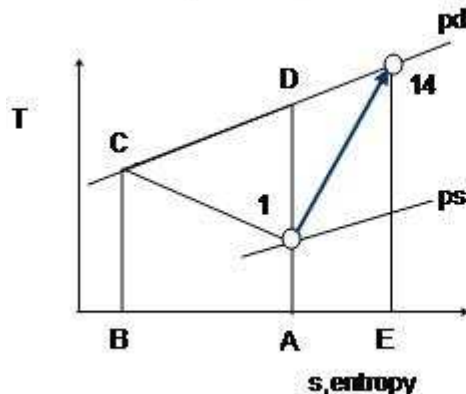


Fig. 5. Compression process of gas in centrifugal compressor

Gas compression process is presented in enthalpy versus entropy chart. Gas enter compressor through suction nozzle (1) at  $p_s = p_1$  measured as total pressure and become  $p_2$  as static pressure in isentropic process. Gas goes to 1'st impeller eye (3) with little losses and then compressed to condition (4) and then in diffuser (6). Gas flows through vane (redirected) until condition (7) then come into 2'nd impeller eye (9). Next compression is in 2'nd impeller through condition (10) until (13). Gas goes out through discharge nozzle at condition (14) or at  $p_2 = p_d$ . To determine adiabatic and polytropic efficiency, use the following chart and equations.

## Generalized process in T vs entropy chart



1-D : Isentropic process

1-14 : Polytropic process

Adiabatic efficiency =  
ABCD area divided by BC-14-E area

Polytropic efficiency =  
ABC-14-1 area divided by BC-14-E area

## VI. INTERCOOLER

After compression, gas temperature will rise up but it is limited before entering to the next compression. Temperature limitation is depending to what sealing material to be used and gas properties. To decrease temperature before entering to the next compression, compressor needs intercooler.

| Gas         | Temperature limitation (C)                                         |
|-------------|--------------------------------------------------------------------|
| General gas | 250 for labyrinth seal<br>180 for oil film seal or mechanical seal |
| Ammonia     | 160                                                                |
| Hydrocarbon | 120                                                                |
| Freon       | 120                                                                |
| Chlorine    | 110                                                                |
| Acetylene   | 60                                                                 |

## VII. AFTERCOOLER

Aftercooler is used when discharge gas temperature leaving compressor shall be decreased before entering to other equipment or system.

## VIII. ANTISURGE CONTROL

Antisurge control shall be installed to centrifugal compressor because at low flow, compressor will surge. Antisurge control is instruments to detect pressure and flow at where compressor will surge. Antisurge control is completed with control valve to by pass discharge gas back to suction or vented to atmosphere. See Fig. 6.

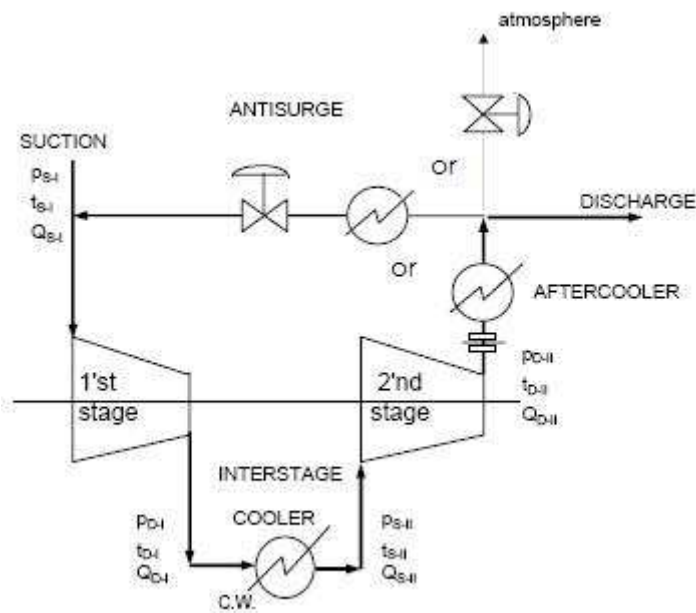


Fig. 6. Typical antisurge control for centrifugal compressor

## IX. EQUATIONS

This manual uses the following simple equations. All symbols and unit are according to symbols and units described in chapter II.

### Brake horse power

$$\text{BHP} = \text{GHP} + \text{Pml} \quad (\text{kW}) \quad (1)$$

Where Pml : **Mechanical Losses**

$$\text{Pml} = \text{Pml at bearing} + \text{Pml at seal} = \text{Pmlb} + \text{Pmls} \quad (\text{kW}) \quad (2)$$

$$\text{Pmlb} = R_L (0.001 \text{ N})^2 \quad (\text{kW}), \quad 2 \text{ journal brg.} + 1 \text{ thrust brg}$$

$$\text{Pmls} = R_S (0.001 \text{ N})^2 \quad (\text{kW}), \quad 2 \text{ Oil Seal type}$$

$$\text{Pmls} = 0.001 \cdot R_D \cdot N \quad (\text{kW}), \quad 2 \text{ Mechanical Contact Seal}$$

$R_L$  ,  $R_S$  and  $R_D$  are factor depending to suction flow

| Suction flow ( $\text{m}^3 / \text{hr}$ ) | $R_L$ | $R_S$ | $R_D$ |
|-------------------------------------------|-------|-------|-------|
| 2500                                      | 0.13  | 0.07  | 0.54  |
| 10,000                                    | 0.45  | 0.24  | 1.1   |
| 50,000                                    | 2.9   | 1.55  | 3.2   |
| 300,000                                   | 10    | 5.4   | 6.5   |



Flow losses through labyrinth seal is between 1 s/d 5 %. Smaller compressor has bigger flow loss percentage.

### Gas horse power

$$GHP = \frac{G.H.g.10^{-6}}{3.6(EFp)} \quad (\text{kW}) \quad (3)$$

Where G is mass flow = DSs.Qs (kg/h), DSs is density (kg/m<sup>3</sup>), Qs is vol. flow (m<sup>3</sup>/hr) (4)

See **Appendix B** for polytropic efficiency (EFp)

For perfect gas, **suction volume flow** is

$$Q_s = \frac{T_s.Q_n}{269.69(ps)} \quad \text{and} \quad Q_d = \frac{T_d.Q_n}{269.69(pd)} \quad (\text{m}^3/\text{hr}) \quad (5)$$

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

$$DS_s = \frac{100(ps)}{R_s.T_s}, \quad DS_n = \frac{101.3}{273(R)} \quad \text{and} \quad DS_d = \frac{DS_s.T_s.pd}{T_d} \quad (\text{m}^3/\text{hr}) \quad (6)$$

### Hydrodynamic head

$$H = \frac{1000(Z_s)(R)(T_s)}{g} \left\{ \frac{n}{n-1} \right\} \left\{ \left( \frac{pd}{ps} \right)^{\frac{n-1}{n}} - 1 \right\} \quad (\text{m}) \quad (7)$$

Where (pd/ps) is compression ratio. Pd and ps are in absolute pressure (bar A) and

$$\frac{n}{n-1} = \frac{k}{k-1} (EFp) \quad (8)$$

$$R = R_o / MW \quad (\text{kJ/kg.K})$$

$$R_o = 8.314 \quad (\text{kJ/kgmole.K})$$

See **Appendix A** for R, MW, k and Z.

### Polytropic head

$$H_p = \frac{H}{EFp} \quad (\text{m}) \quad (9)$$

### Discharge Temperature

$$T_d = T_s \cdot \left( \frac{pd}{ps} \right)^{\frac{n-1}{n}} \quad (10)$$



If discharge temperature is limited at  $T_{dmax}$ , then maximum pressure ratio become

$$\left(\frac{pd}{ps}\right)_{MAX} = \left(\frac{T_{dmax}}{T_s}\right)^{\left(\frac{n}{n-1}\right)} \quad (11)$$

Equations related to impeller geometry

**Impeller tip speed,**

$$U = \frac{3.14(D)(N)}{60,000} \quad (\text{m/s}) \quad (12)$$

Impeller tip Mach number ratio,

$Mau = U / a$ , where  $a = (1000.k.Z.R.T)^{0.5}$

**Flow coefficient,**

$$CQ = \frac{353.68(Q_s)}{(U)(D^2)} \quad \text{in the range} \quad 0.01 \text{ up to } 0.15 \text{ see } \mathbf{Appendix B} \quad (13)$$

**Head coefficient,**

$$Y = \frac{19.62(Hp)}{U^2} \quad (14)$$

Y values in the range 0.80 up to 1.1 for impeller with "backward leaning blades"  
1.30 up to 1.45 ----- "90 degree exit blades "

## X. PERFORMANCE CURVE

In general, centrifugal performance curve presented in head or discharge pressure against suction flow, see Fig. 7.

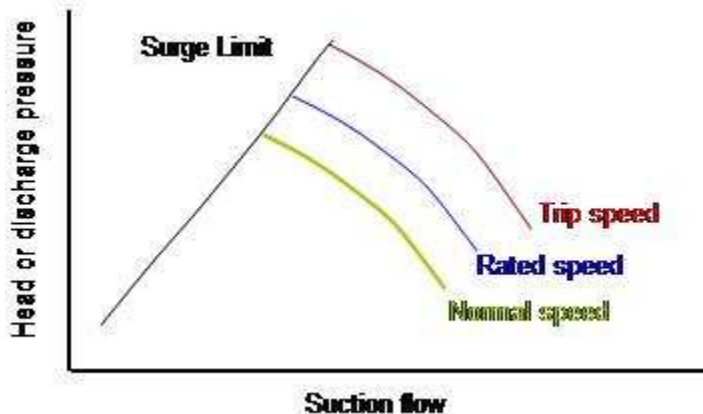


Fig. 7. Typical performance curve of centrifugal compressor

## APPENDIX A. GAS PROPERTIES

### A.1. SINGLE GAS

The following table presents single gas properties. There are MW (molecular weight), k (adiabatic exponent), p<sub>CR</sub> (critical pressure), T<sub>CR</sub> (critical temperature) and MCp (=MW x Cp).

Table 1. Pure Gas Properties

| Gas or Vapor Name               | Hydrocarbon Refer. Symbols | Chemical formula                 | MW (kg/kgmol) | k at 15.5 °C | Critical condition      |                      | MCp (kJ/kgmol.°K) |           |           |
|---------------------------------|----------------------------|----------------------------------|---------------|--------------|-------------------------|----------------------|-------------------|-----------|-----------|
|                                 |                            |                                  |               |              | p <sub>CR</sub> (bar A) | T <sub>CR</sub> (°K) | at 0 °C           | at 100 °C | at 197 °C |
| Acetylene                       | C <sub>2</sub> =           | C <sub>2</sub> H <sub>2</sub>    | 26.04         | 1.24         | 62.4                    | 309.4                | 42.16             | 48.16     | 53.17     |
| Air (dry)                       |                            | N <sub>2</sub> +O <sub>2</sub>   | 28.97         | 1.4          | 37.7                    | 132.8                | 29.05             | 29.32     | -         |
| Ammonia                         |                            | NH <sub>3</sub>                  | 17.03         | 1.31         | 112.8                   | 406.1                | 34.65             | 37.93     | -         |
| Argon                           | iC <sub>4</sub>            | Ar                               | 39.94         | 1.66         | 48.6                    | 151.1                | 20.79             | 20.79     | 20.79     |
| Benzene                         |                            | C <sub>6</sub> H <sub>6</sub>    | 78.11         | 1.12         | 49.2                    | 562.8                | 74.18             | 103.52    | -         |
| Iso-Butane                      |                            | C <sub>4</sub> H <sub>10</sub>   | 58.12         | 1.1          | 36.5                    | 408.3                | 89.75             | 116.89    | 141.88    |
| n-Butane                        | nC <sub>4</sub>            | C <sub>4</sub> H <sub>10</sub>   | 58.12         | 1.09         | 38                      | 425.6                | 93.03             | 117.92    | 141.04    |
| Iso-Butylene                    | iC <sub>4</sub> _          | C <sub>4</sub> H <sub>8</sub>    | 56.1          | 1.1          | 40                      | 418.3                | 83.36             | 104.96    | 124.87    |
| Butylene                        | nC <sub>4</sub> _          | C <sub>4</sub> H <sub>8</sub>    | 56.1          | 1.11         | 40.2                    | 420                  | 83.4              | 105.06    | -         |
| Carbon Dioxide                  |                            | CO <sub>2</sub>                  | 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 <sub>2</sub>                  | 70.91         | 1.36         | 77.2                    | 417.2                | 35.29             | 35.53     | 35.9      |
| Coke Oven Gas <sup>1)</sup>     | nC <sub>10</sub>           | -                                | 10.71         | 1.35         | 28.1                    | 109.4                | 31.95             | 34.21     | -         |
| n-Decane                        |                            | C <sub>10</sub> H <sub>22</sub>  | 142.28        | 1.03         | 22.1                    | 619.4                | 218.35            | 280.41    | -         |
| Ethane                          |                            | C <sub>2</sub> H <sub>6</sub>    | 30.07         | 1.19         | 48.8                    | 305.6                | 49.49             | 62.14     | 74.37     |
| Ethyl Alcohol                   | C <sub>2</sub> _           | C <sub>2</sub> H <sub>5</sub> OH | 46.07         | 1.13         | 63.9                    | 516.7                | 69.92             | 81.97     | -         |
| Ethyl chloride                  |                            | C <sub>2</sub> H <sub>4</sub> Cl | 64.52         | 1.19         | 52.7                    | 460.6                | 59.61             | 70.16     | -         |
| Ethylene                        |                            | C <sub>2</sub> H <sub>4</sub>    | 28.05         | 1.24         | 51.2                    | 283.3                | 40.9              | 51.11     | 60.55     |
| Flue Gas <sup>1)</sup>          |                            | -                                | 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 <sub>7</sub>            | C <sub>7</sub> H <sub>16</sub>   | 100.2         | 1.05         | 27.4                    | 540.6                | 161.2             | 202.74    | 239.8     |
| n-Hexane                        | nC <sub>6</sub>            | C <sub>6</sub> H <sub>14</sub>   | 86.17         | 1.06         | 30.3                    | 508.3                | 138.09            | 174.27    | 206.88    |
| Hydrogen                        | C <sub>1</sub>             | H <sub>2</sub>                   | 2.02          | 1.41         | 13                      | 33.3                 | 28.67             | 29.03     | 29.25     |
| Hydrogen Sulfide                |                            | H <sub>2</sub> S                 | 34.08         | 1.32         | 90                      | 373.9                | 33.71             | 35.07     | 36.88     |
| Methane                         |                            | CH <sub>4</sub>                  | 16.04         | 1.31         | 46.4                    | 191.1                | 34.5              | 40.13     | 44.64     |
| Methyl Alcohol                  |                            | CH <sub>3</sub> OH               | 32.04         | 1.2          | 79.8                    | 513.3                | 42.67             | 55.32     | -         |
| Methyl Chloride                 |                            | CH <sub>3</sub> Cl               | 50.49         | 1.2          | 66.7                    | 416.7                | 45.6              | 49.82     | -         |
| Natural Gas <sup>1)</sup>       |                            | -                                | 18.82         | 1.27         | 46.5                    | 210.6                | 34.66             | 39.54     | -         |
| Nitrogen                        | nC <sub>9</sub>            | N <sub>2</sub>                   | 28.02         | 1.4          | 33.9                    | 126.7                | 29.1              | 29.31     | 29.46     |
| n-Nonane                        |                            | C <sub>9</sub> H <sub>20</sub>   | 128.25        | 1.04         | 23.8                    | 596.1                | 197.07            | 253.1     | -         |
| Iso-Pentane                     |                            | C <sub>5</sub> H <sub>12</sub>   | 72.15         | 1.08         | 33.3                    | 461.1                | 112.09            | 145.56    | -         |
| n-Pentane                       | nC <sub>5</sub>            | C <sub>5</sub> H <sub>12</sub>   | 72.15         | 1.07         | 33.7                    | 470.6                | 115.21            | 145.94    | 173.96    |
| Pentylene                       | C <sub>5</sub> _           | C <sub>5</sub> H <sub>10</sub>   | 70.13         | 1.08         | 40.4                    | 474.4                | 102.11            | 130.37    | -         |
| n-Octane                        | nC <sub>8</sub>            | C <sub>8</sub> H <sub>18</sub>   | 114.22        | 1.05         | 25                      | 569.4                | 176.17            | 226.17    | -         |
| Oxygen                          | C <sub>3</sub> ..          | O <sub>2</sub>                   | 32            | 1.4          | 50.3                    | 154.4                | 29.17             | 29.92     | 30.78     |
| Propane                         |                            | C <sub>3</sub> H <sub>8</sub>    | 44.09         | 1.13         | 42.5                    | 370                  | 68.34             | 88.68     | 107.71    |
| Propylene                       |                            | C <sub>3</sub> H <sub>6</sub>    | 42.08         | 1.15         | 46.1                    | 365.6                | 60.16             | 75.7      | 90.54     |
| Blast Furnace Gas <sup>1)</sup> |                            | -                                | 29.6          | 1.39         | -                       | -                    | 29.97             | 30.64     | -         |
| Cat Cracker Gas <sup>1)</sup>   |                            | -                                | 28.83         | 1.2          | 46.5                    | 286.1                | 46.16             | 57.31     | -         |
| Sulphur Dioxide                 |                            | SO <sub>2</sub>                  | 64.06         | 1.24         | 78.7                    | 430.6                | 38.05             | 40        | 45.7      |
| Water Vapor                     |                            | H <sub>2</sub> O                 | 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

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

$$\text{Specific heat } C_p = \frac{R \cdot k}{k - 1} \quad (\text{A.2})$$

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

## Compressibility factor (Z)

Z determined by gas compressibility chart using reduction temperature ( $T_{red}$ ) and pressure ( $p_{red}$ ) as the variables.  $T_{red} = T/T_{cr}$  and  $p_{red} = p/p_{cr}$ . See following Fig. 8.

Density of gas,

$$DS = \frac{100(p)}{R \cdot T} \quad (\text{A.3})$$

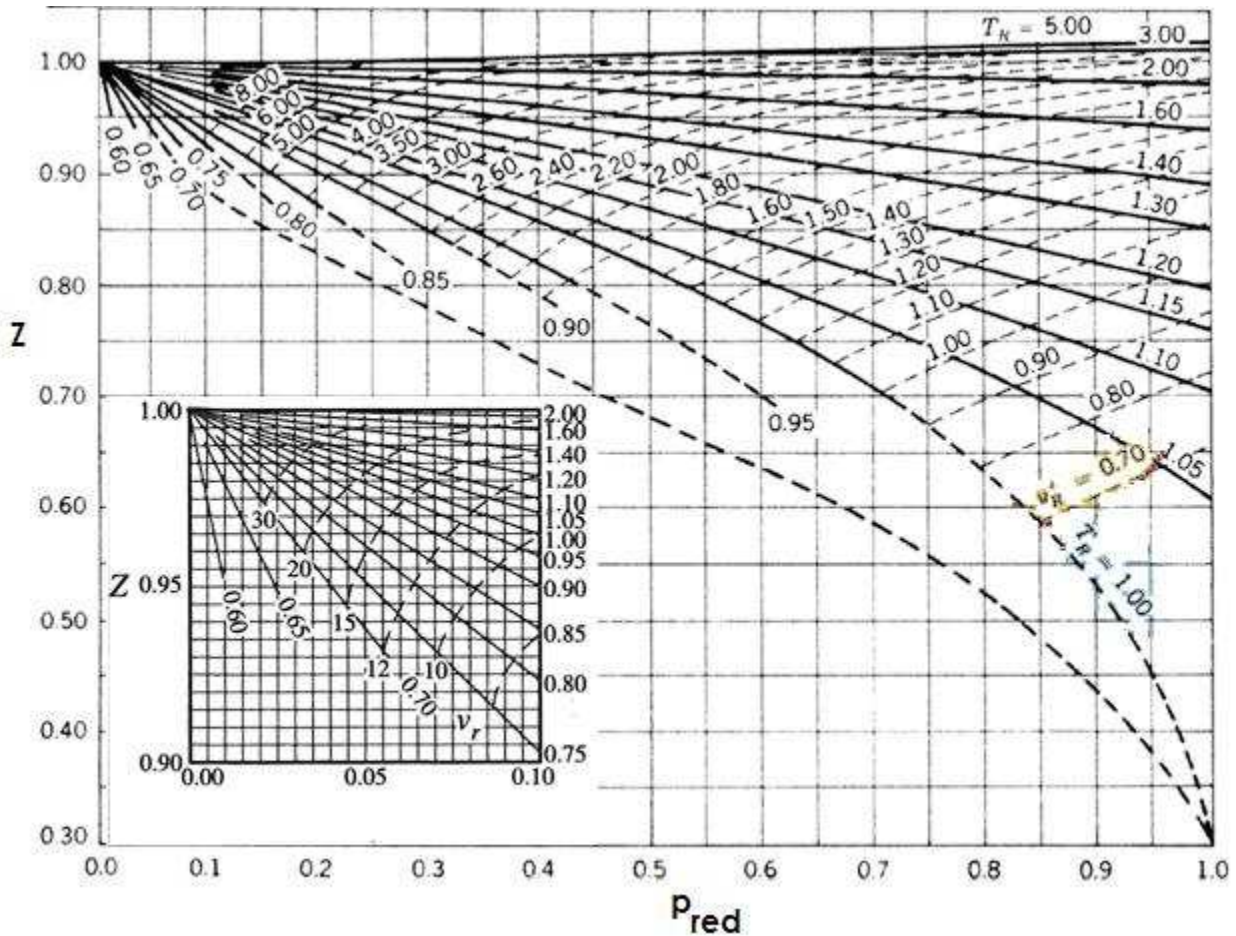


Fig. 8. Gas compressibility chart for  $p_{red} < 1$

Fig. 8 presents Z factor for  $p_{red} = 1$  and lower. For  $p_{red}$  higher than 1 see Fig. 9.

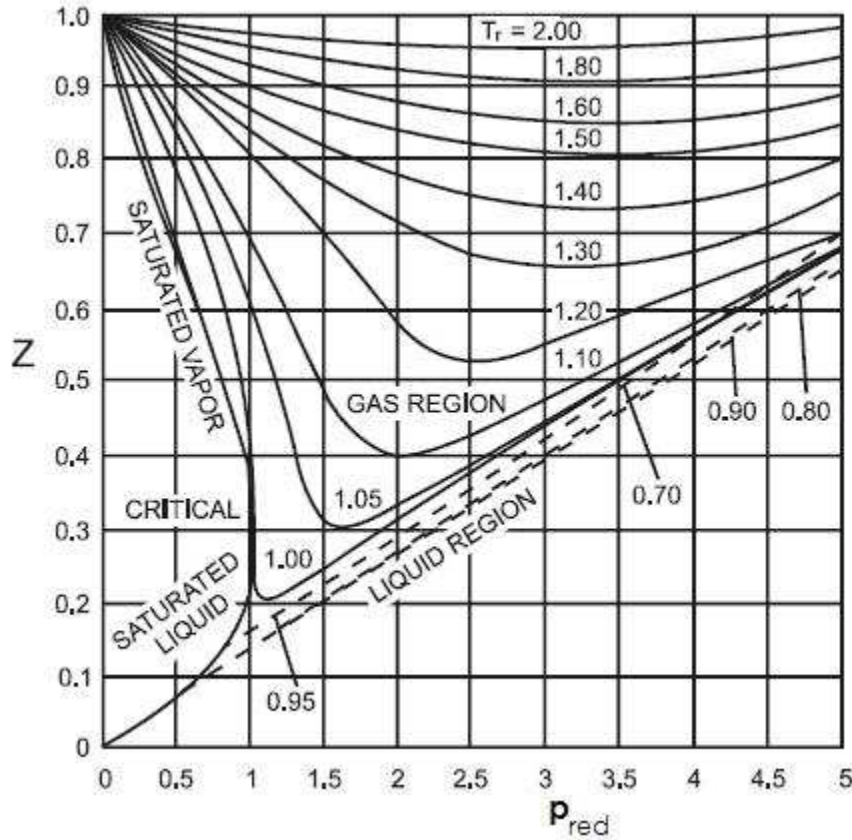


Fig. 9. Gas compressibility chart for  $p_{red}$  higher than 1.

## A.2. MIXED GAS

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

Subscript (i) indicates partial of pure gas.

$$MW = \sum_i \{0.01(\%Mi)(MW_i)\} \quad (A.4)$$

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

$$\% Mi = \frac{100(MMi)}{\sum MMi} \quad (A.5)$$

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

$$MMi = \frac{Mgi}{MW_i} \quad (A.6)$$

Where Mgi is mass of each gas in kg

$$k = \frac{\sum 0.01(MC_{pi})(\%Mi)}{\sum 0.01(MC_{pi})(\%Mi) - 8.314} \quad (A.7)$$

$$\text{Gas constant } R = \frac{8.314}{MW}$$

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

### Compressibility factor (Z)

$$p_{cr} = \sum 0.01(\%Mi)(p_{cri}) \quad (A.8)$$

$$T_{cr} = \sum 0.01(\%Mi)(T_{cri}) \quad (A.9)$$

Z factor determined using Fig. 8 and 9 at above  $p_{cr}$  and  $T_{cr}$  of mixed gas.

**Density** of mixed gas,

$$DS = \frac{100(p)}{R.T} \quad (A.10)$$

### A.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.

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

| 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 <sub>2</sub> S        | 1.29E-18 | 7.716  |
| NH <sub>3</sub>         | 1.23E-23 | 9.6    |
| Cl <sub>2</sub>         | 6.73E-22 | 8.86   |
| SO <sub>2</sub>         | 4.58E-27 | 10.816 |
| Water<br>(dias 1 bar A) | 6.71E-28 | 10.578 |
|                         |          |        |

### A.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  $T_{db} = 273 + t_{db}$  in K



3. Atmospheric pressure  $p_{atm}$  at bar A
4. From psychrometric chart, determine wet bulb temperature  $t_{wb}$  and  $T_{wb} = 273 + t_{wb}$
5. From H<sub>2</sub>O saturated pressure table, determine saturated pressure at  $t_{wb}$ ,  $p_g$
6. Partial pressure of H<sub>2</sub>O  $p_w = 0.01 (\%RH) (p_g)$
7. Partial pressure of dry air  $p_a = p_{atm} - p_g$
8. Mole fraction of dry air  $X_a = p_a / p_{atm}$
9. Mole fraction of H<sub>2</sub>O  $X_w = p_w / p_{atm}$
10. Molal mass of wet air  $MW = (MW_{dry\ air}) (X_a) + (MW_{H_2O}) (X_w)$
11. MCp of wet air  $MCp = (MCp_{dry\ air}) (X_a) + (MCp_{H_2O}) (X_w)$
12. Gas constant  $R = 8.314 / MW$
13. k  $k = MCp / (MCp - 8.314)$
14. Density  $DS = 100.p_{atm} / (R.T_{db})$

Table 2. Saturated pressure of H<sub>2</sub>O

| 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  $t_{db}$  determine  $t_{wb}$  from following typical psychrometric chart

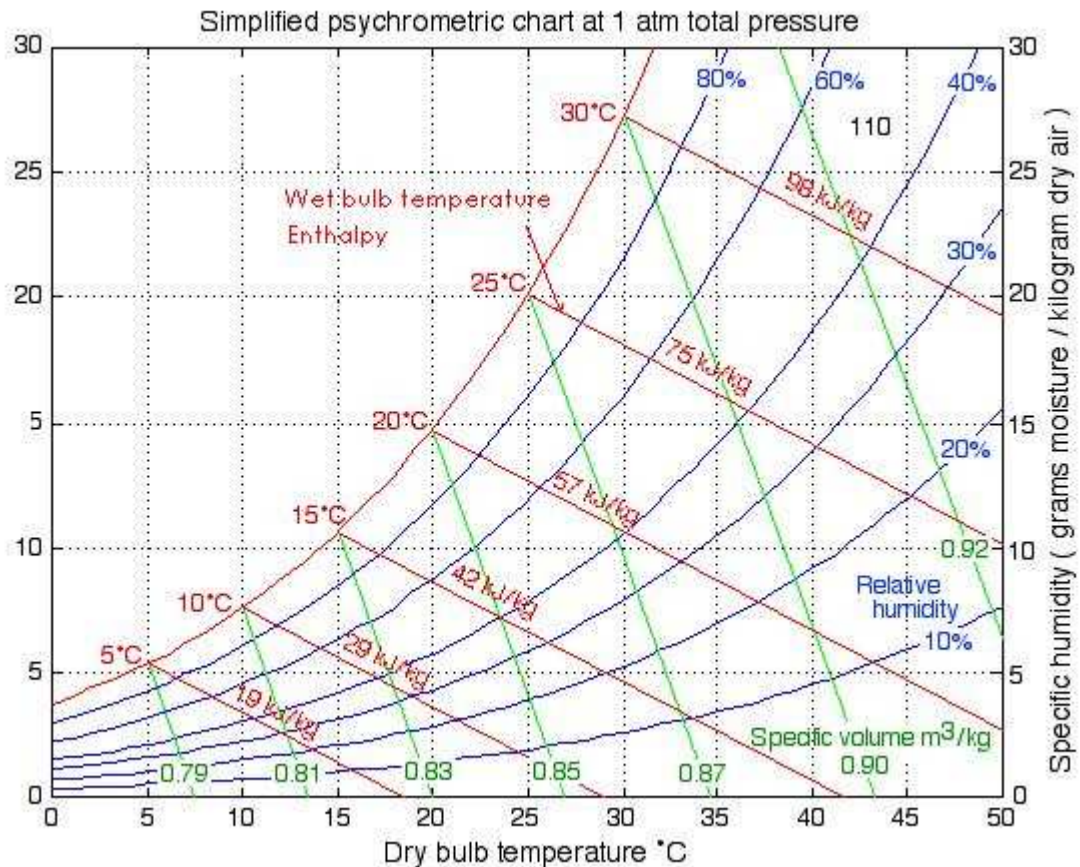


Fig. 10. Psychrometric chart for air at 1 atm.

## APPENDIX B. EFFICIENCY OF CENTRIFUGAL COMPRESSORS

A lot of parameter shall be considered in determining centrifugal compressor efficiency such as operating condition (flow, pressure, speed), impeller geometry and gas properties. In general, compressor manufacturer will offer compressor with efficiency as best as available after receiving user's specification. For preliminary estimation, use Fig. 11. In horizontal axis present actual flow which is not at standard condition or not at normal condition. Actual flow means suction flow.

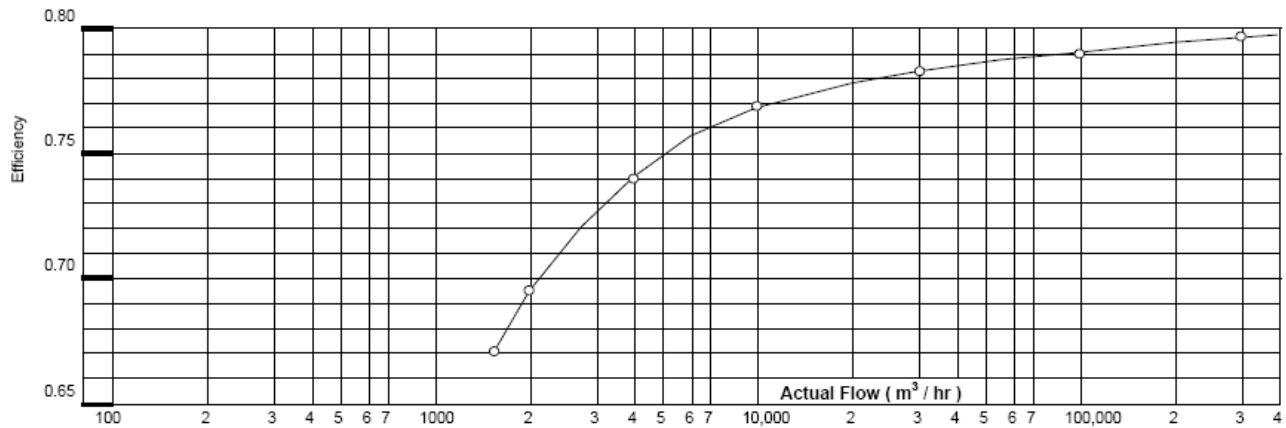
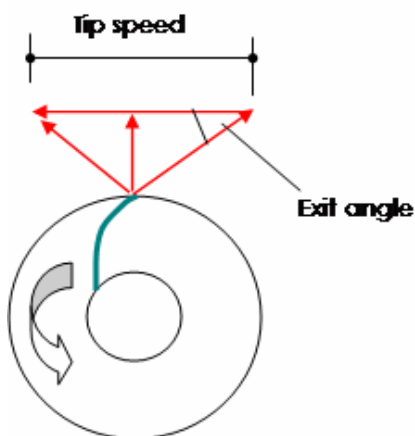


Fig. 11. Efficiency of centrifugal compressor for preliminary estimation.

### 1. Impeller geometry and their characteristics

Following figure is simplified figure of impeller in relation with their performances. tip speed (U) and exit angle. Tip speed is limited due to material strength and sound velocity in compressed gas.



Shrouded Impeller  
Radial inlet  
Exit angle about 45 - 45 degree  
Typical stage efficiency about 78 %  
Max. polytropic head approx. 50 kJ/kg  
Typical surge point 65 %  
Relative max. flow coefficient 100%



Shrouded Impeller  
Diagonal inlet  
Exit angle about 50 degree  
Typical stage efficiency about 83 %  
Max. polytropic head approx. 55 kJ/kg  
Typical surge point 50 %  
Relative max. flow coefficient 150%



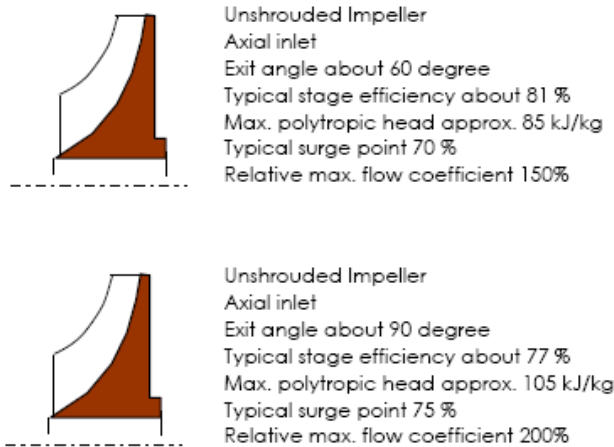


Fig. 12. Impeller geometry and their characteristic.

Shrouded impeller is equal with enclosed impeller where there is disc in the front integral with vanes or blades (casting, welded or riveted) .

Backward curve impeller is when exit angle smaller than 90 degree and radial curve impeller is when exit angle is equal to 90 degree.

To convert head from J/kg to m, divide J/kg unit by g (gravity in m/s<sup>2</sup>). Example 55 kJ/kg = 55,000 J/kg = 55,000/9.81 = 5606.5 m

Tip speed is limited due to material strength and sound velocity in compressed gas.

There is criteria to determine tip speed such as the following table

| <u>MW</u> | <u>Average tip speed (m/s)</u> |
|-----------|--------------------------------|
| Below 35  | 310                            |
| Below 45  | 250                            |
| Below 65  | 200                            |
| Below 120 | 150                            |

Even MW below 35 but gas contain corrosive matter or will be operated at low temperature below -50 C, maximum tip speed is 250 m/s.

Maximum tip speed shall not higher than sound velocity. For approaching, using  $U_{max} = 0.9 \times a$ , where  $a$  is sound velocity =  $(1000 \times k \times T \times Z \times R)^{0.5}$  or =  $(8314 \times k \times T \times Z / MW)^{0.5}$ .  $U = 3.14 \times D \times N / 60,000$ , or  $D = 60,000 \times U / (3.14 \times N)$  or  $D = 60,000 \times 0.9 \times (8314 \times k \times T \times Z / MW)^{0.5} / (3.14 \times N)$  or  $D = 1568000 \times (k \times T \times Z / MW)^{0.5} / N$ . And "0.9" is factor for incorrect approaching for all assumption and calculation related to sound velocity and tip speed. This equation can be plot at several  $(k \times T \times Z / MW)^{0.5}$ , see Fig. 13 blue dot line. D and N pair under blue dot line is accepted because tip speed is lower than 0.9 time sound velocity.

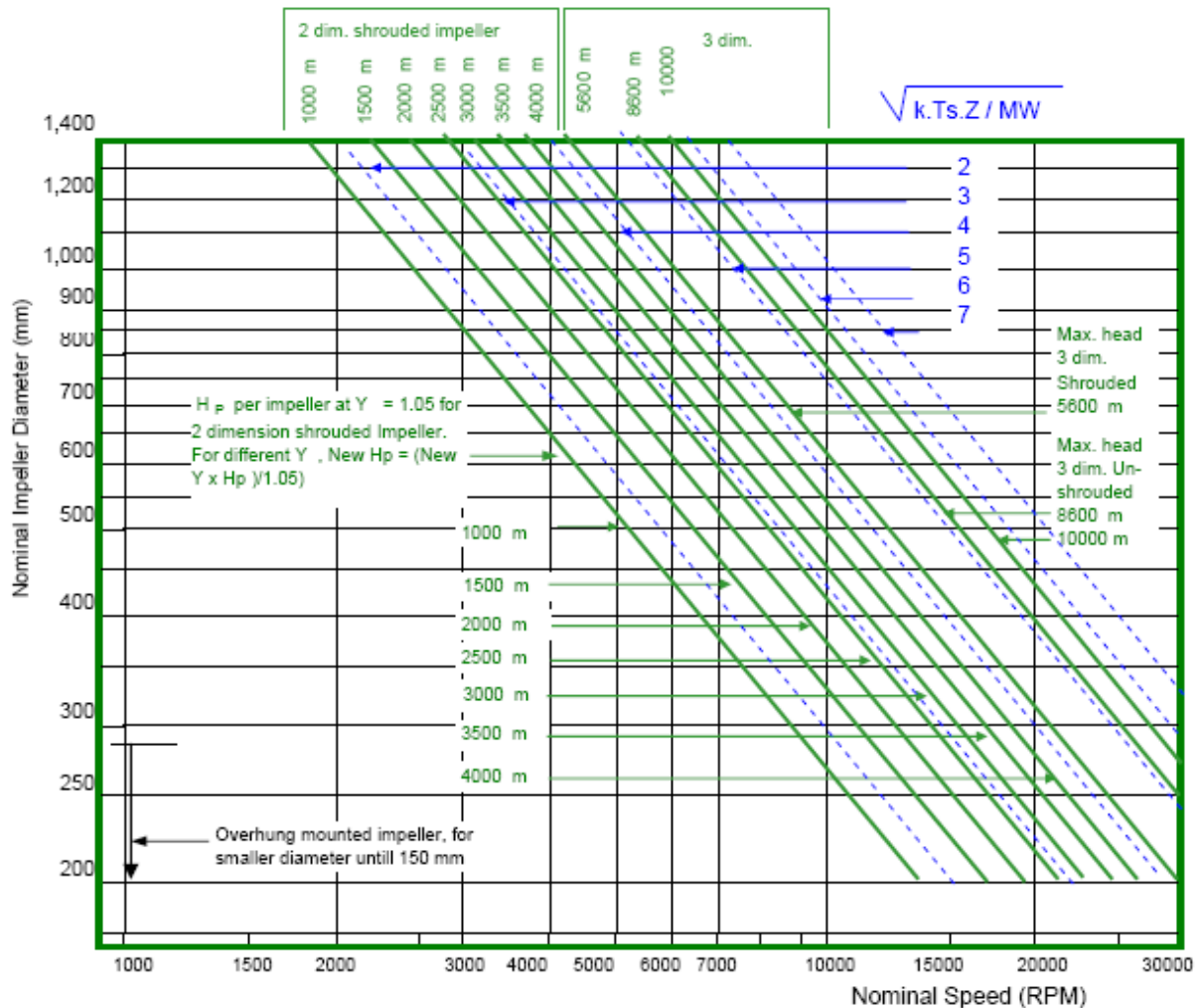


Fig. 13. Impeller performance in head

Example : Air at 30 C (303 K) and 1.013 bar A to be compressed 6 barA. Suction flow 2000 m<sup>3</sup>/hr. From table 1,  $k=1.4$ ,  $p_{cr}=37.7$  bar A,  $T_{cr}=132.8$  K,  $MW=28.97$ . Determine  $p_{red}=1.013/37.7=0.027$  and  $T_{red}=303/132.8=2.28$ . From Fig. 8,  $Z$  near = 1. Ratio value of  $(k.T.Z/MW)^{0.5}=3.8$ . From Fig. 13, this line is near head per stage 4000 m line. At this line, if  $N=10,000$  RPM can be determined diameter of 550 m and maximum tip speed  $U$  become  $=3.14.D.N/60,000=3.14 \times 550 \times 10,000 / 60,000=287$  m/s.

## 2. Contribution of impeller geometry, speed and diameter for efficiency

Compressor size is designed according to suction flow of gas. Compressor size includes impeller diameter, impeller width and number of impeller. Manufacturer usually indicates impeller diameter in each compressor model. The following Fig. 14 presents nominal size indicated by average impeller diameter. From suction flow can be seen approximately the nominal size and also speed in RPM.

Example : Continued from above example. At suction flow = 2000 m<sup>3</sup>/hr, draw vertical line until cross the range of each nominal size, provide nominal size 300 mm with impeller geometry "C".

Cross point between flow and maximum tip speed 287 m/s is at maximum about 20,000 RPM. In C impeller geometry, at flow 2000 m<sup>3</sup>/hr speed in the range of 11,000 up to 20,000 RPM or tip speed from 200 up to 287 m/s.

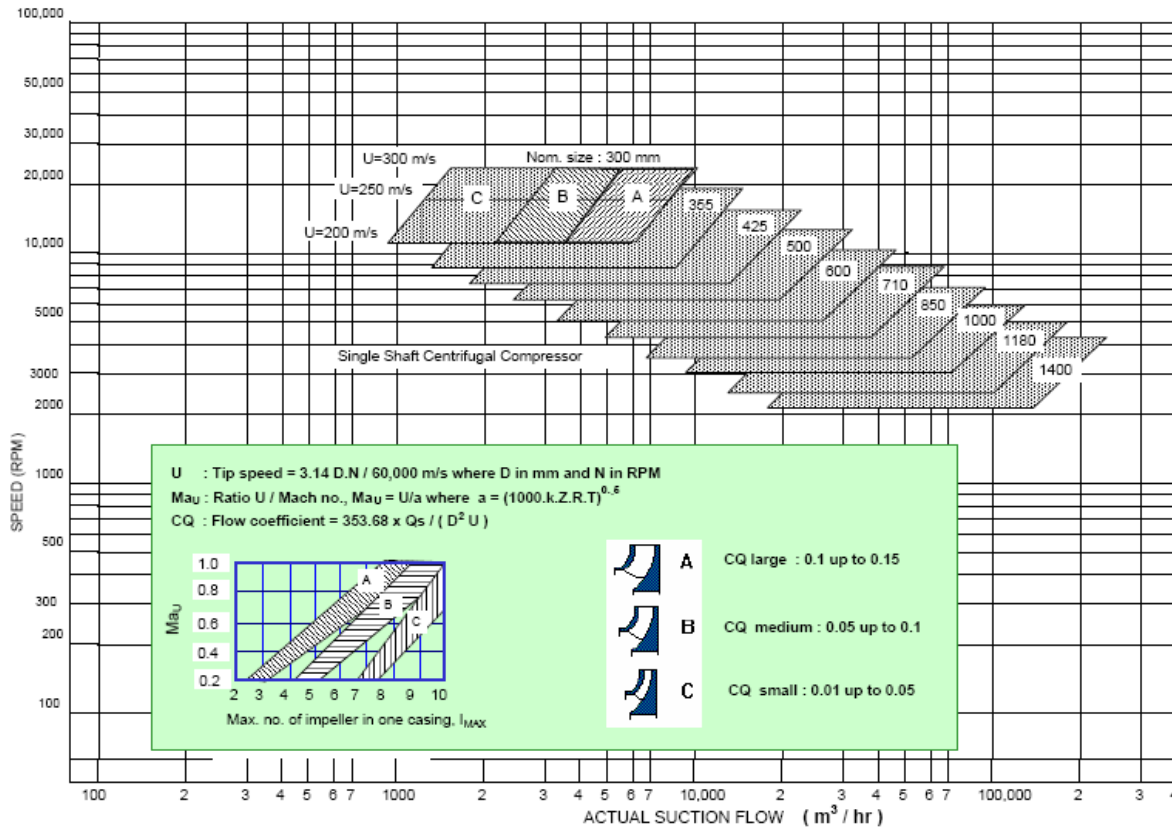


Fig. 13. Impeller performance in capacity

From rectangular bloc at the bottom of chart, geometry C impeller has flow coefficient CQ small = 0.01 up to 0.05.

Number of impeller in one casing is limited. Maximum number of impeller can be estimated from Fig. 13 as function of Mau and impeller geometry.

Example, continued from above example. If geometry C and nominal size 300 mm is selected, approximate diameter is 300 mm. And if tip speed is selected at 280 m/s, then Mau become =  $280 / (1000.k.R.T)^{0.5} = 280 / \{1000 \times 1.4 \times (8.314/28.97) \times 303\}^{0.5} = 0.8$ . From Fig. 13 maximum number of impeller  $l_{max} = 10$ .

Number of impeller will decrease if there are additional nozzle is installed such as for inter cooler, admission or extraction. Each 1 nozzle will reduce 1 impeller.

Instead of preliminary efficiency that determined from Fig. 11, efficiency of compressor can also be determined after preliminary diameter and tip speed is selected. Fig. 14 shows efficiency as function of head coefficient and flow coefficient.

Example, continued from above example. D = 300 mm, U = 280 m/s have been selected at above example. N = 17,800 RPM. Assumed impeller is backward 2 dimension shrouded impeller.

Calculate flow coefficient  $CQ = 353.68 \times Q / (U \times D^2) = 353.68 \times 2,000 / (280 \times 300^2) = 0.028$

Determine efficiency correction factor from Fig. 14.  $C_o = 0.915$

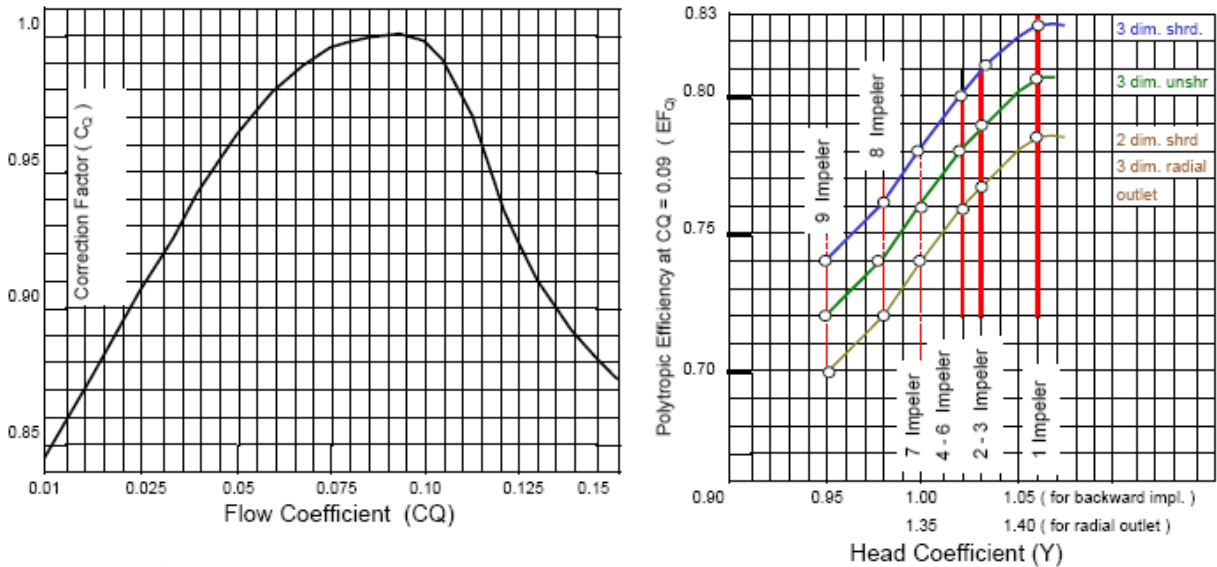


Fig. 14. Efficiency of centrifugal compressor

To determine head coefficient, preliminary efficiency shall be determine from Fig. 11,  $EF_p = 0.695$ .

$$n/(n-1) = EF_p \cdot k/(k-1) = 0.695 \times 1.4 / (1.4-1) = 2.432$$

assume maximum temperature  $t_{dmax} = 200$  C,  $T_{d1max} = 473$  K

$$\text{pressure ratio max. at section 1} = \left(\frac{pd}{ps}\right)_{MAX} = \left(\frac{T_{d \max}}{T_s}\right)^{\frac{n}{n-1}} = 2.95$$

extract air to 1'st intercooler at pressure  $pd_1 = 2.95 \times 1.013 = 2.99$  barA

and then entering to next compression at 40 C,  $T_{s2} = 313$  K

by the same way and assumed pressure drop is neglected across intercooler,

$$\text{pressure ratio at section 2, } pd_2/ps_2 = 6 / 2.99 = 2$$

$$H_1 = \frac{1000(Z_s)(R)(T_s)}{g} \left\{ \frac{n}{n-1} \right\} \left\{ \left( \frac{pd}{ps} \right)^{\frac{n-1}{n}} - 1 \right\} = 12,260 \text{ (m)}$$

$$H_{p1} = H / EF_p = 12,260 / 0.695 = 17,600 \text{ m}$$

Plot again  $N=15,000$  and  $D=300$  mm on Fig. 12. Cross point is at head per stage = 3250 m

Number of impeller at section 1,  $I-1 = 17,600 / 3,750 = 4.7$ , take  $I-1 = 5$

$$H_{p2} = 10,600 \text{ m}$$

Number of impeller at section 2,  $I-2 = 10,600/3,750 = 2.82$ , take  $I-2 = 3$

Total impeller =  $5 + 3 = 8$  acceptable because  $I_{max} = 10$  minus for nozzle 2 = 8

From Fig. 14 with number of impeller = 8 and 2 dim. Shrouded impeller, uncorrected efficiency = 0.72. Corrected efficiency become

$EF_p = 0.72 \times C_o = 0.72 \times 0.915 = 0.66$  or 66 % . This result is smaller than first assumption = 0.695 or 69.5 %

## APPENDIX C. CALCULATION SHEET AND SYSTEM (AS ATTACHMENTS)

Typical calculation sheets as **attachment 1** of this article are presented in excel file, named "Cal\_sheet\_c\_comp.xls" which includes :

1. Pure gas properties
2. Mixed gas properties
3. Wet air properties
4. Power absorption and Cooling water required
  - a. Without considering detail of impeller
  - b. Considering detail of impeller

Typical system around centrifugal compressor as attachment 2 are presented in PDF file, named "Sys\_c\_comp.pdf" which includes :

1. Intercooler, aftercooler and antisurge system
2. Lube oil system
3. Sealing system