NTNU – Trondheim
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REVIEW OF WET GAS COMPRESSOR PERFORMANCE

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ABSTRACT

Subsea wet gas compression without preliminary separation give an opportunity to develop mature and remote gas/condensate field. Predicting wet gas compressor performance is important to develop those fields. Currently there is no standard exist for wet gas compression performance calculation (Hundseid et al., 2008). The current standards (ISO 5389:2005) exist only for dry gas by utilizing Schultz method.

In wet gas compression, fluid properties are changing as fluid being compressed. Schultz method may not be accurate to be applied in wet gas compression since it uses average fluid properties between inlet and outlet of the compressor.

The necessities of standard in wet gas compression encourage this project to conduct a research in wet gas compression performance. This project will evaluate Huntington direct integration method (Huntington, 1985) which originally for dry gas to be used in wet gas compression calculation and compare the result with Schultz method.

In this project, visual basic script was created to calculate wet gas compressor performance by using direct integration method. Fluid properties are calculated by HYSYS^{TM} software. It is also desired to know how HYSYS^{TM} calculate wet gas compression. Compressor off design operation effect on compressor performance is also taken into consideration when calculating wet gas compressor performance.

The results show that direct integration method is much more suitable for wet gas compression calculation compared to Schultz method. As wet gas being compressed, more liquid will form in the mixture and it will affect fluid properties. The presence of heavier fluid in the mixture and cooling effect is one of the factor that affecting compressor performance. This factor will reduce specific polytopic head of compressor. Direct integration method calculation is considering this effect.

Off design operation affect compressor performance calculation significantly. The deviation between original performance and corrected performance become larger as actual and reference condition become much more different. At large deviation, the corrected compressor performances become uncertain.

i

In HYSYS^{TM} software, interaction between liquid and vapor phase is taken into consideration. The software does not calculate compressor performance by treating each phase separately.

Further recommendations for this project are to compare calculated performance using direct integration method with actual experiment and improvement of current compressor off design correction. By comparing compressor performance calculation with real data, the accuracy of direct integration method will be discovered. In gas condensate field, fluid properties will change significantly with decreasing pressure. Therefore, actual and test reference condition will be different over time and will affect gas condensate field performance. This condition need attention since current off design correction accuracy will be reduced if the deviation is large. Good prediction of wet gas compression performance is required in developing gas condensate field

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ACKNOWLEDGEMENT

TABLE OF CONTENTS

LIST OF FIGURE

vii

LIST OF TABLES

1. BACKGROUND

As technology developed and giant gas/condensate field have been explored, major oil and gas companies start to explore and develop mature and remote gas/condensate field (Knudsen and Solvik, 2011). A big portion of remaining hydrocarbon reserve is located in remote deep water area and harsh condition (Hjelmeland et al., 2011). Installing floating production facilities on those areas is a big challenge. In case of mature gas field, the pressure has been declined yielding lower production rate and increasing liquid content in the flow. Subsea wet gas compression without preliminary separation process give a promising solution to those problems by increasing the pressure and to avoid installing floating production facilities in harsh condition.

Subsea wet gas compression gives many benefits such as increased recovery factor, accelerated production, reduced CAPEX & OPEX, operation flexibility and HSE benefit (Vinterstø, 2014). Figure 1.1 shows the effect of installing subsea wet gas compressor on field production. By installing compressor, production rate will increase and field life time will be extended. In some case, CAPEX & OPEX is reduced because subsea wet gas compressor eliminate the need of implementing expensive floating production facilities in harsh offshore condition (Hjelmeland et al., 2011).
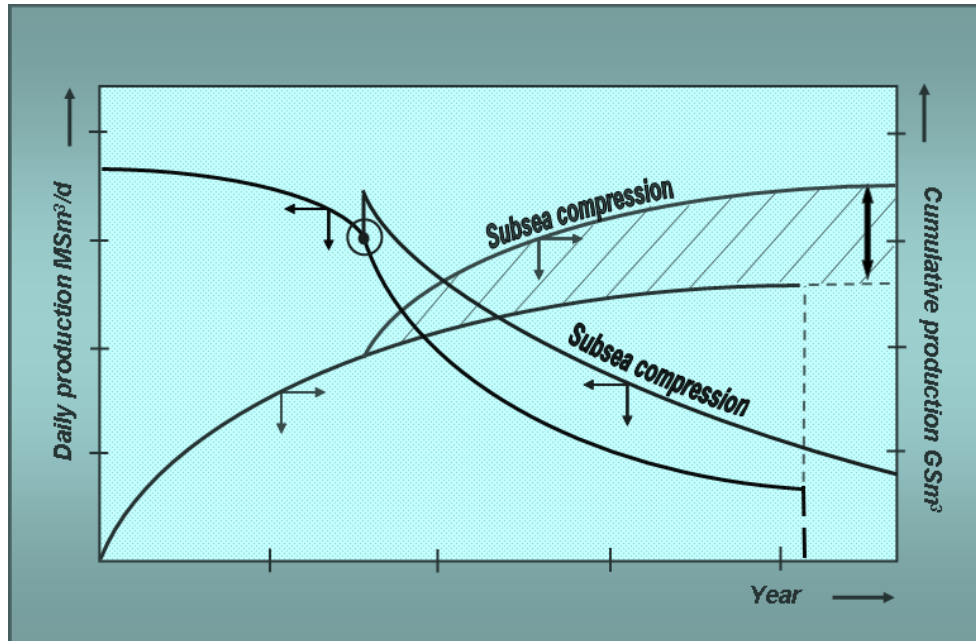
Figure 1.1 Effect of installing subsea wet gas compression to gas/condensate field performance (Courtesy of Vinterstø, 2014).

To give satisfying forecast of a gas condensate field project installed with subsea wet gas compressor, a good compressor performance model for wet gas fluid should be used. Currently no standard exist for wet gas compressor performance (Hundseid et al., 2008). For dry gas, Schultz method (Schultz, 1962) gives satisfying result and already used in a standard ISO 5389:2005. But for wet gas compression, Schultz method may not be accurate. It is because in a wet gas fluid, the composition on each phase is changing from inlet condition into outlet condition of the compressor as the pressure increase. Therefore, fluid properties changes as gas compressed. Schultz made a simplification in his method by using average gas properties at exit and outlet compressor. However, this assumption may have a significant impact on the Schultz compressor performance that reduces accuracy of compressor performance prediction (Hundseid et al, 2006).

The necessities of standard in wet gas compression encourage this project to conduct a research in wet gas compression performance. This project will evaluate Huntington direct integration method (Huntington, 1985) which originally for dry gas to be used in wet gas compression calculation. Direct integration method predicted to be suitable for wet gas compression since fluid properties change along compression is taken into account.

2. THEORY

Compressors are a device to pass work to the fluid in order to change the state of the fluid, generally to increase pressure and/or elevation (Moran et al., 2011). Fluid goes into the compressor at low pressure. Inside the compressor, energy converted from electricity into pressure energy. This conversion process in general convert electricity into kinetic energy to a part of the compressor. This kinetic energy then transferred into the fluid and after several processes, it produces higher pressure at outlet compressor. In depth how the process occurred, depend on type of compressor.

2.1. Type of compressor

Compressor divided into two big groups which are positive displacement type and dynamic type (Giampaolo, 2010). The positive displacement type and dynamic type is divided into several types as seen in Figure 2.1. Positive displacement compressor types characteristic are constant volume, variable energy, and not affected by gas characteristic. It is used for low flow rate and/or low gas density. The dynamic compressors are variable volume, constant energy, and influenced by gas characteristic (Forsthoffer, 2005).
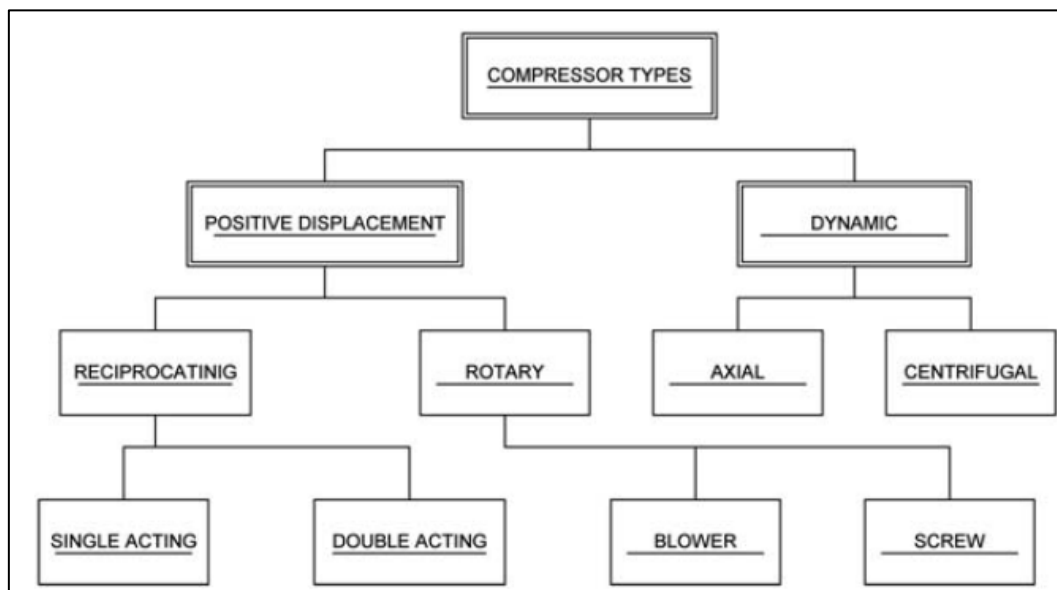
Figure 2.1 Compressor type (Courtesy of Giampaolo, 2010).

Choosing the type of compressor to be used is depend on several factors such as flow rate, pressure, cost and gas characteristic (Forsthoffer, 2005). Figure 2.2 show the range of pressure and flow rate range for each compressor type. Beside flow range and pressure criteria, cost also becomes an important factor. In general, dynamic compressor (centrifugal and axial compressor) usually become the first choices since it have low maintenance cost.
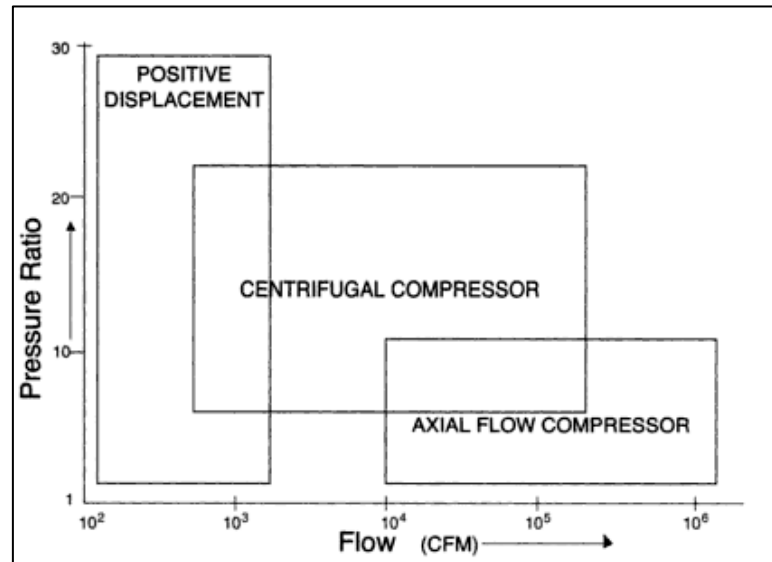
Figure 2.2 Compressor application range (Courtesy of Boyce, 2003)

In oil and gas industries, the centrifugal compressor type is the most dominant type of compressor that being used. It is because centrifugal compressor have high efficiency, can handle high flow capacity and robust (Brenne et al, 2008; Guo et al, 2007).

The basic principle of centrifugal compressor is converting electrical energy into kinetic energy and finally into fluid pressure. Figure 2.3 show the cross section of a centrifugal compressor. Electricity converted by rotating shaft and moves the impeller. The impeller transfer work into the gas and move the gas at high velocity. Gas moves into a diffuser and slow the gas. Inside diffuser, gas kinetic energy converted into static pressure (Guo et al, 2007).
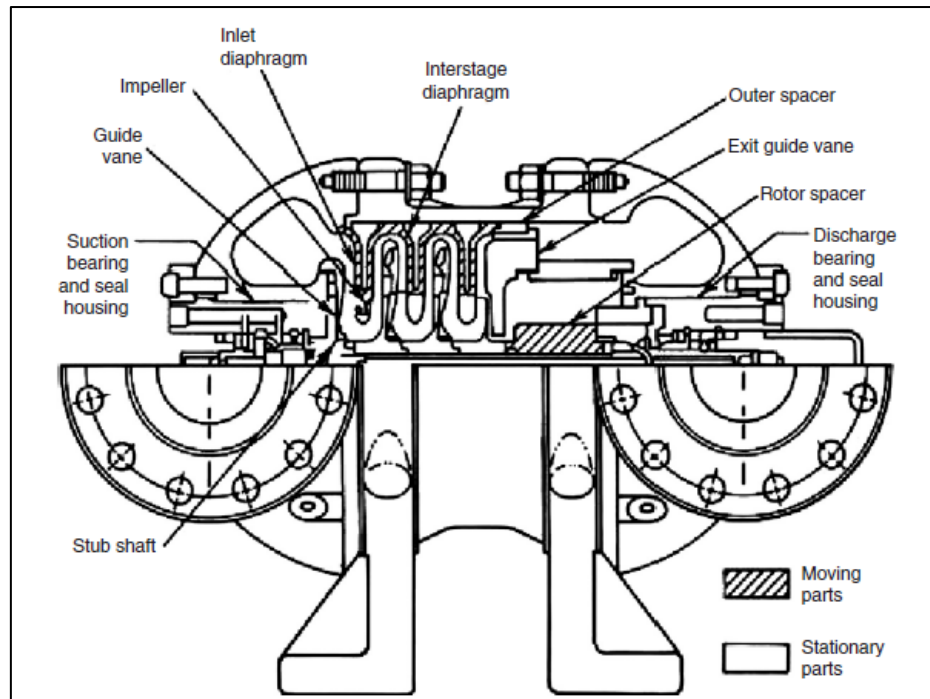
Figure 2.3 Cross section of centrifugal compressor (Courtesy of petroleum extension service)

2.2. Basic thermodynamic of compression process

Work/head done by compressor can be represented by Equation 1 (Moran et al., 2011).

Equation 1:

$$W = \int_{V1}^{V2} pdV$$

Graphical representation of work described by Equation 1 can be seen in Figure 2.4. In the figure, line A and B represent state change during compression process (for compression, the arrow should be reversed). The initial and end point are the same for both lines. From Equation 1, work done on compression process is area under curve pressure-volume which is area under line A or B in Figure 2.4. It can be seen that work done in a compression process depends on state change during entire compression process. It is not only depends on initial and final state. Thus to find work in a compression process, the relation between pressure and volume have to be known for the entire compression process.
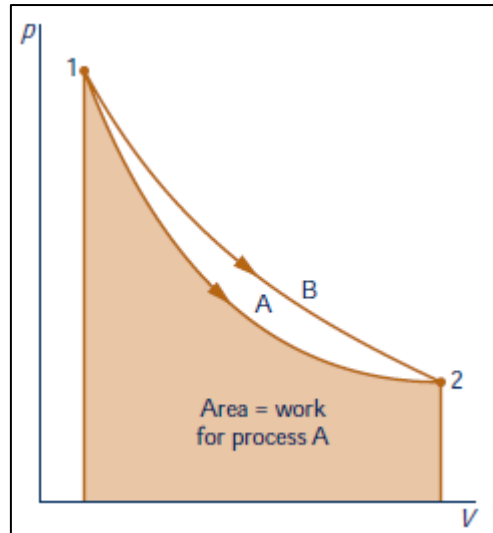
Figure 2.4 Work in graphical representation (Courtesy of Moran et al., 2011)

Modeling an actual pressure-volume relation as Figure 2.4 in real compression process is complicated. Energy loss during compressor such as caused by friction and heat make it difficult. Therefore to make it simple, several assumptions have to be made and a thermodynamic reference process is selected to approximate the real compression process (ISO 5389, 2005). The reference processes in compression are (ISO 5389, 2005):

- Isothermal (constant temperature): used for cooled compressor
- Isentropic (constant entropy): for uncooled compressor in moderate pressure ratio (P2/P1)
- Polytropic (constant polytropic ratio): for uncooled compressor in high pressure ratio (P2/P1) and real gas

Figure 2.5 is pressure-volume relationship for three compression reference process (ISO 5389, 2005). Initial state are point 1 for all reference process and final state are 2T, 2s, and 2p for isothermal, isentropic, and polytropic respectively. From the figure it can be seen that isothermal processes require the smallest work since area under pressure-volume curve is the smallest one. This is the reason why compressor being cooled to increase compressor efficiency.
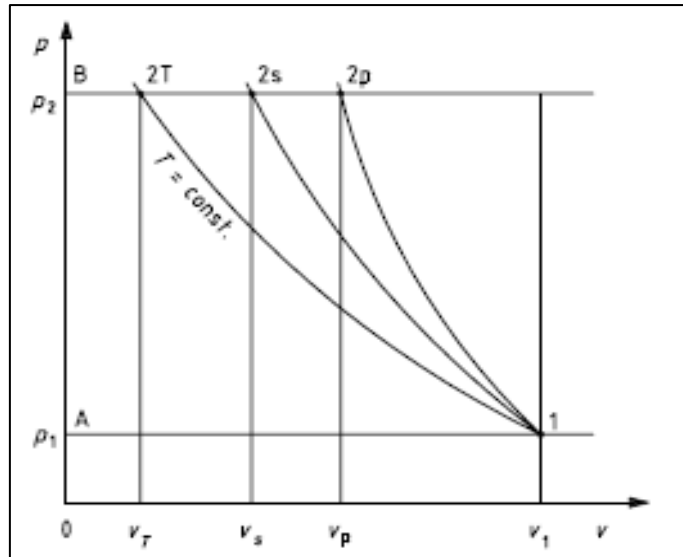
Figure 2.5 Compressor reference processes (Courtesy of ISO 5389, 2005)

2.2.1. Isothermal compression

Isothermal compression is a compression at constant temperature. The relationship between pressure and volume for isothermal compressions are:

Equation 2:

$$p * v = constant$$

By using Equation 2 and Equation 1, specific head for isothermal compression is (ISO 5389, 2005):

Equation 3:

$$h_T = R * z * T_1 * \ln\left(\frac{p_2}{p_1}\right)$$

Mean value of z between initial and final condition should be used in Equation 3:

$$z = \frac{z_1 + z_2}{2}$$

With the definition of isothermal efficiency as (ISO 5389, 2005)

Equation 4:

$$\eta_s = \frac{h_T}{h_2 - h_1 + q_{out}}$$

16

2.2.1. Isentropic compression

Isentropic is an adiabatic reversible (no heat transfer, no friction loss) process (Moran et al., 2011). Pressure-volume relationships for isentropic processes are:

Equation 5:

$$p * v^k = constant$$

Using real gas equation, the relation between pressure and temperature become:

Equation 6:

$$\frac{T_2}{T_1} = \frac{z_1}{z_2} * \left(\frac{p_2}{p_1}\right)^{\frac{k}{k-1}}$$

From Equation 5, Equation 6, and Equation 1 specific compression head for real gas isentropic compression become (ISO 5389, 2005)

Equation 7:

$$h_s = \frac{k}{k-1} * R * z_1 * T_1 * \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]$$

Mean value of k between initial and final condition in Equation 7 should use

Equation 8:

$$k = \frac{k_1 + k_2}{2}$$

Figure 2.6 Show isentropic and actual compression process in a Mollier diagram (Moran et al., 2011). It is shown that actual compression processes requires more energy compared to isentropic process. The relation between actual compression and isentropic compression related by isentropic efficiency:

Equation 9:

$$\eta_s = \frac{h_s}{h} = \frac{h_{2s} - h_1}{h_2 - h_1}$$
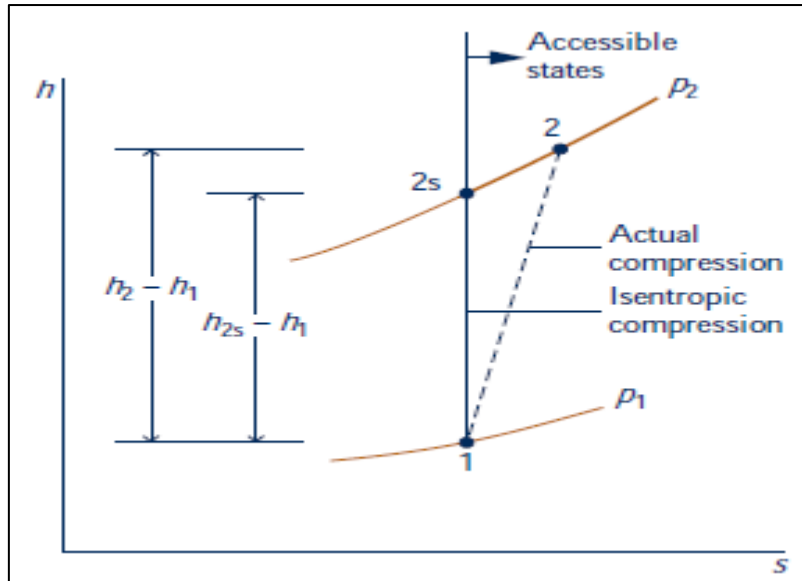
Figure 2.6 Comparison between isentropic and actual compression (Courtesy of Moran, 2011)

2.2.2. Polytropic compression

Polytropic compressions are compression with pressure-volume relationship defined by:

Equation 10:

$$p * v^n = constant$$

In polytropic compression, the ratios of differential enthalpy to work for the entire compression are constant and it is the same for all compression ratios (ISO 5389, 2005):

Using Equation 10 and Equation 1, the work of polytropic compression become:

Equation 11:

$$h_p = \frac{n}{n-1} * R * z_1 * T_1 * \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

From Equation 10, relation between pressure and temperature for real gas are:

Equation 12:

$$\frac{T_2}{T_1} = \frac{z_1}{z_2} * \left(\frac{p_2}{p_1} \right)^{\frac{n}{n-1}}$$

The polytropic exponent n can be defined from (NEL Fluid Rep, 1959):

Equation 13

$$n = \frac{1+X}{\frac{1}{k_V} * \left(\frac{1}{\eta_p} + X\right) - Y * \left(\frac{1}{\eta_p} - 1\right)}$$

Polytropic efficiency defined as (ISO 5389, 2005):

Equation 14

$$\eta_p = \frac{h_p}{h} = \frac{h_p}{h_2 - h_1}$$

2.3. Compressor performance method

From three reference process described in section 2.2, polytropic process is widely used in compressor performance calculation. Polytropic process is more appropriate since performance variation due inlet condition is taken into account (Hundseid et al., 2006). Fot isentropic reference process, the performance varies with different operating condition (suction pressure). This variation is due to the deviation in isobar$\left(\frac{dh}{ds}\right)_p = T$. For isothermal condition, it assumes constant temperature. This will cause inaccuracy since gas temperature increase as pressure rise (except for compressor for cooler).

Even though polytropic reference process calculation already take into account effect of different operating condition, it is still not good enough to predict compressor performance. It is because Equation 11 was derived by assuming constant polytropic exponent along the compression path. It is not true since polytropic exponent is a function of polytropic efficiency and isentropic exponent, which is changing along compression path (Hundseid et al., 2006).

To resolve the changing gas property along compression path, several authors propose solution. There are three methods that widely used in industry. They are:

- Schultz method (Schultz, 1962)
- Huntington method (Huntington, 1985)
- Reference/Direct integration method (Huntington, 1985)

2.3.1. Schultz method

To settle the issue of changing gas property along the path, Schultz propose new solution by introducing new variable (Schultz, 1962). The new variable will take consideration the effect of changing gas property along the path. In his solution, he still use polytropic compression path, but add f factor (Schultz correction factor) into Equation 11. Schultz equation is used in ISO 5389:2005 standard (ISO 5389, 2005). The modified equation is:

Equation 15:

$$h_{p,S} = f * \frac{n_v}{n_v - 1} * R * z_1 * T_1 * \left[\left(\frac{p_2}{p_1} \right)^{\frac{n_v - 1}{n_v}} - 1 \right]$$

Schultz assumed that n_v is constant along compression. To compensate this assumption, he proposed a correction factor f. Where f is Schultz correction factor given by

Equation 16:

$$f = \frac{h_{2s} - h_1}{\frac{k_v}{k_v - 1} * (p_2 * v_{2s} - p_1 * v_1)}$$

n_v is given by

Equation 17:

$$n_v = \frac{1 + X}{\frac{1}{k_V} * \left(\frac{1}{\eta_p} + X \right) - Y * \left(\frac{1}{\eta_p} - 1 \right)}$$

Where X and Y given by

Equation 18:

$$X = \frac{T}{v} * \left(\frac{\partial v}{\partial T} \right)_P - 1$$

Equation 19:

$$Y = -\frac{p}{v} * \left(\frac{\partial v}{\partial p} \right)_T$$

And k_v

Equation 20:

$$k_v = \frac{\ln(\frac{P_2}{P_1})}{\ln(\frac{V_1}{V_{2s}})}$$

Or

Equation 21:

$$k_v = \frac{\kappa}{Y}$$

When calculating κ, Schultz suggest to use the following equation

Equation 22:

$$\bar{\kappa} = \frac{\kappa_1 + 2 * \kappa_m + \kappa_2}{4}$$

The midpoint temperature and pressure are

Equation 23:

$$T_m = \frac{T_1 + T_2}{2}$$

Equation 24:

$$p_m = \sqrt{p_1 * p_2}$$

2.3.2. Huntington method

Huntington uses the following formulation to improve the accuracy of compressor performance calculation (Huntington, 1985):

- Use polytropic path equation (Equation 25) when deriving his method

Equation 25:

$$\eta_p dh = vdp$$

- Assume general relationship between pressure and compressibility factor along compression path (Equation 26).

Equation 26:

$$z = a + b * \left(\frac{p}{p_1}\right) + c * ln\left(\frac{p}{p_1}\right)$$

Huntington starts the derivation from Equation 25, Equation 26, and Maxwell Equation 27 below to calculate polytropic efficiency (Equation 28).

Equation 27:

$$dh = Tds + vdp$$

Equation 28:

$$\frac{1}{\eta_{p,h}} = 1 + \frac{(S_2 - S_1)/R}{a * \ln\left(\frac{p_2}{p_1}\right) + b * \left[\left(\frac{p_2}{p_1}\right) - 1\right] + \frac{c}{2} * \left[\ln\left(\frac{p_2}{p_1}\right)\right]^2}$$

The constant a, b, and c in Equation 26 are calculated from initial point, end point, and intermediate point along the compression path. The intermediate pressure given by

Equation 29:

$$p_m = \sqrt{p_1 * p_2}$$

Initial guess of intermediate temperature given by

Equation 30:

$$T_m = \sqrt{T_1 * T_2}$$

The constant a, b, and c calculated by

Equation 31:

$$a = z_1 - b$$

Equation 32:

$$b = \frac{z_1 + z_2 - 2 * z_m}{\left[\left(\frac{p_2}{p_1}\right)^{0.5} - 1\right]^2}$$

Equation 33:

$$c = \frac{z_2 - a - b * \left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{p_2}{p_1}\right)}$$

Using above equation, head can be calculate by equation

Equation 34:

$$h_{p,h} = \frac{h_p}{\eta_{p,h}}$$

The error of this method can be further reduced by improve the midpoint temperature estimate as follow

Equation 35:

$$T'_m = T_m * \exp\left[\frac{(S_m' - S_m)}{C_p}\right]$$

Equation 36:

$$S'_m = S_1 + (S_2 - S_1) * \left\{ \frac{\frac{a}{2} * \ln\left(\frac{p_2}{p_1}\right) + b * \left[\left(\frac{p_2}{p_1}\right)^{0.5} - 1\right] + \frac{c}{8} * \left[\ln\left(\frac{p_2}{p_1}\right)\right]^2}{a * \ln\left(\frac{p_2}{p_1}\right) + b * \left[\left(\frac{p_2}{p_1}\right) - 1\right] + \frac{c}{2} * \left[\ln\left(\frac{p_2}{p_1}\right)\right]^2} \right\}$$

Huntington found out that iteration of T_m once is enough to reduce variation of T_m to less than 0.1 K.

2.3.3. Reference/direct integration method

In the same paper as section 2.3.2, Huntington calculates compression process by numerical integration (Huntington, 1985). He divides the polytropic compression path into series of small pressure steps. If the pressure step divided sufficiently small enough, compression work at each step can be calculated by

Equation 37:

$$h_{p,r,i} = v_{avg,i} * \Delta p_i$$

And

Equation 38:

$$h_{p,r,i} = \eta_p * \Delta h_i$$

Work/head calculation on each part calculated by trial and error. For the case where initial pressure and temperature known, but only final pressure known an estimate of sub step final temperature must be assumed. Head calculated by Equation 37 compared to head calculated by Equation 38. The sub step final temperature is altered until Equation 37 equal to Equation 38 (Huntington, 1985).

Total work calculated by this method is sum of each sub step work:

Equation 39:

$$h_{p,r,t} = \sum_i h_{p,r,i}$$

2.4. Compressor curve map

Manufacturer of compressor give their compressor performance in a curve map. Figure 2.7 show typical compressor curve map of compressor. The abscissa is normalized volume flow and the ordinate is head, discharge pressure, or pressure ratio. The solid lines represent performance at several constant compressor speeds. The dashed curve in the middle is constant efficiency curve. There is an optimum operating point as shown in the graph. The operating point of the compressor must between surge limit and stonewall limit to avoid damage or to avoid reduced efficiency (Hanlon, 2001).
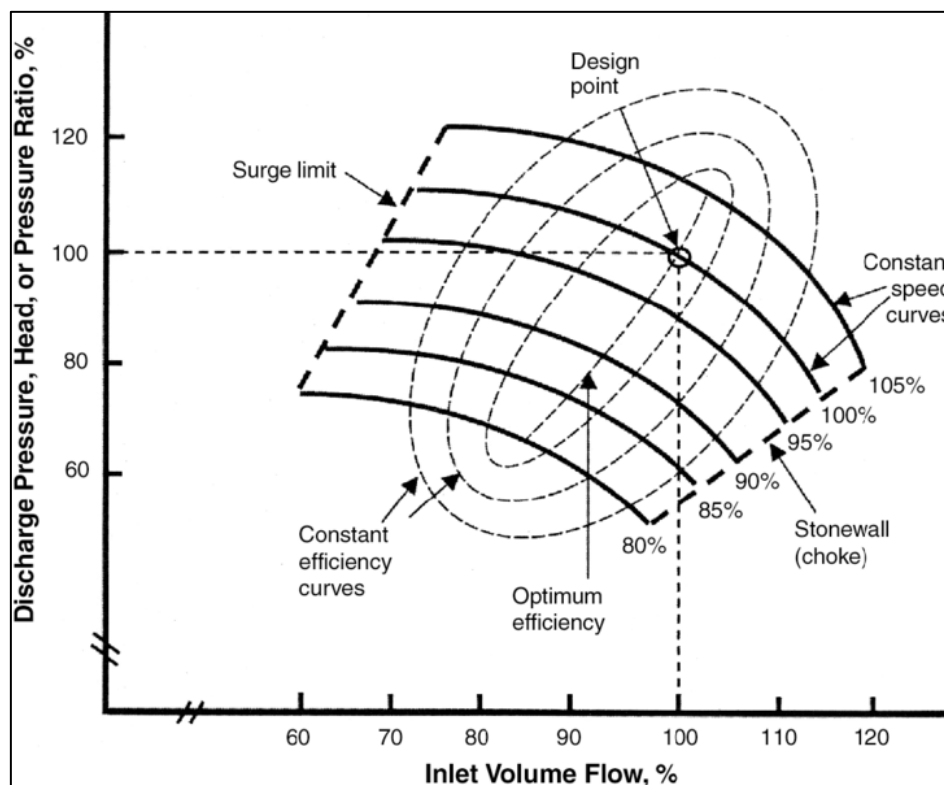
Figure 2.7 Compressor curve map (Courtesy of Dresser-Rand)

Stonewall in Figure 2.7 is a condition which increasing capacity will give rapid decrease in head as flow increased. This is occurred because fluid velocity approaching sound velocity (M=1.0). When compressor operates at rate higher than stonewall limit, it will reduce compressor efficiency and may damage the compressor (Hanlon, 2001).

Surge limit is peak head of compressor curve (Hanlon, 2001). If flow rate reduced below surge limit, head will decrease. Surge will damage compressor and should be avoided. When surge take place, nearly all of compressor component will reverse bended (Hanlon, 2001).

2.5. Effect of wet gas

Wet gas flow is defined by fluid with high gas volume fraction with liquid volume fraction up to 5% (Hundseid et al., 2008). Wet gas fluid flow in gas condensate field usually flows as an annular flow. Figure 2.8 show annular flow in horizontal pipe. Annular flow characterized by very high gas velocity that moves in the center of pipe. Liquid will flow as a thin film covering the pipe and as a droplet in the gas.
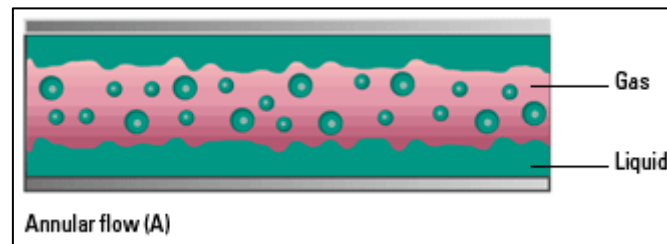
Figure 2.8 Annular flow (Courtesy of Schlumberger)

The presence of liquid alters compressor performance by momentum, heat, and mass transfer between phases (Hundseid et al., 2008). In more detail, there are several phenomena that will occur in wet gas compressor such as evaporate cooling, heat transfer, liquid entrainment/deposition, and liquid film.

Two phenomena that will reduce temperature of the compressed fluid are evaporate cooling and heat transfer (Hundseid et al., 2008). Evaporate cooling is a process of evaporation of liquid into gas by heat transfer from gas phases into liquid phases. The phase change event will result internal loss in the fluid and increase in entropy. The cooling effect will take place even no phase change event occurred. This is because of high heat capacity of the liquid phase.

Liquid entrainment is a situation that will reduce the total kinetic energy of the fluid (Hundseid et al., 2008). The kinetic energy of the fluid will reduced if entrained liquid is accelerated. And also, total kinetic energy is reduced if the droplets are move into the liquid film.

Liquid film in the compression process will increase frictional loss of the system (Hundseid et al., 2008). It can be explained as follow. The liquid film will cover the surface of impeller. This will increase the surface roughness due to liquid wave and droplet impact. Another effect is the liquid film act as a blockage to the flow area. Both effects will further increase friction loss in the system.

Figure 2.9 show effect of gas volume fraction to compressor performance (Hundseid et al., 2008). The data obtained from experiment data using closed loop system at StatoilHydro test facility. From the figures it can be seen that by increasing liquid content in the flow, the specific polytropic head is reduced.
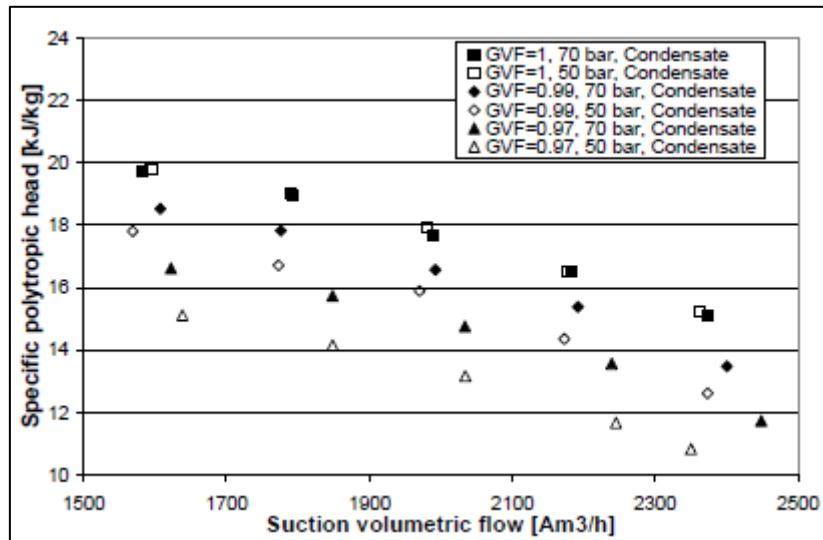
Figure 2.9 Effect of wet gas presence to specific polytropic head (Courtesy of Hundseid et al, 2008)

In the paper, Hundseid et al describe that the reduced specific polytropic head is caused by the effect of high liquid density (mass flow), high flow rate, and compressibility effect (Hundseid et al., 2008). Their calculation is based on direct integration method in section 2.3.3. From Equation 37 it is clear that by increasing density, polytropic head will be reduced.

By performing compressor performance correction with compressibility and mass flow effect, the performance between dry and wet gas flow can be directly compared (Hundseid et al, 2008). The mass flow correction was done by comparing mass flow in a dry condition to wet gas condition. For compressibility correction, Wood's correction method was used (Wood, 1994). The result of the mass correction shown in Figure 2.10, while the Wood's correction result shown in Figure 2.11.
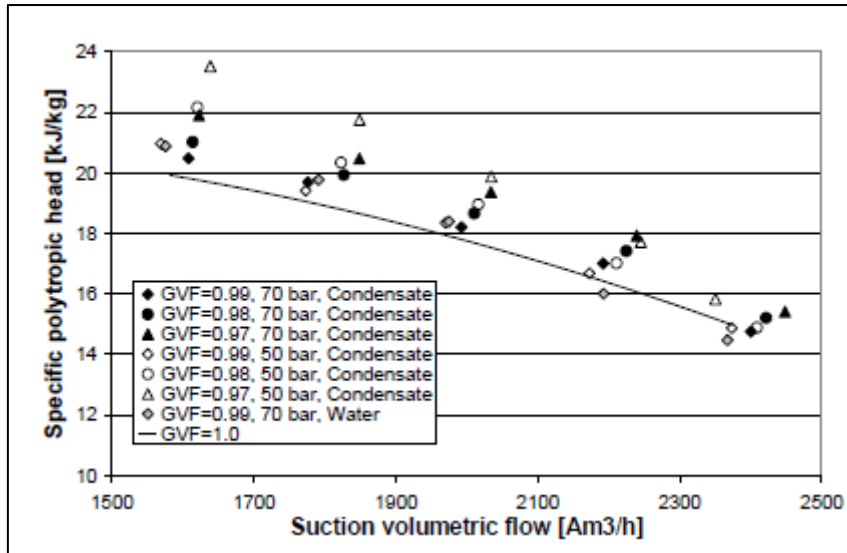
Figure 2.10 Mass flow corrected specific polytropic head (Courtesy of Hundseid et al, 2008)
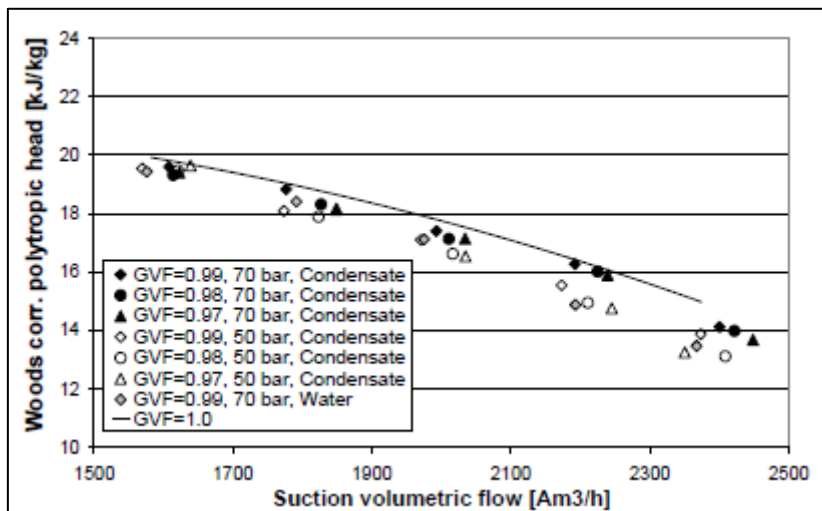
Figure 2.11 Wood 's corrected specific polytropic head (Courtesy of Hundseid et al, 2008)

2.6.   Compressor off design operation

Data of compressor curve map in Figure 2.7 was gathered from test reference condition at certain operating condition which may differ from actual operating condition. The difference between test reference condition and actual condition (off design) can affect compressor curve map in a considerable amount (Hanlon, 2001). Any change in inlet condition such as pressure, temperature, and gas composition can change head in the curve.

Figure 2.12 show the effect of different fluid density into compressor curve (Hanlon, 2001). From the figure it can be seen that by increasing density, the head curve will increase.

27
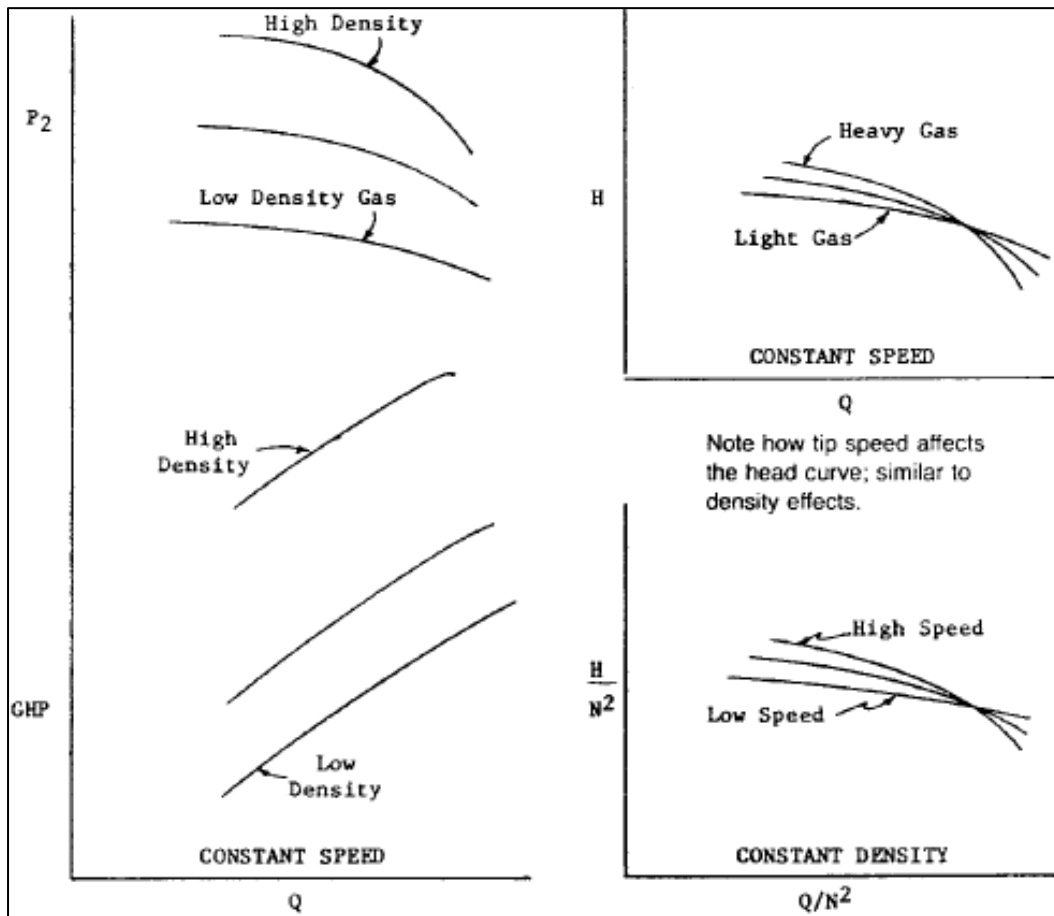
Figure 2.12 Effect of fluid density to compressor curve (Courtesy of Hanlon, 2001)

2.7. Compressor off design correction

As discussed in section before, actual inlet condition may differ from compressor test reference/design condition (off design). If this is the case, compressor curve map should be corrected (Boyce, 2003). In off design operational condition, some value should be corrected into design/reference condition. There are several methods to do this correction. The method that widely used for this correction is dimensional analysis method. Another method being considered is an iterative method from Ma et al (Ma et al., 2013).

2.7.1. Dimensional analysis method

The corrections of compressor performance are based on dimensional analysis. The following equations are used to correct compressor parameter (Boyce, 2003):

Equation 40 (corrected compressor mass flow):

$$\dot{m}_{corr} = \frac{\dot{m}_{act} * \sqrt{\dfrac{T_1}{T_{ref}}}}{\dfrac{P_1}{P_{ref}}} * \frac{1}{\sqrt{\dfrac{MW_{act}}{MW_{corr}}}}$$

Equation 41 (corrected compressor volume flow):

$$Q_{corr} = \frac{Q_{act} * \sqrt{\dfrac{MW_{act}}{MW_{corr}}}}{\sqrt{\dfrac{T_1}{T_{ref}}}}$$

Equation 42 (corrected speed):

$$N_{corr} = \frac{N_{act} * \sqrt{\dfrac{MW_{act}}{MW_{corr}}}}{\sqrt{\dfrac{T_1}{T_{ref}}}}$$

Equation 43 (corrected power):

$$HP_{corr} = \frac{HP_{act} * \sqrt{\dfrac{MW_{act}}{MW_{corr}}}}{\dfrac{P_1}{P_{ref}} \sqrt{\dfrac{T_1}{T_{ref}}}}$$

Equation 44 (corrected adiabatic or polytropic head):

$$h_{corr} = \frac{h_{act} * \dfrac{MW_{act}}{MW_{corr}}}{\dfrac{T_1}{T_{ref}}}$$

Equation 45 (corrected pressure):

$$p_{corr} = \frac{p_{act}}{\frac{p_1}{p_{ref}}}$$

Equation 46 (corrected temperature):

$$T_{corr} = \frac{T_{act} * \frac{MW_{act}}{MW_{corr}}}{\sqrt{\frac{T_1}{T_{ref}}}}$$

2.7.2. Iterative method

Ma et al (2013) propose a new procedure for off design compressor operation by iterative method. Figure 2.13 show general correction procedure by iterative method. First task is to transform operating inlet condition into test reference condition. After correcting operating inlet condition into reference test condition, the discharge condition is calculated iteratively based on corrected inlet condition. The final procedures are to recalculate polytropic head, power, and efficiency based on corrected inlet condition.
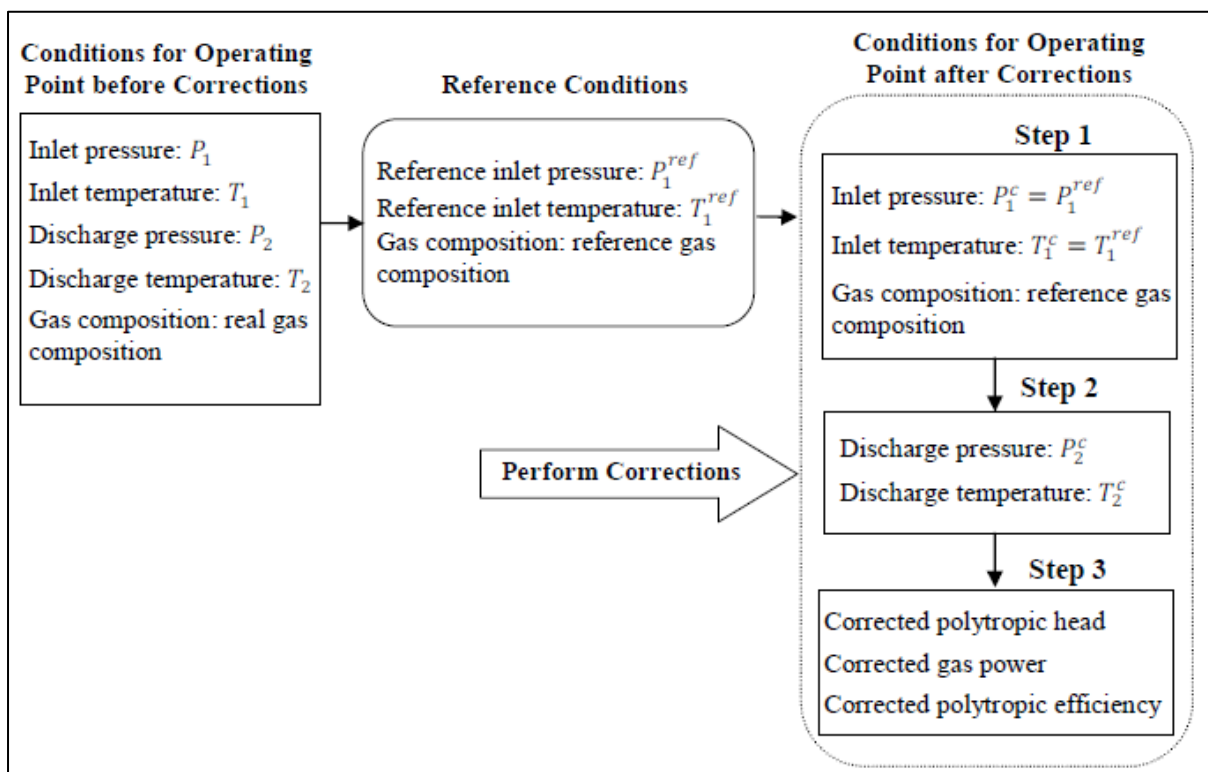
Figure 2.13 Basic procedure for off design correction by iterative method (Courtesy of Ma et al, 2013)

In the paper, they claimed that this method eliminate some limitation in ASME-PTC-10(ASME, 1998) standard. The limitations of the standard are it does not account the change in pressure and temperature change in the inlet, thus it cannot be applied in general case. Another limitation of the standard is it requires complex input data to do the correction.

The detailed procedures of iterative method are the following:

1. Calculate average inlet-outlet gas property. n, k, X, Y which are calculated from Equation 17, Equation 18, Equation 19, and Equation 21

Equation 47:

$$n = \frac{n_1 + n_2}{2}$$

Equation 48:

$$k = \frac{k_1 + k_2}{2}$$

Equation 49:

$$X = \frac{X_1 + X_2}{2}$$

Equation 50:

$$Y = \frac{Y_1 + Y_2}{2}$$

2. Transforming inlet condition (pressure, temperature, and composition) into test reference condition. Then calculate n_1^c, k_1^c, X_1^c, and Y_1^c at corrected inlet condition by gas properties, Equation 17, Equation 18, Equation 19, and Equation 21

Equation 51:

$$p_1^c = p_1^{ref}$$

Equation 52:

$$T_1^c = T_1^{ref}$$

Equation 53:

$$fluid\ composition_1^c = fluid\ composition_1^{ref}$$

3. Calculate n^c initial

Equation 54:

$$n^c_{initial}$$

$$= \frac{Y * n * (1 - k) * k^c_1 * (1 + X^c_1)}{[k * (1 + X) - Y * n * (k + X)] * Y^c_1 * (1 - k^c_1) + Y * n * (1 - k) * Y^c_1 * (k^c_1 + X^c_1)}$$

4. Set $n^c = n^c$ initial

Equation 55:

$$n^c = n^c_{initial}$$

5. Calculate corrected discharge condition

Equation 56:

$$p^c_2 = p^c_1 * \left(\frac{p_2}{p_1}\right)^{\frac{n^c}{n}}$$

Equation 57:

$$T^c_2 = T^c_1 * \left(\frac{T_2}{T_1}\right)^{\frac{n^c}{n}}$$

6. Calculate corrected outlet discharge properties (z factor, enthalpy, specific heat capacity, and molecular weight).

7. Calculate polytropic exponent at corrected discharge condition and assume $\eta_p{}^c = \eta_p$

Equation 58:

$$n^c_2 = \frac{1 + X^c_2}{\frac{1}{k^c_{2,v}} * \left(\frac{1}{\eta^c_p} + X^c_2\right) - Y^c_2 * \left(\frac{1}{\eta^c_p} - 1\right)}$$

8. Calculate average corrected inlet-outlet polytropic exponent

Equation 59:

$$n^c = \frac{n^c_1 + n^c_2}{2}$$

9. Repeat step 5-8 100 with new n^c calculated from Equation 59.

10. Calculate Schultz correction factor f by

Equation 60:

$$f = \frac{(k_s^c - 1) * (h_{2s}^c - h_1^c)}{k_s^c * (z_{2s}^c * R * \dfrac{T_{2s}^c}{MW_s^c} - z_1^c * R * \dfrac{T_1^c}{MW^c})}$$

Where

Equation 61:

$$k_s^c = \frac{1}{2} * (\frac{k_1^c}{Y_1^c} + \frac{k_2^c}{Y_2^c})$$

11. Calculate polytropic head $h_p{}^c$

Equation 62:

$$h_p^c = f * \frac{n^c}{n^c - 1} * \frac{1}{MW^c} * (z_2^c * R * T_2^c - z_1^c * R * T_1^c)$$

12. Correct speed and mass flow using fan law (Godse, 2006).

Equation 63:

$$N^c = N * \sqrt{\frac{h_p^c}{h_p}}$$

Equation 64:

$$M^c = M * \frac{N^c}{N}$$

13. Calculate power

Equation 65:

$$HP = \frac{m^c * h_p^c}{\eta^c}$$

3. OBJECTIVE AND METHODOLOGY

The objectives of this paper are:

1. Review direct integration method (Huntington, 1985) to be used in wet gas compressor performance.
2. Review off design correction in wet gas compressor
3. Effect of wet gas to compressor performance
4. Identify how HYSYS^{TM} software calculate wet gas compression

To accomplish the objectives, compressor performance (Schultz method, direct integration method) and off design correction method (Dimensional analysis, iterative method) described in section 2 was programmed in Excel^{TM} visual basic. The fluid properties were calculated using HYSYS^{TM} Peng-Robinson equation of state and used as input to calculate compressor performance.

3.1. Data input

3.1.1. Fluid properties

Table 1 show fluid properties data used as input in this project. The fluid is a typical wet gas/gas condensate hydrocarbon fluid (McCain, 1990). The table consists of separator gas compositions and separator liquid compositions. Table 2 show the property of C_{7+} component

Table 1 Separator gas and liquid compositions (Courtesy of McCain, 1990)

Fluid compositions		
component	Mole fraction separator gas	Mole fraction separator liquid
C1	0.837	0.0869
C2	0.096	0.0569
C3	0.046	0.0896
i-C4	0.006	0.0276
n-C4	0.009	0.0539
i-C5	0.003	0.0402
n-C5	0.002	0.0400
n-C6	0.001	0.0782
C_{7+}	0.000	0.5267
Mw total	19.68	83.84

Table 2 C$_{7+}$ properties (Courtesy of McCain, 1990)

C7+ properties	Molecular weight	Specific gravity
	Lb/lb mole	
	113	0.837

To observe the effect of different GVF (Gas volume fraction) on compressor performance, several cases of fluid properties were created in HYSYS^{TM} with different molar flow from each separator gas and liquid and mix them in a mixture (Figure 3.1). The variations of GVF are shown in Table 3. All fluid properties were calculated using HYSYS^{TM} by Peng-Robinson equation of state.
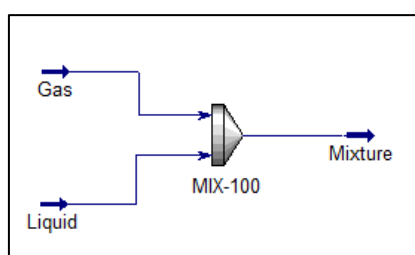
Figure 3.1 Process flow diagram of mixing liquid and gas phase

Table 3 Variation of inlet gas volume fraction case

Cases	1	2	3	4
Gas volume fraction (at inlet condition Case A and B)	1	0.99	0.97	0.96
Gas molar flow (kgmole/hr)	1500	1429	1364	1304
Liquid molar flow (kgmole/hr)	0	71	136	196
Mixture component	mole fraction	mole fraction	mole fraction	mole fraction
C1	0.837	0.801	0.769	0.739
C2	0.096	0.094	0.092	0.091
C3	0.046	0.048	0.050	0.052
i-C4	0.006	0.007	0.008	0.009
n-C4	0.009	0.011	0.013	0.015
i-C5	0.003	0.005	0.006	0.008
n-C5	0.002	0.004	0.005	0.007
n-C6	0.001	0.005	0.008	0.011
C7+	0.000	0.025	0.048	0.069

3.1.2. Calculation cases and workflow

Figure 3.2 shows general flowchart for calculating compressor performance. In summary, the first thing to do is to check whether compressor test design condition differ from operating condition. If it is different, then the compressor curve map needs to be corrected by dimensional analysis method or iterative method. If no correction needed, the calculation goes directly into compressor performance calculation by Schultz method (Schultz, 1962) or direct integration method (Huntington, 1985). The final outputs are compressor performance, outlet condition, or head.
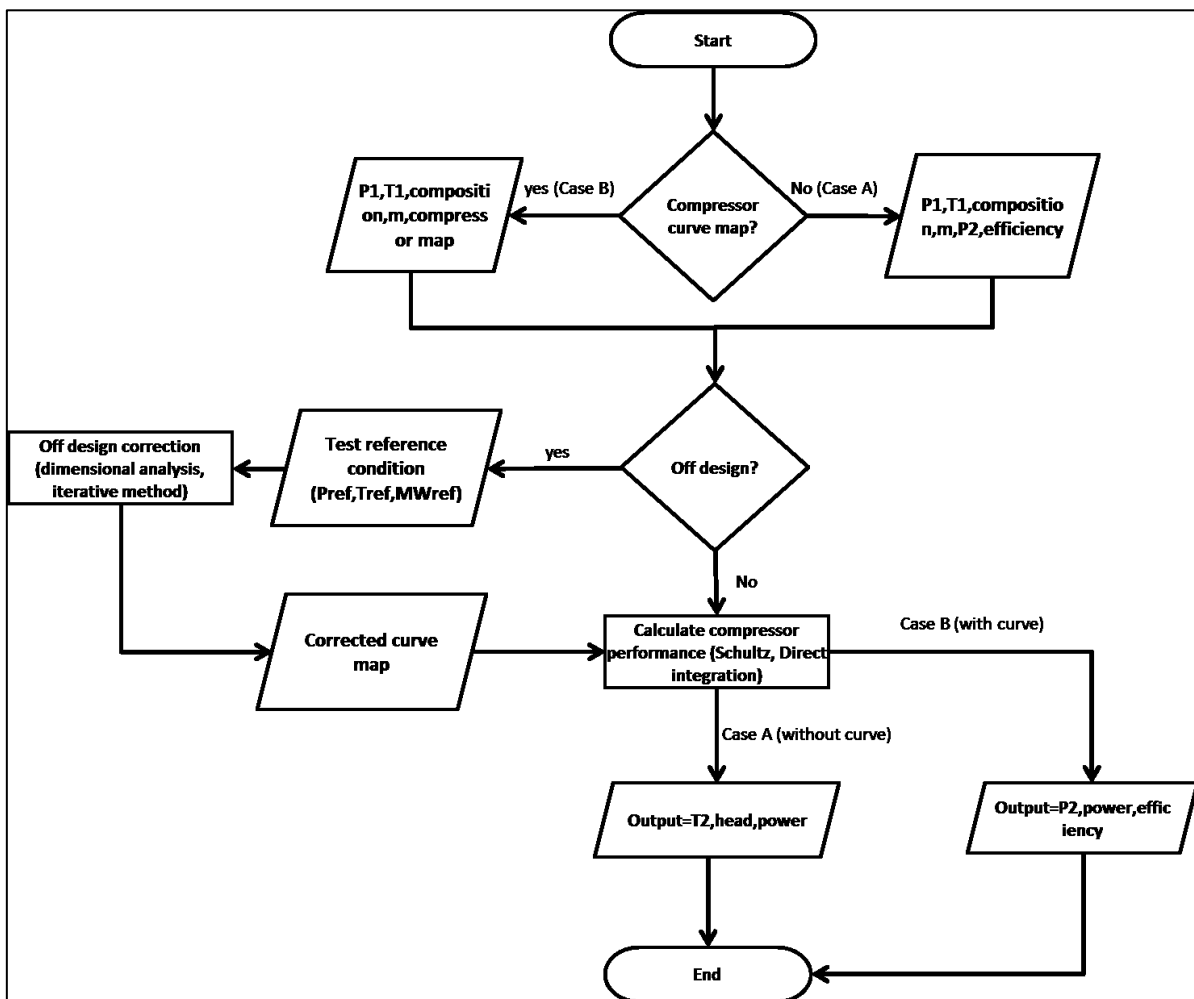
Figure 3.2 Flowchart of compressor performance calculation

In this project, two cases of compressor calculation were created (Figure 3.2). The first case (case A) is compressor performance calculation without compressor curve map, and second case (Case B) is case with compressor curve map. On both cases, fluid properties were varied according to Table 3 and produce fluid variation case in Figure 3.3.
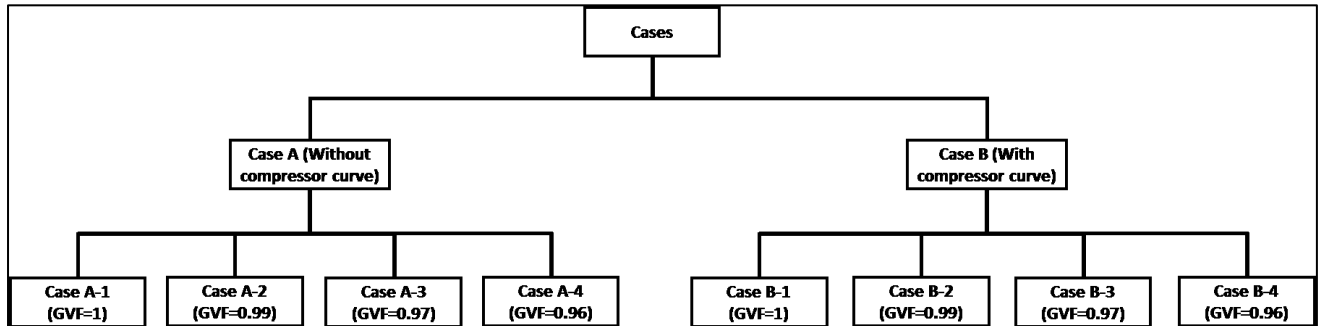
Figure 3.3 Compressor performance cases

Table 4 gives input parameter such as inlet condition, compressor efficiency, and outlet pressure for case A. In this case, no compressor curve map was given and compressor test reference condition is assumed to be the same with actual condition. Thus, no off design correction needs to be done.

Table 4 Case A parameter condition

Case A parameter (without compressor curve)								
Inlet condition			Compressor properties			Outlet condition		
P1	700.0	psia	efficiency	75	%	P2	1000	psia
T1	563.0	R						
molarflow	500	kgmole/hr						

For case B, the inlet condition is given by Table 5. Table 6 and Figure 3.4 is the compressor curve map tested at condition described in Table 7. When performing compressor curve map, dry gas composition in Table 3 was used as test fluid. As can be seen from Table 5 and Table 7, the reference test condition and actual condition is different. Thus, off design correction need to be done in this case.

37

Table 5 Case B inlet condition

Case B parameter (with compressor curve)		
Inlet condition		
P1	500.0	psia
T1	563.0	R
molarflow	1500	kgmole/hr

Table 6 Initial compressor curve map

Compressor curve at initial condition		
Volume flow	Head original	Efficiency
act m3/hr	m	%
781	7680	69.20
838	7575	72.00
896	7481	72.48
950	7347	72.58
1008	7153	73.08
1062	6717	72.46
1070	6588	71.99
1119	5858	69.39
1148	4957	62.91
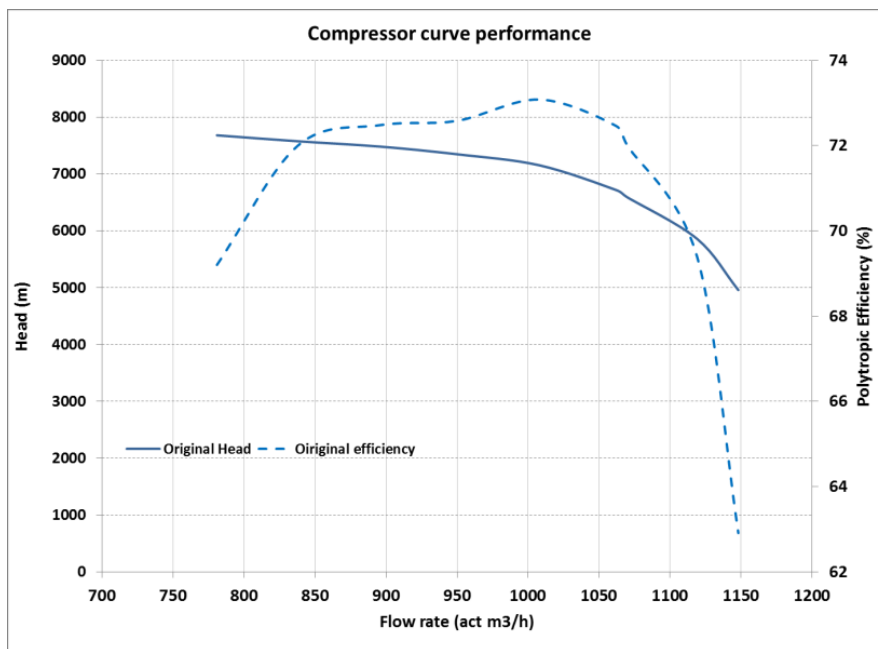
Figure 3.4 Compressor curve performance map

Table 7 Compressor test reference

Compressor test reference		
Ptest	530.0000	psia
Ttest	580.0	R
Mw test	19.683	kg/kg-mole

The calculation for off design correction is using iterative method described in section 2.7.2. The off design result from iterative method will be compared with dimensional analysis method described in section 2.7.1.

For compressor performance calculation, both Schultz method and direct integration method will be calculated. The calculation procedures have been described in section 2.3.1 and 2.3.3. The direct integration method needs to be programmed to facilitate large step size. Excel^{TM} visual basic program for direct integration method is on Appendix. Result from direct integration method will be compared by Schultz method calculated by HYSYS^{TM}.

It is desired to know how HYSYS^{TM} calculate wet gas compressor performance. One hypothesis is that the wet gas compression can be represented by compression on of each phase separately as seen in Figure 3.5. In the figure, the wet gas fluid will be separated before being compressed. Vapor phase goes into compressor while liquid phase goes into pump. After both fluids being compressed, the fluids will be mixed again. The result of this method will be compared with normal compression without separator as seen in Figure 3.6. Schultz method will be used to calculate both compressor performances.
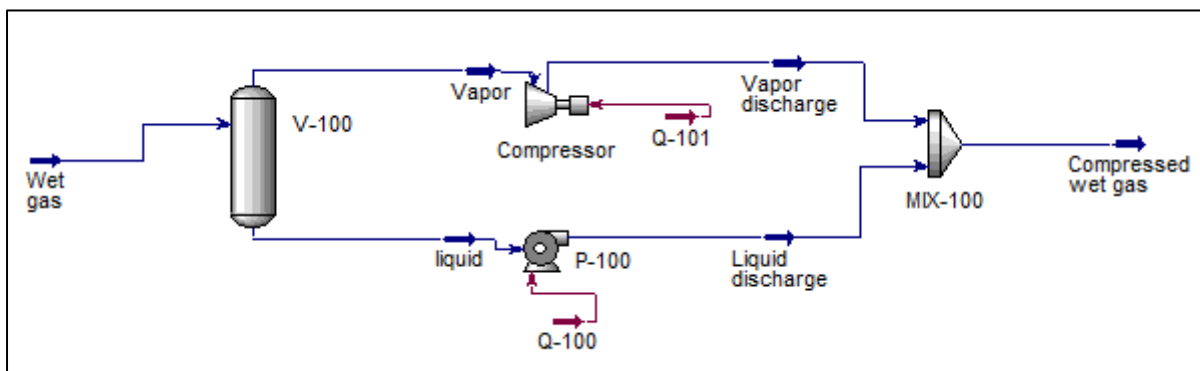
Figure 3.5 Compressor performance calculation with separator
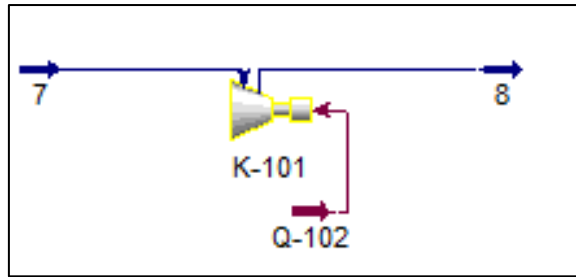
Figure 3.6 Compressor performance calculation without separator

4. RESULT

As described in previous section, two cases was created (Case A and B) in this project. On each case, the fluid gas volume fraction properties were varied according to Table 3. The difference between case A and case B is the data input and off design correction. In case A, no compressor curve map was given and no off design correction. For case B, the input data are compressor curve and off design correction need to be done in case B. In both case, the result of gas compression using prior separator and no separator will also be compared.

4.1. Case A

Figure 4.1 show compression path graph (pressure-molar volume diagram) for case A with various gas volume fraction (GVF=1, GVF=0.98, GVF=0.97, GVF=0.96). Fluid compressed from 700 psia to 1000 psia. The pressure-volume data was gathered using direct integration method at 1, 10, and 60 total pressure step size. The direct integration method compression path compared with Schultz method in the graph.
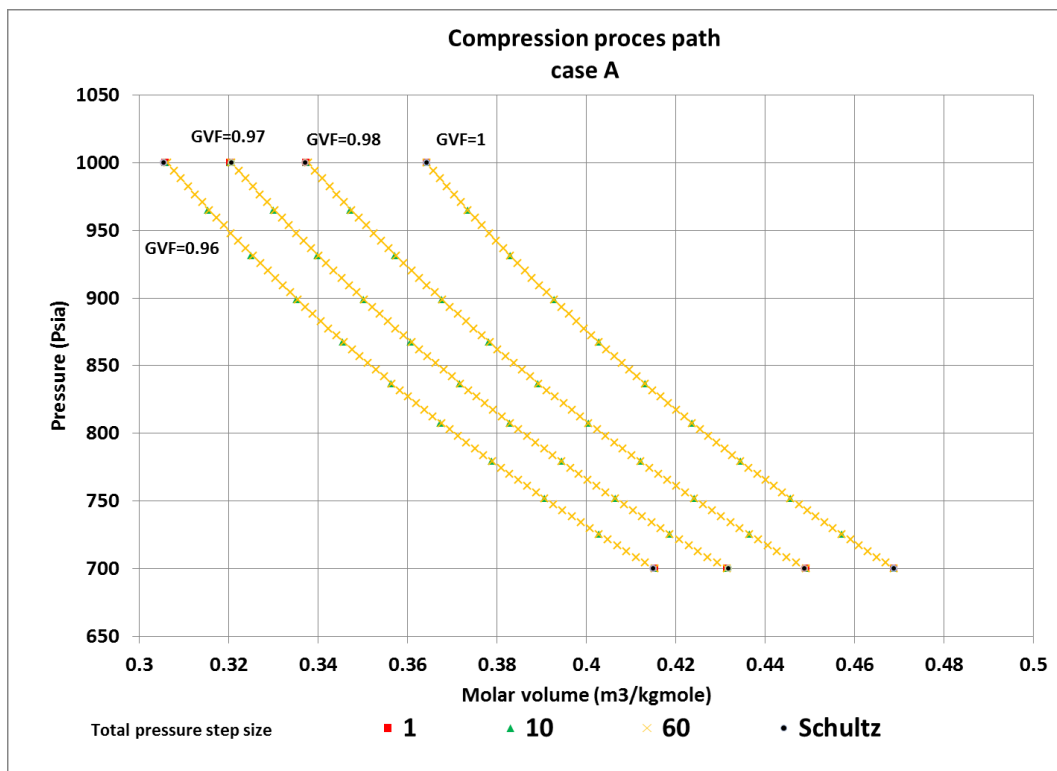
Figure 4.1 Compression process path at various GVF for case A

Figure 4.2 shows fluid properties (gas volume fraction) change on each pressure step as the fluid compressed from initial pressure into final pressure for case A. Each point in the graph calculated using direct integration method with total pressure step size equal to 10. Four initial GVF (GVF=1, GVF= 0.99, GVF=0.97, and GVF=0.96) cases also shown in the figure.
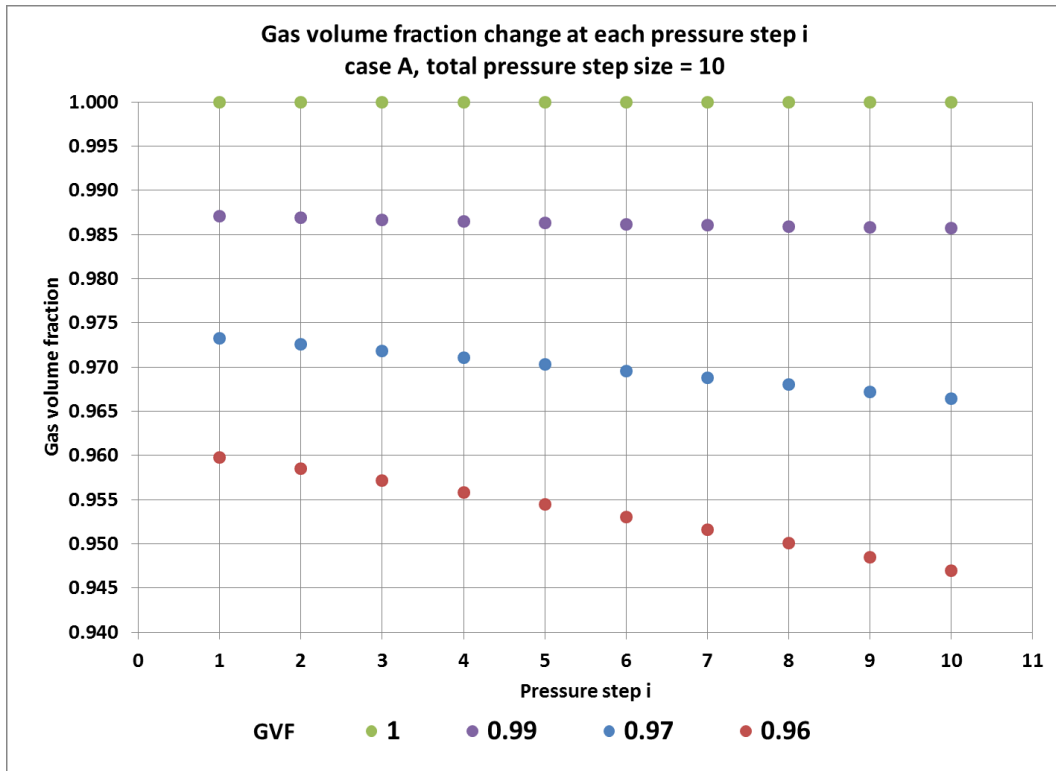
Figure 4.2 Gas volume fraction change at each pressure step i with total number of pressure step = 10 for case A

Figure 4.3 through Figure 4.6 Show polytropic exponent change as the pressure step increase toward final pressure for case A. The graph show direct integration calculation data for various gas volume fractions (GVF) at total pressure step size of 1, 4, 10, 18, 30, and 60. The figures also show Schultz polytropic exponent parameter as a line (Schultz polytropic exponent is not a function of pressure step size, but it is shown in the figure for comparison purpose).
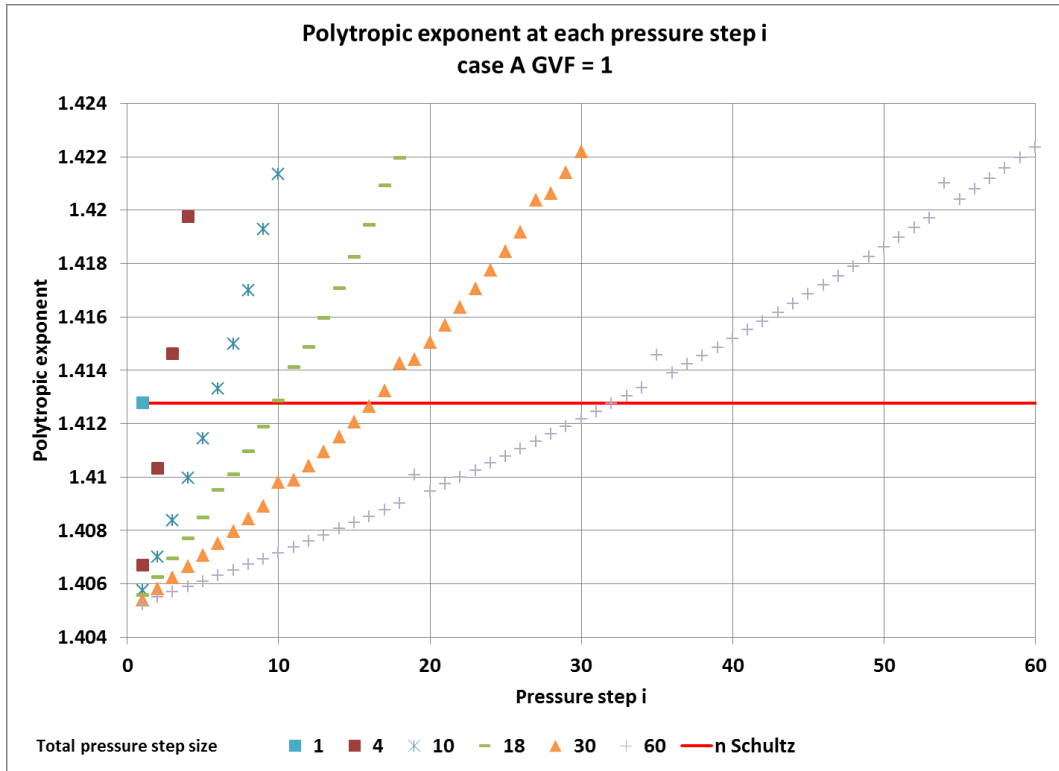
Figure 4.3 Polytropic exponent change at each pressure step i, case A GVF = 1
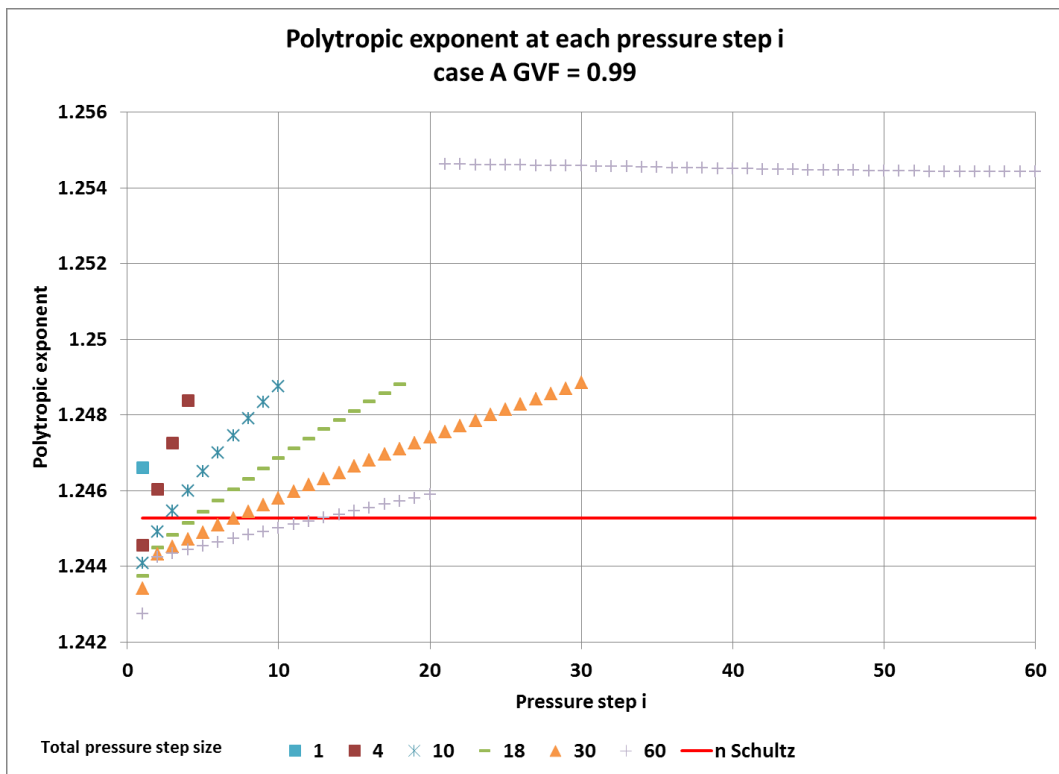
Figure 4.4 Polytropic exponent change at each pressure step i, case A GVF = 0.99

43
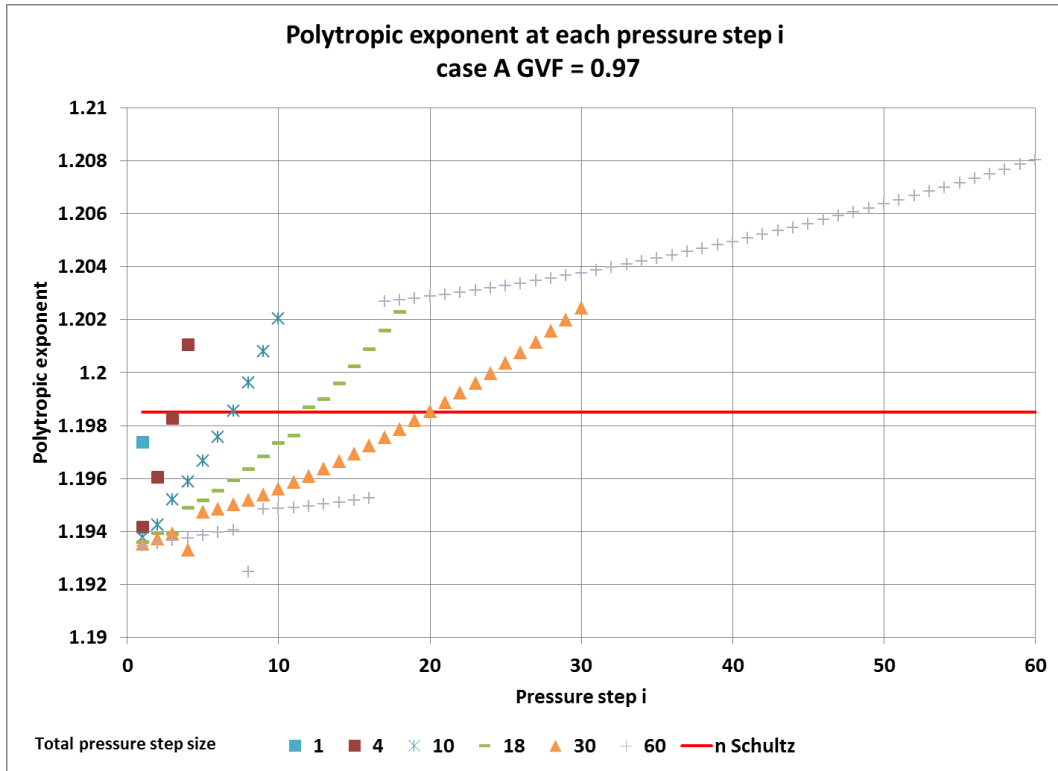
Figure 4.5 Polytropic exponent change at each pressure step i, case A GVF = 0.97
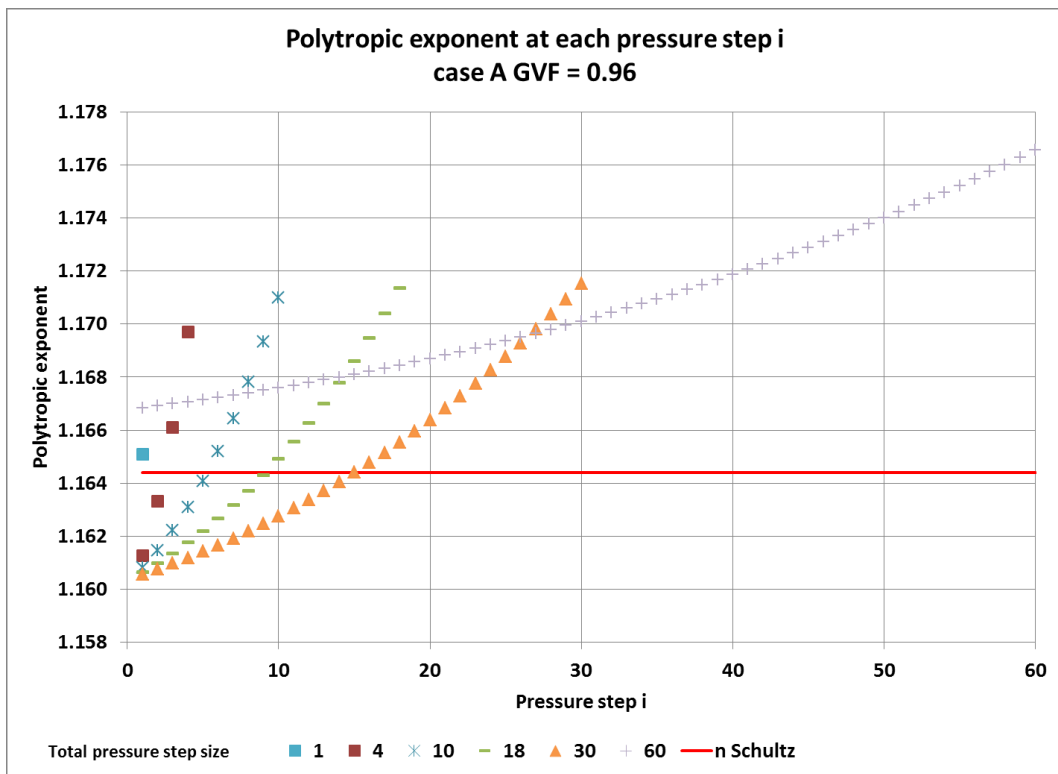
Figure 4.6 Polytropic exponent change at each pressure step i, case A GVF = 0.96

Direct integration method calculation requires Equation 37 and Equation 38 equal. The difference between those equation calculated by Equation 66 below. The calculated errors and total specific head for case A shown in Figure 4.7 through Figure 4.10 below.

Equation 66:

$$Error\ (\%) = \frac{\sum_i v_{avg,i} * \Delta p_i - \sum_i \eta_p * \Delta h_i}{\sum_i v_{avg,i} * \Delta p_i}$$
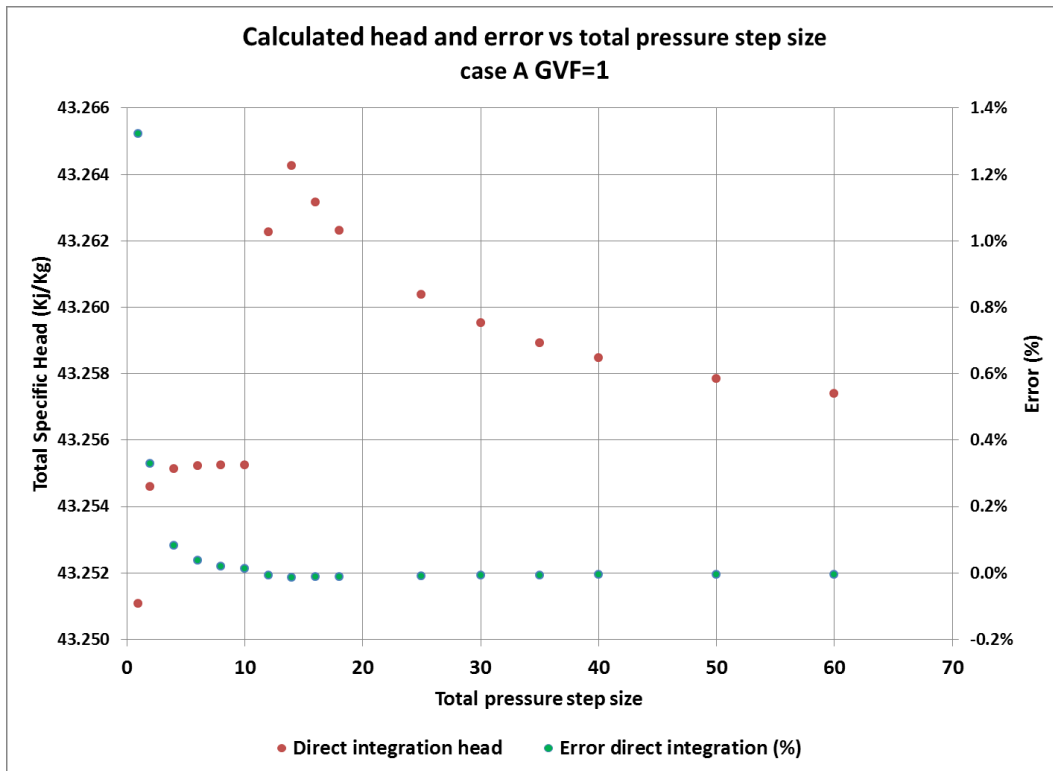
Figure 4.7 Calculated head and error vs total pressure step size, case A GVF = 1
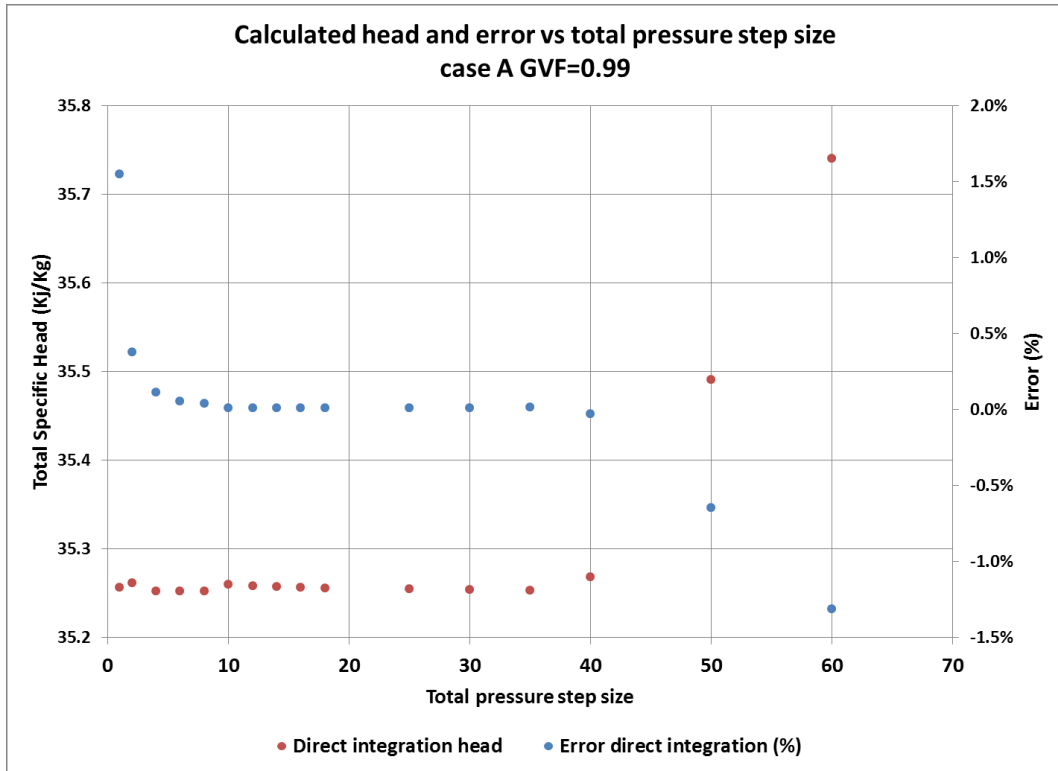
Figure 4.8 Calculated head and error vs total pressure step size, case A GVF = 0.99
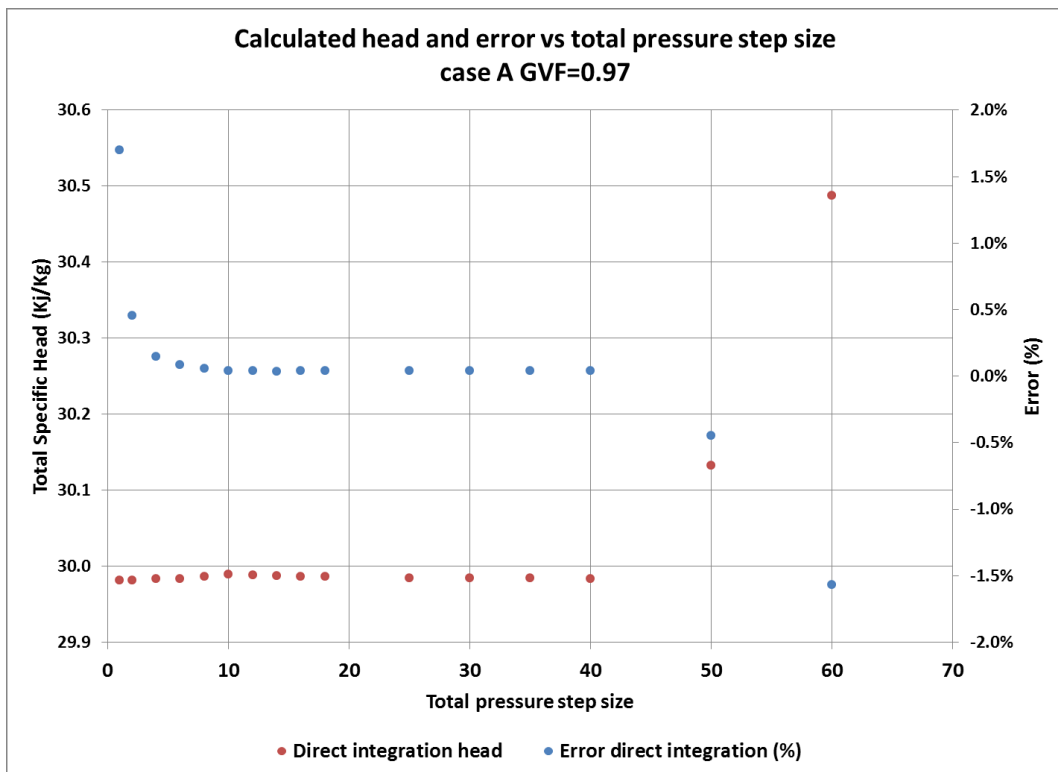
Figure 4.9 Calculated head and error vs total pressure step size, case A GVF = 0.97

46
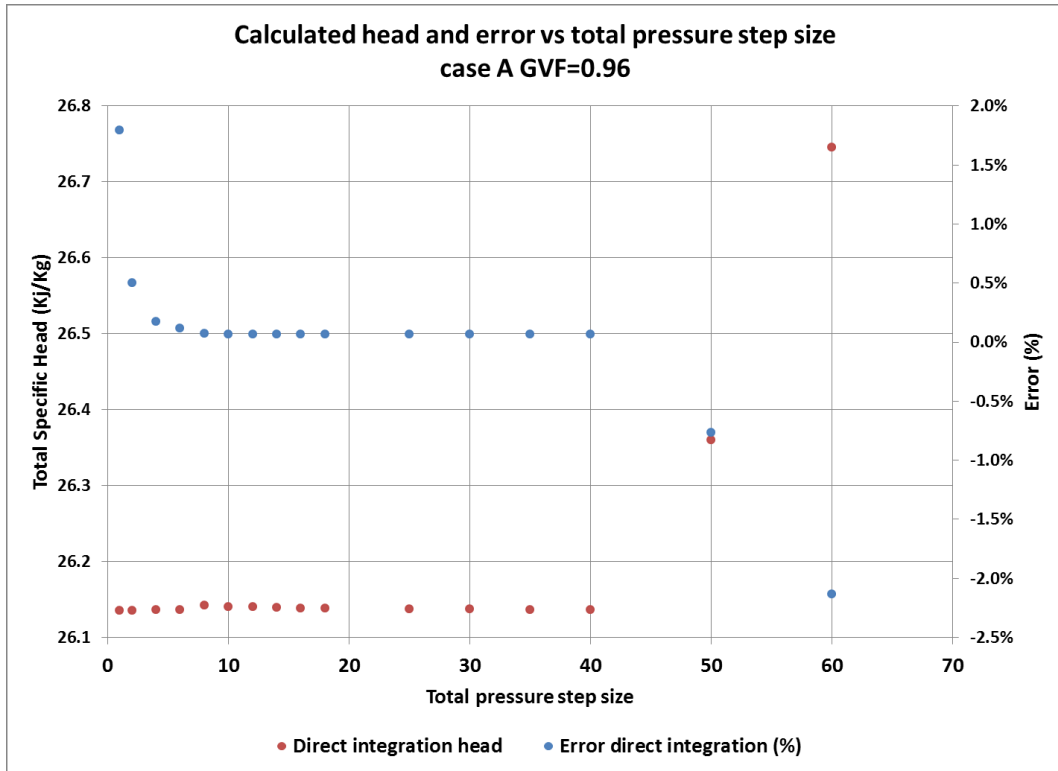
Figure 4.10 Calculated head and error vs total pressure step size, case A GVF = 0.96

Figure 4.11 through Figure 4.14 show the result of calculated total specific head and power using Schultz and direct integration method with various gas volume fractions (GVF) for case A. The abscissa represents total pressure step size in direct integration method. The ordinate show total specific head and power required to compress the gas.
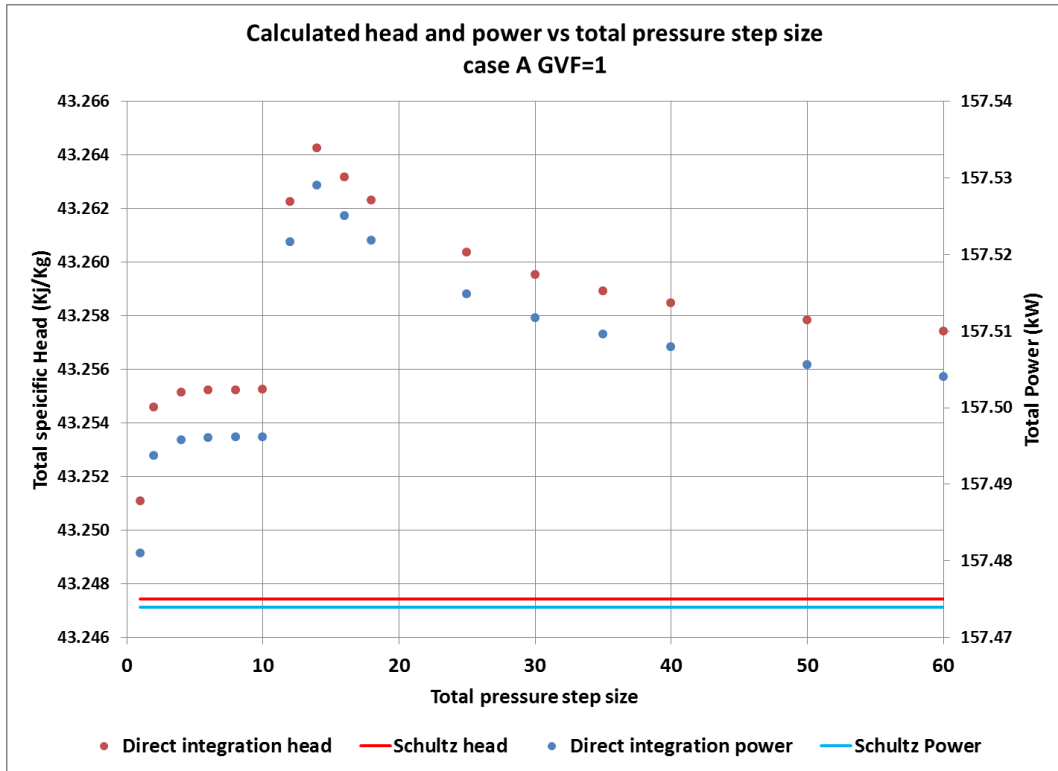
Figure 4.11 Calculated head and power vs total pressure step size, case A GVF = 1
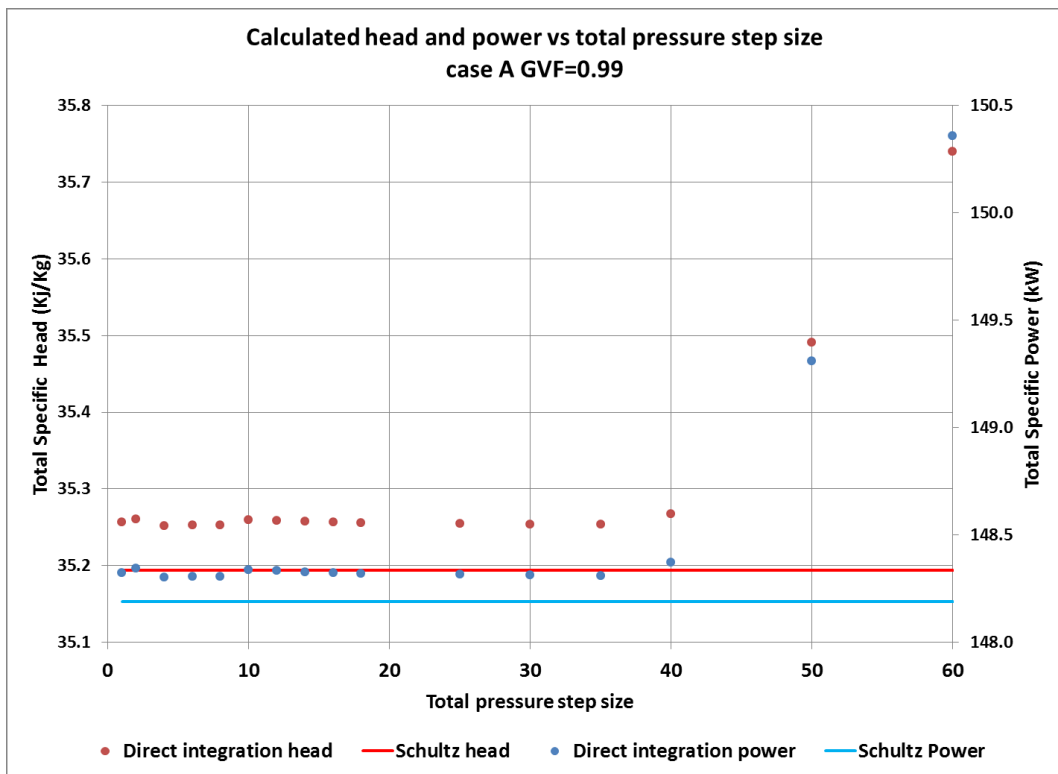
Figure 4.12 Calculated head and power vs total pressure step size, case A GVF = 0.99
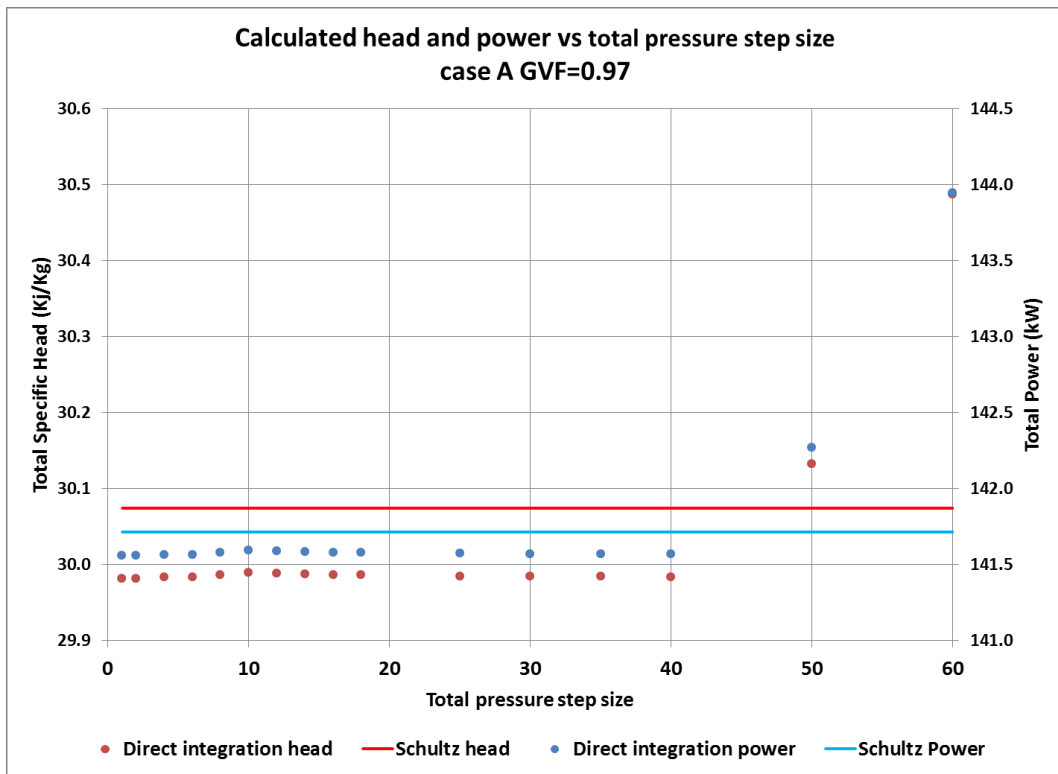
Figure 4.13 Calculated head and power vs total pressure step size, case A GVF = 0.97

Figure 4.14 Calculated head and power vs total pressure step size, case A GVF = 0.96

Figure 4.15 through Figure 4.18 show percentage of calculated specific head at each pressure step relative to total specific head for case A. The percentages are calculated by Equation 67 below

Equation 67:

$$head\ percentage = \frac{h_{p,r,i}}{\sum_i h_{p,r,i}}$$

Specific head on each pressure step are calculated by Equation 38. Data from various gas volume fraction and several total pressure step size (6, 8, and 10) also shown in the figures.
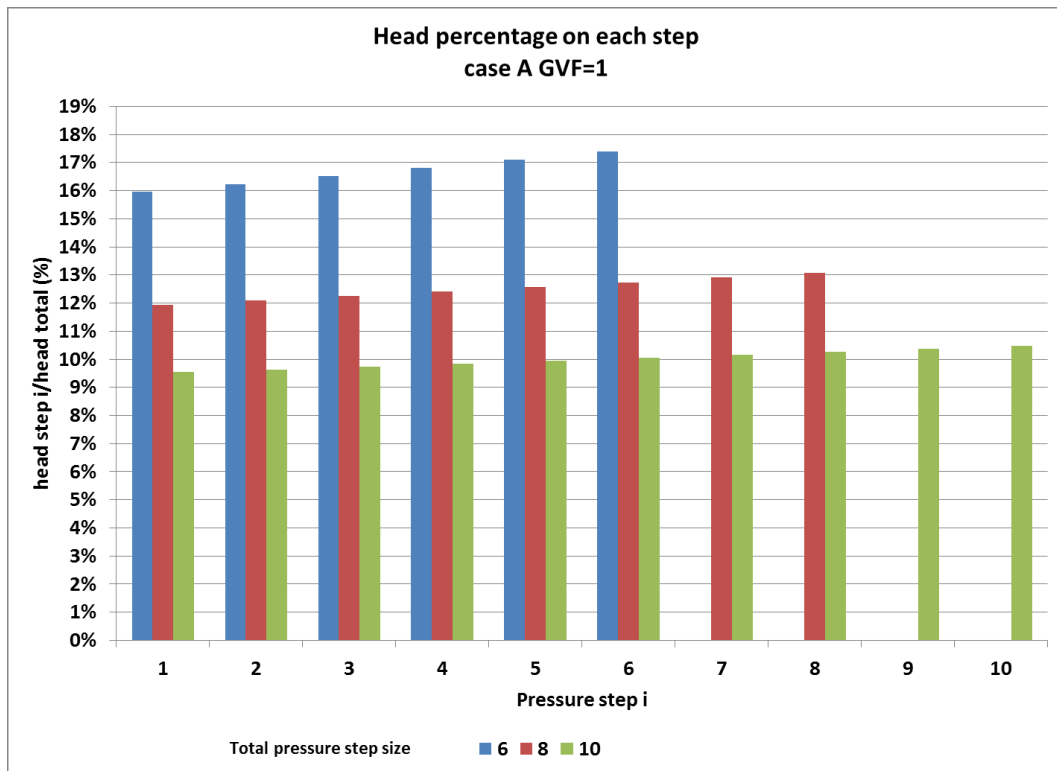
Figure 4.15 Percentage of head on each pressure step i, case A GVF = 1
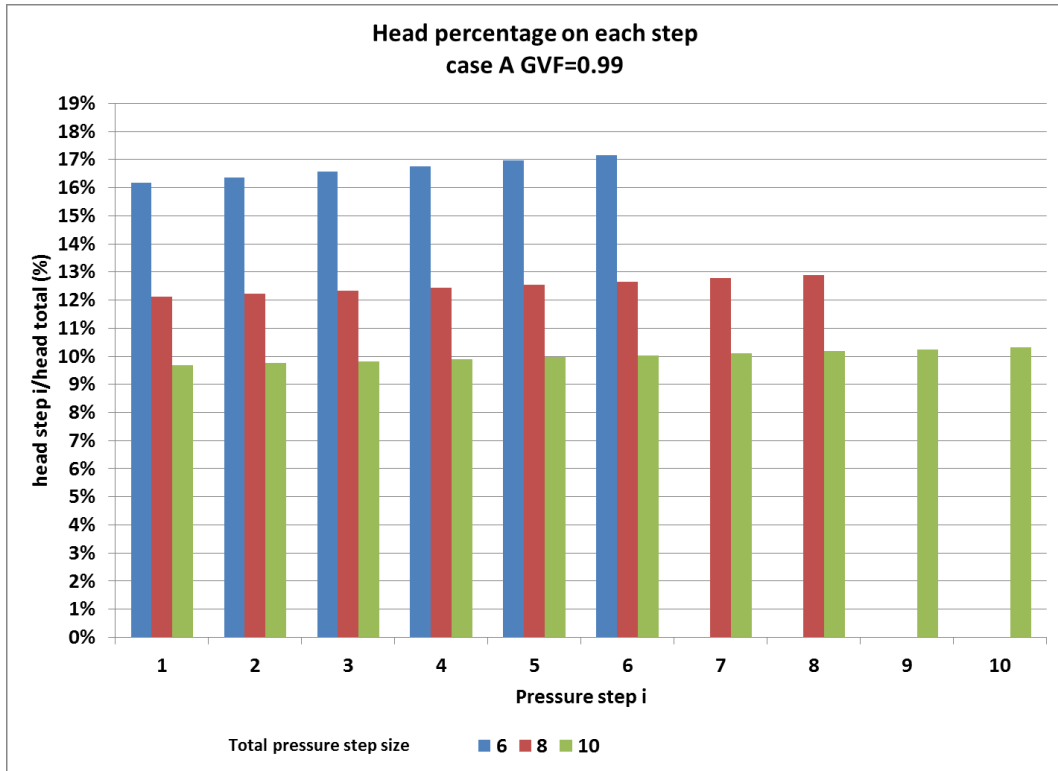
Figure 4.16 Percentage of head on each pressure step i, case A GVF = 0.99
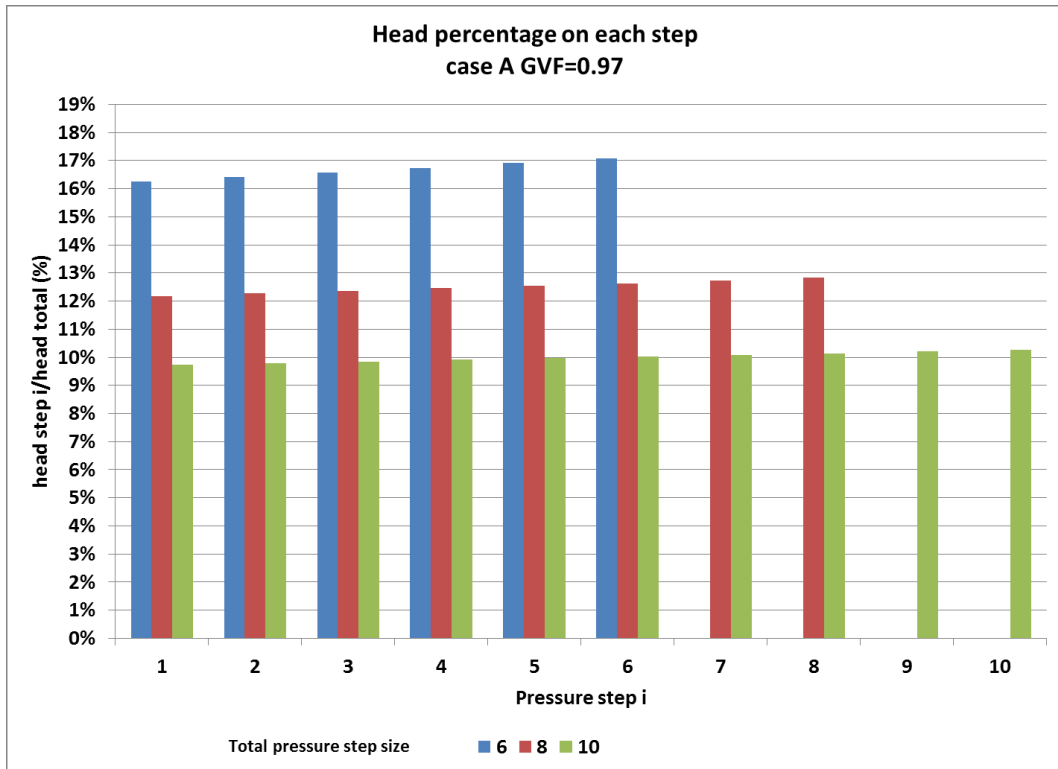
Figure 4.17 Percentage of head on each pressure step i, case A GVF = 0.97
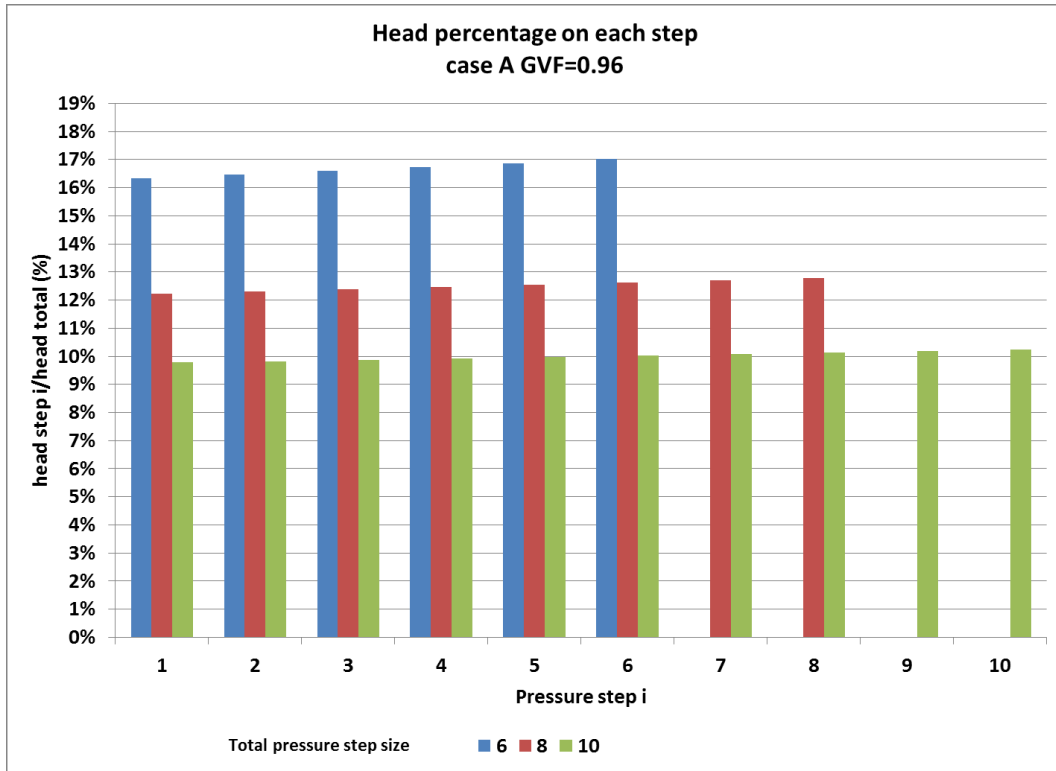
Figure 4.18 Percentage of head on each pressure step i, case A GVF = 0.96

4.2. Case B

In case B, compressor curve map is an input and actual condition are different from test reference condition (see Table 5 and Table 7). The compressor curve map needs to be corrected first before used as calculation. Figure 4.19 through Figure 4.22 show the original compressor curve map and corrected compressor curve map for various GVF (GVF=1, GVF=0.99, GVF=0.97, and GVF=0.96). Compressor curve map corrected using dimensional analysis method and iterative method described in section 2.7.1 and 2.7.2.
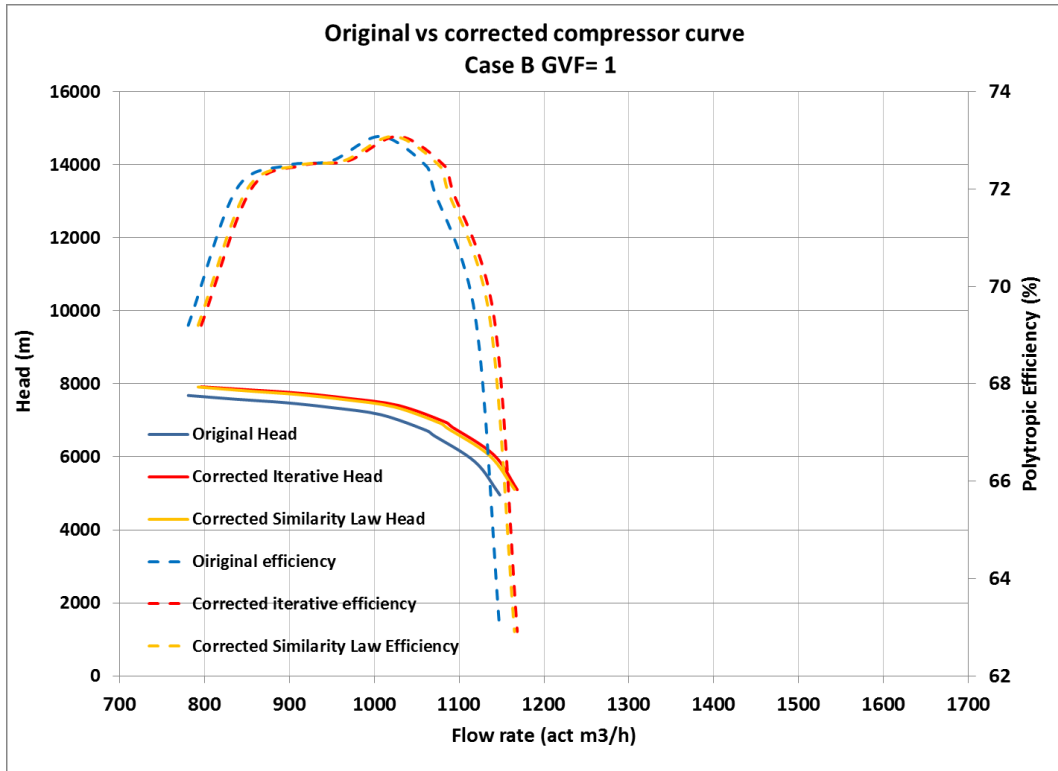
Figure 4.19 Original vs corrected compressor curve, case B GVF = 1
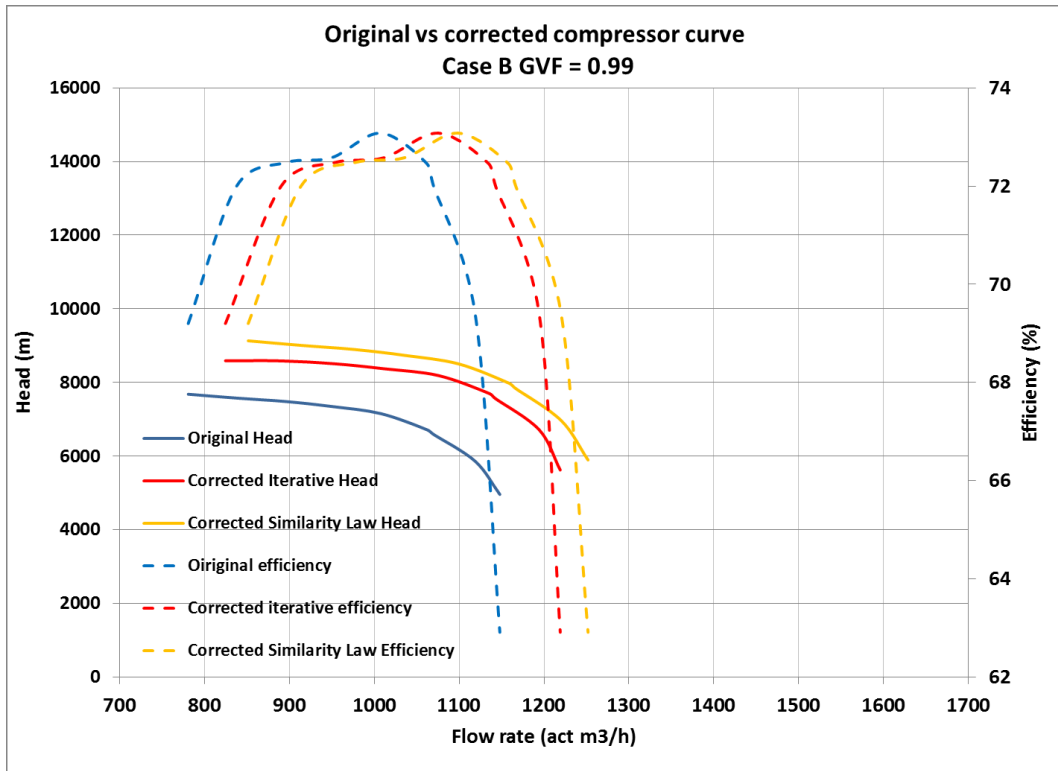
Figure 4.20 Original vs corrected compressor curve, case B GVF = 0.99
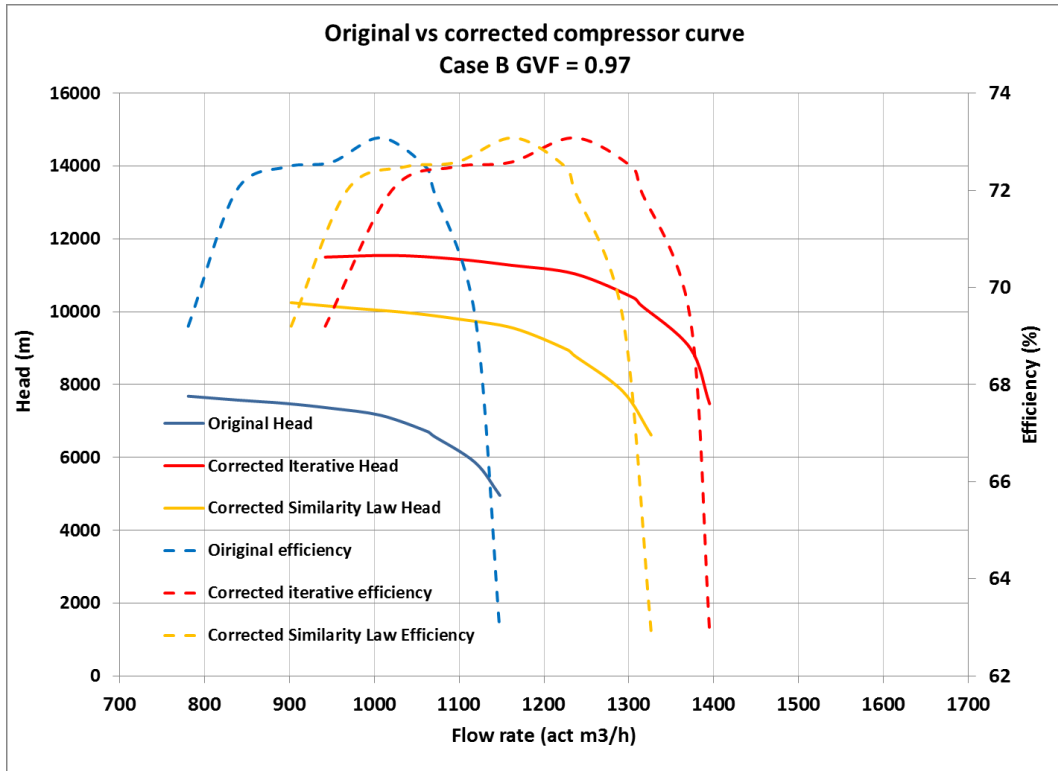
Figure 4.21 Original vs corrected compressor curve, case B GVF = 0.97
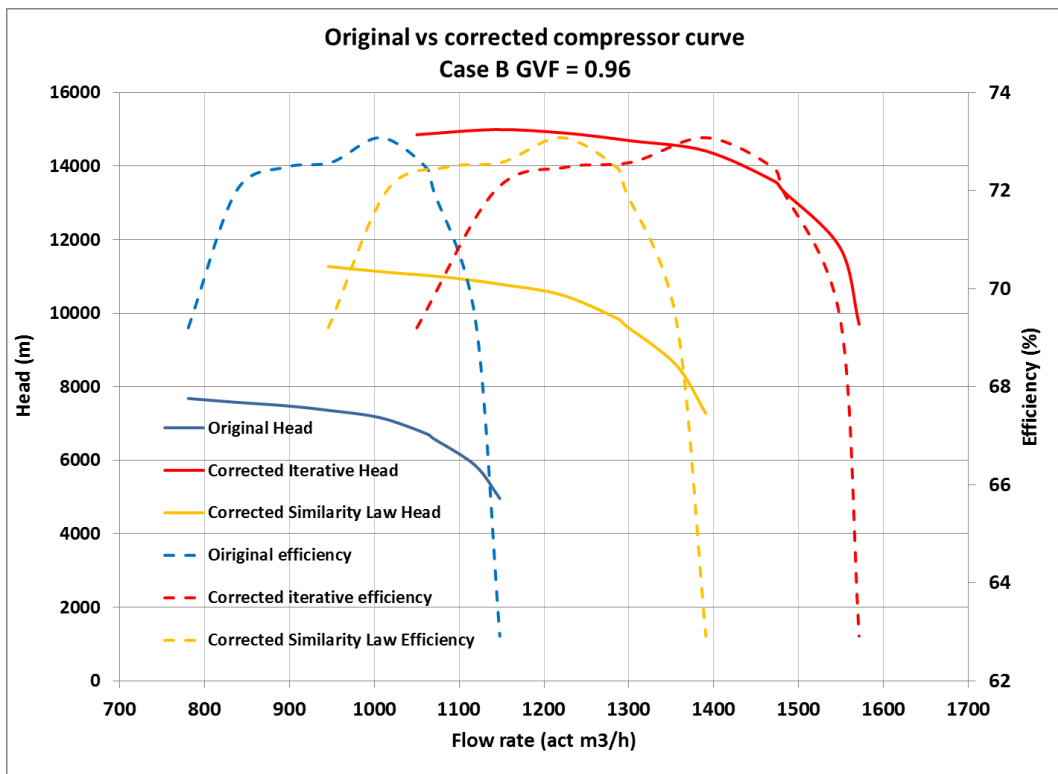
Figure 4.22 Original vs corrected compressor curve, case B GVF = 0.96

54

Figure 4.23 shows compression process path calculated using corrected compressor curve with direct integration method. Fluid compressed from initial pressure of 500 psia into final pressure. In the figure, compression processes of four different fluid properties (gas volume fraction) are shown. Data shown in the figure are for direct integration method with total pressure step size of 1, 10, and 25. Schultz compression path also shown in the figure.
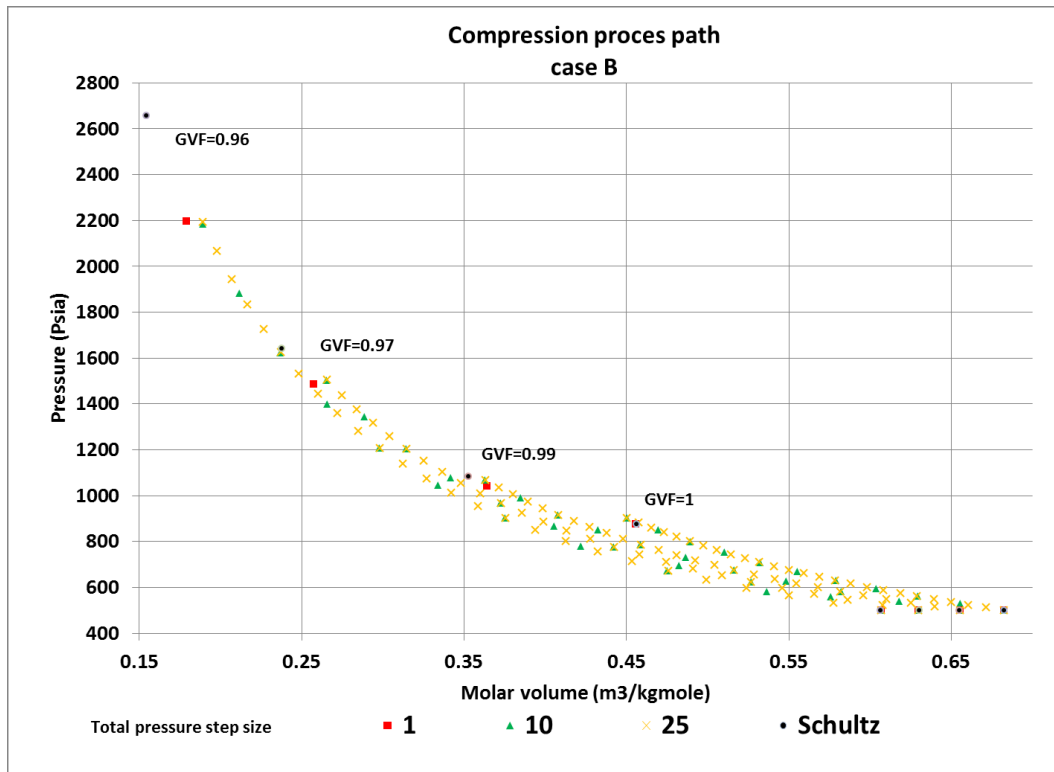
Figure 4.23 Compression process path at various GVF for case B

Figure 4.24 shows fluid properties (gas volume fraction) change on each pressure step as the fluid compressed from initial pressure into final pressure for case B. Data in the graph calculated by direct integration method with total pressure step size of 10. Four initial gas volume fraction (GVF=1, GVF= 0.99, GVF=0.97, and GVF=0.96) cases also shown in the figure.
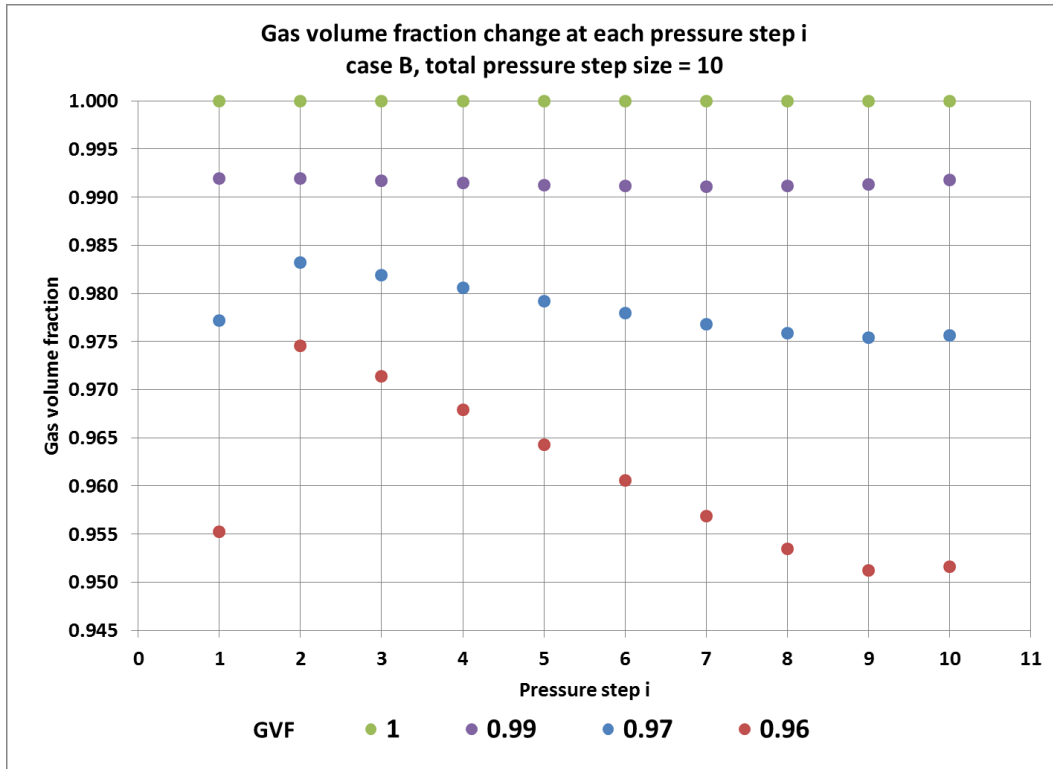
Figure 4.24 Gas volume fraction change at each pressure step i with total number of pressure step = 10 for case B

Figure 4.25 through Figure 4.28 show polytropic exponent on each pressure step size for case B. The data show calculation result using direct integration method at total pressure step size of 1, 4, 10, and 18. Four different fluid properties (GVF=1, GVF=0.99, GVF=0.97, GVF=0.96) calculation result also shown in the graphs. In addition, Schultz polytropic exponent also show in the figure.
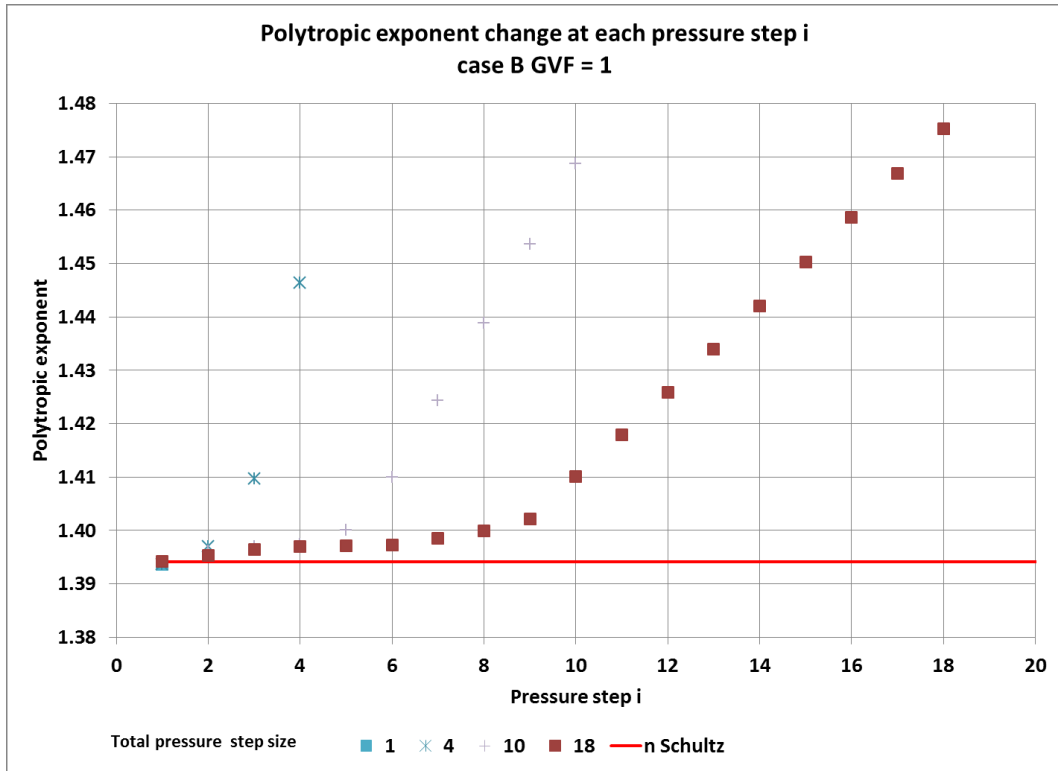
Figure 4.25 Polytropic exponent change at each pressure step i, case B GVF = 1
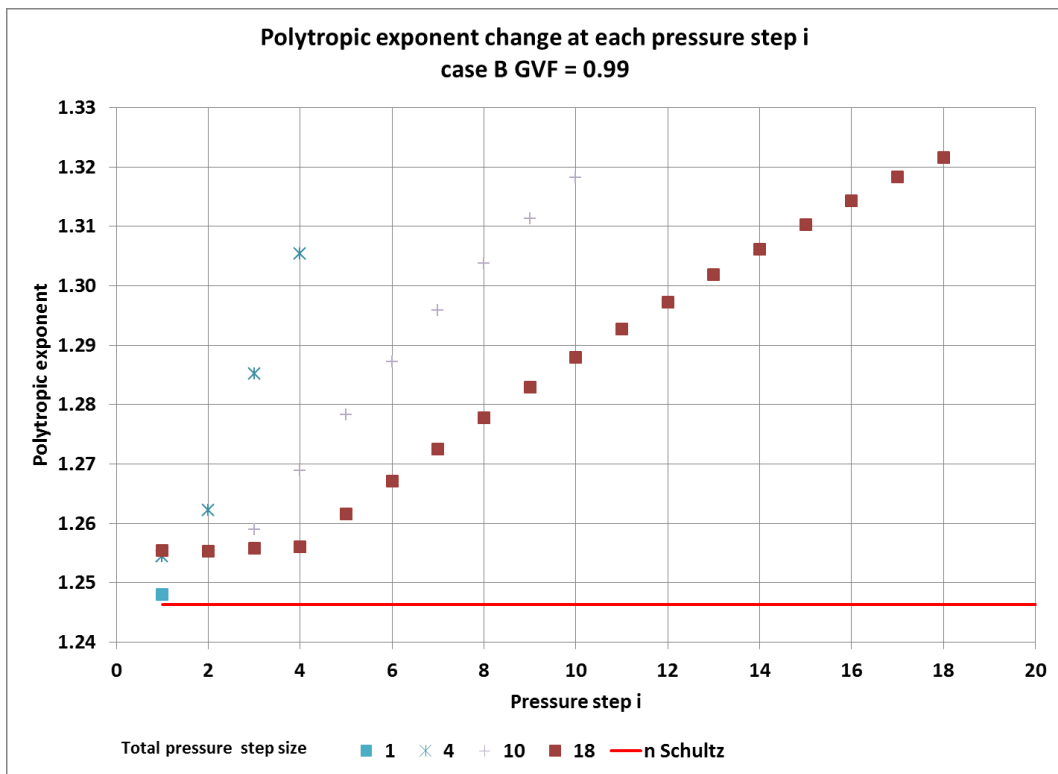
Figure 4.26 Polytropic exponent change at each pressure step i, case B GVF = 0.99
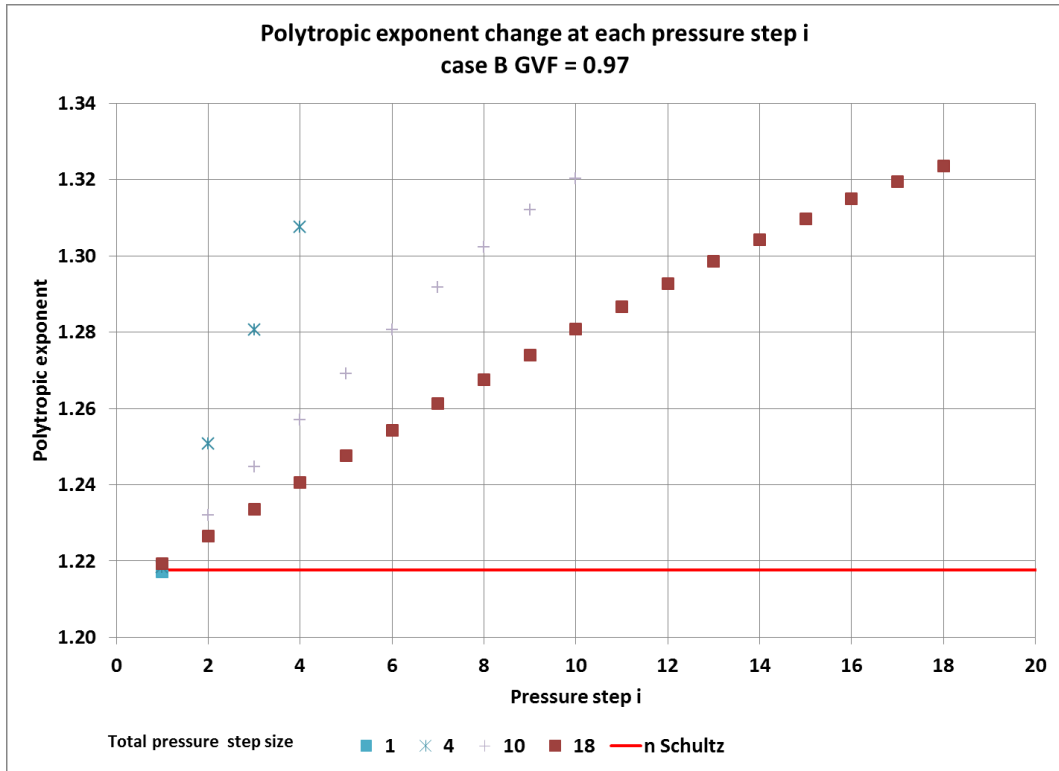
Figure 4.27 Polytropic exponent change at each pressure step i, case B GVF = 0.97
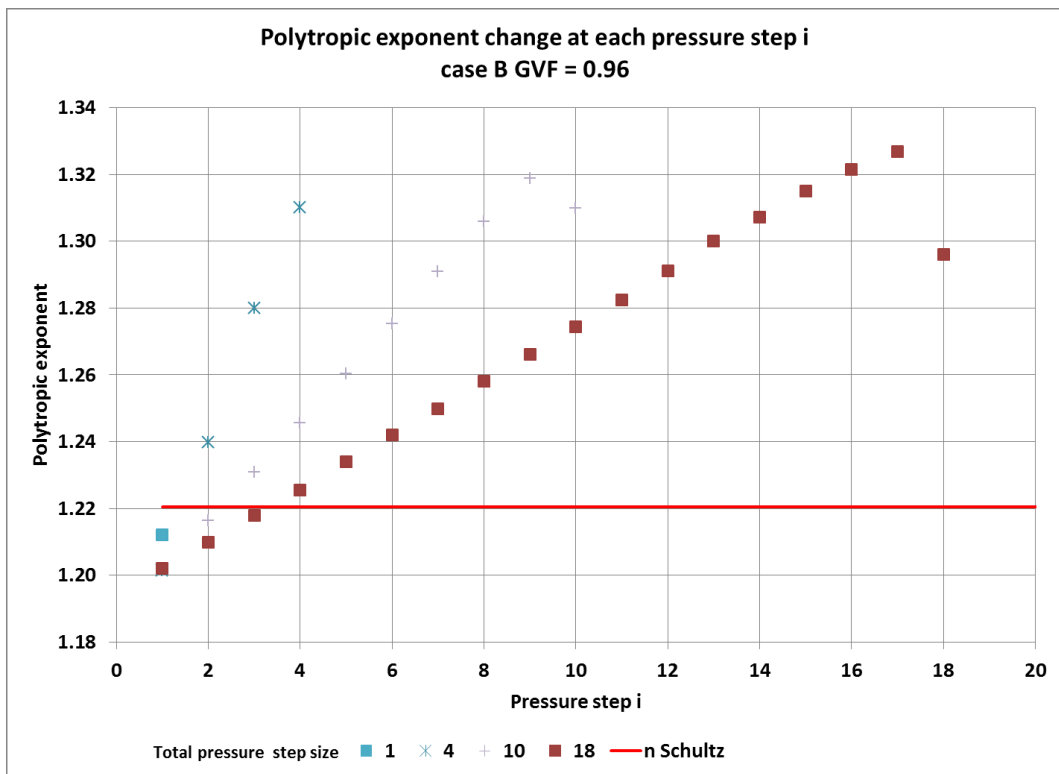
Figure 4.28 Polytropic exponent change at each pressure step i, case B GVF = 0.96

58

Figure 4.29 through Figure 4.32 show calculated error using Equation 66 with various initial gas volume fraction (GVF=1, GVF=0.99, GVF=0.97, GVF=0.96). The abscissa in the figure is total pressure step size. The ordinate show calculated error and total specific head calculated by direct integration method.
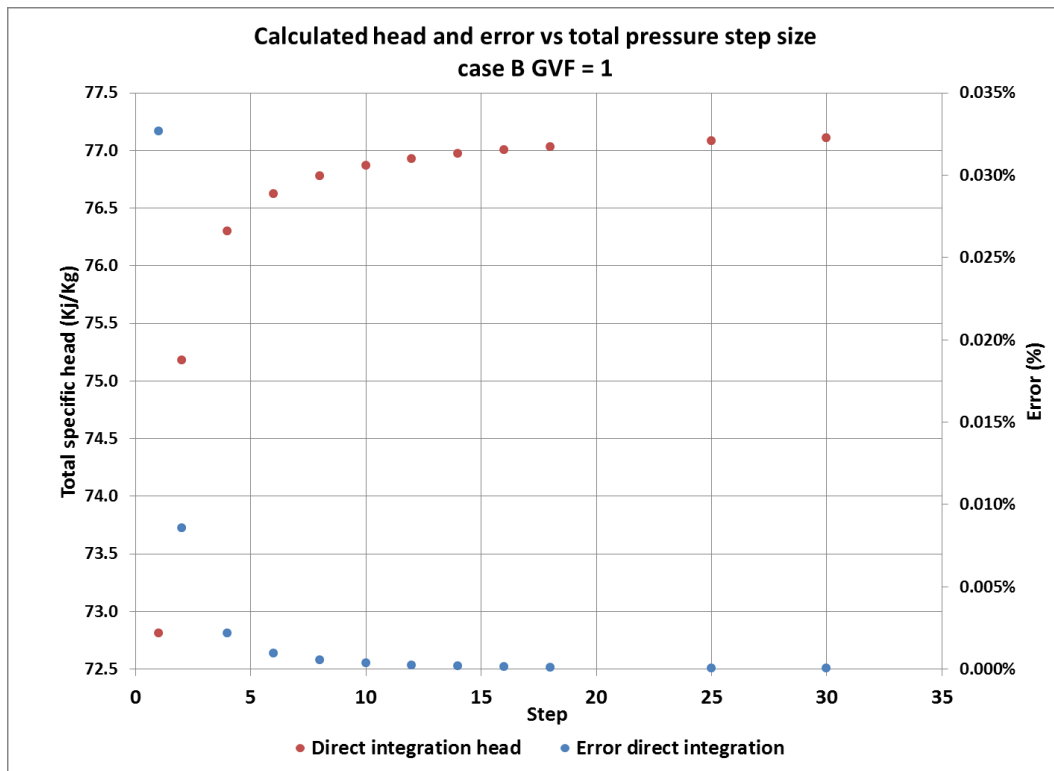
Figure 4.29 Calculated head and error vs total pressure step size, case B GVF = 1
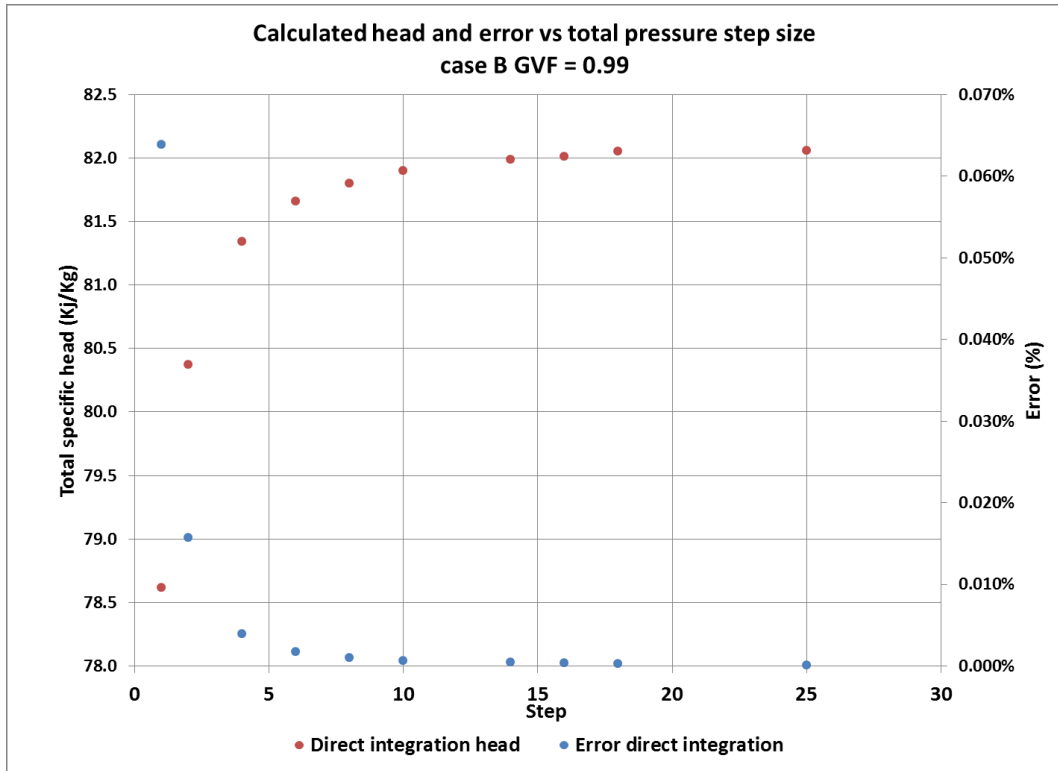
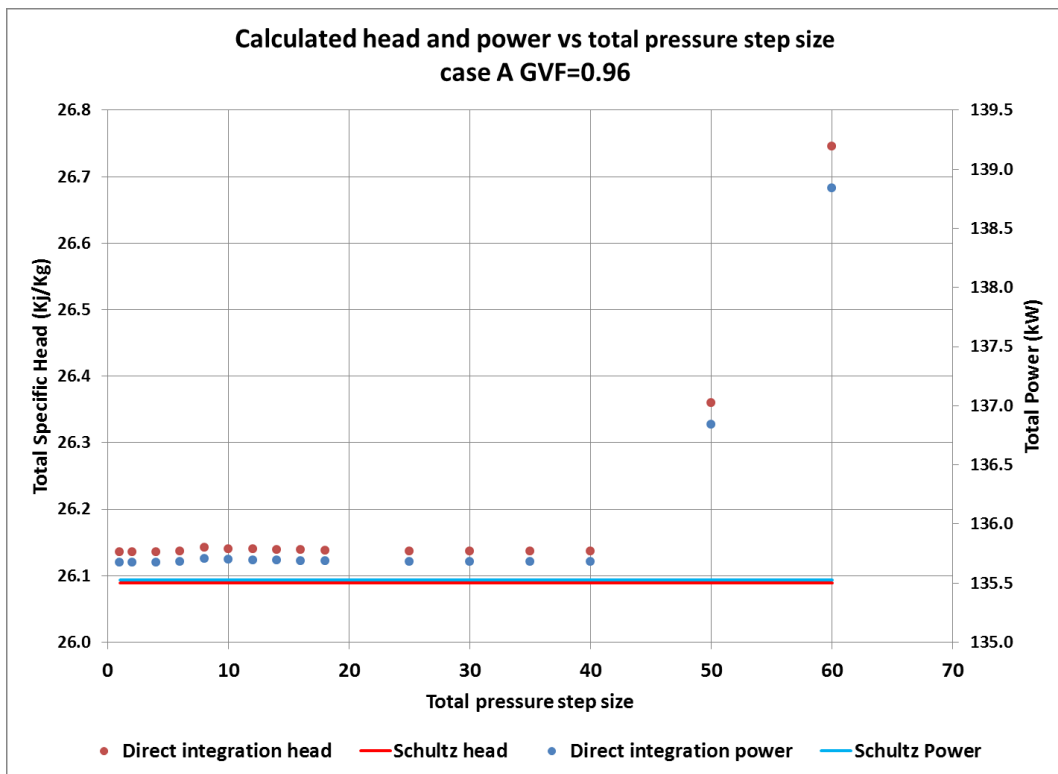**Figure 4.30 Calculated head and error vs total pressure step size, case B GVF = 0.99**
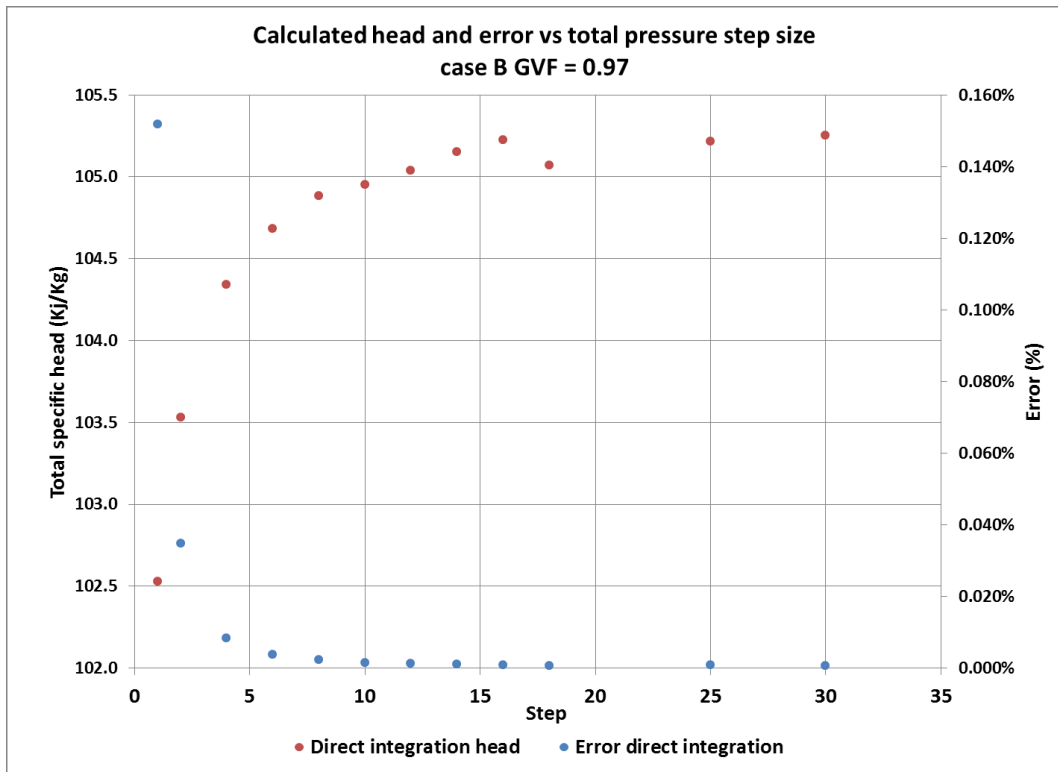
**Figure 4.31 Calculated head and error vs total pressure step size, case B GVF = 0.97**

60
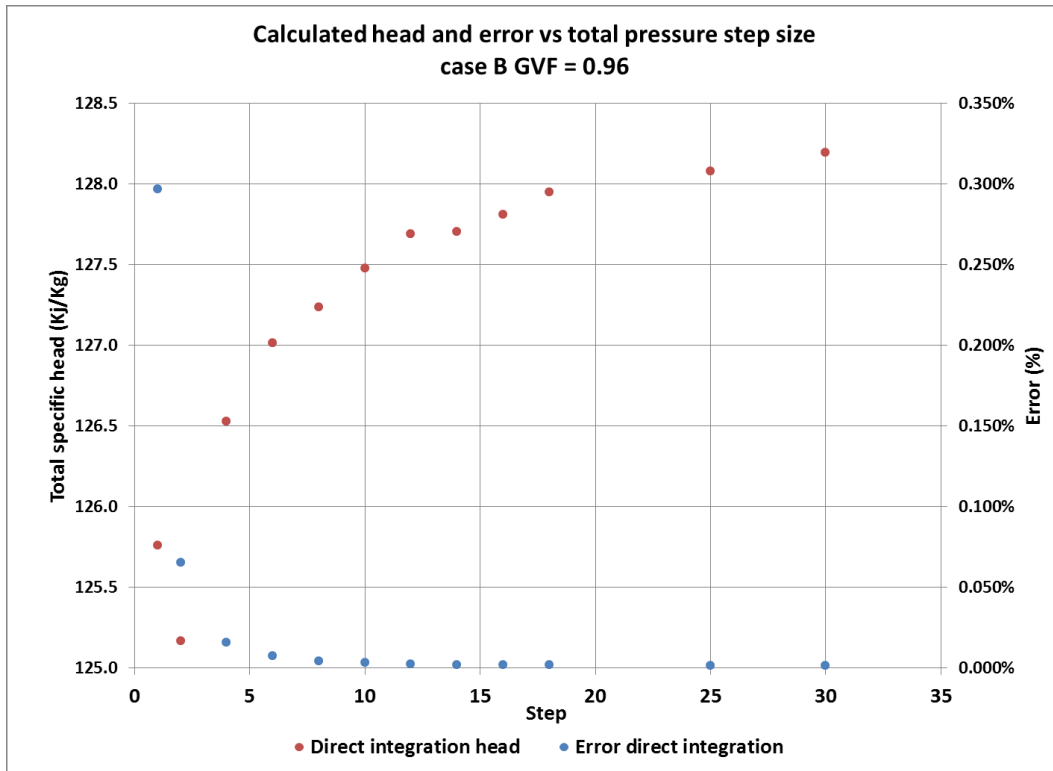
Figure 4.32 Calculated head and error vs total pressure step size, case B GVF = 0.96

Figure 4.33 through Figure 4.34 shows calculated total specific head and power using direct integration method and Schultz method for case B. Calculated data using four initial gas volume fractions are also shown in the figures. The abscissa show total pressure step size in direct integration method. The ordinate show total specific head and power required to compress the fluid. Calculated compressor performance using Schultz method shown as a line in the figure as comparison purpose only. Actually, Schultz method is not a function of total pressure step size.

61
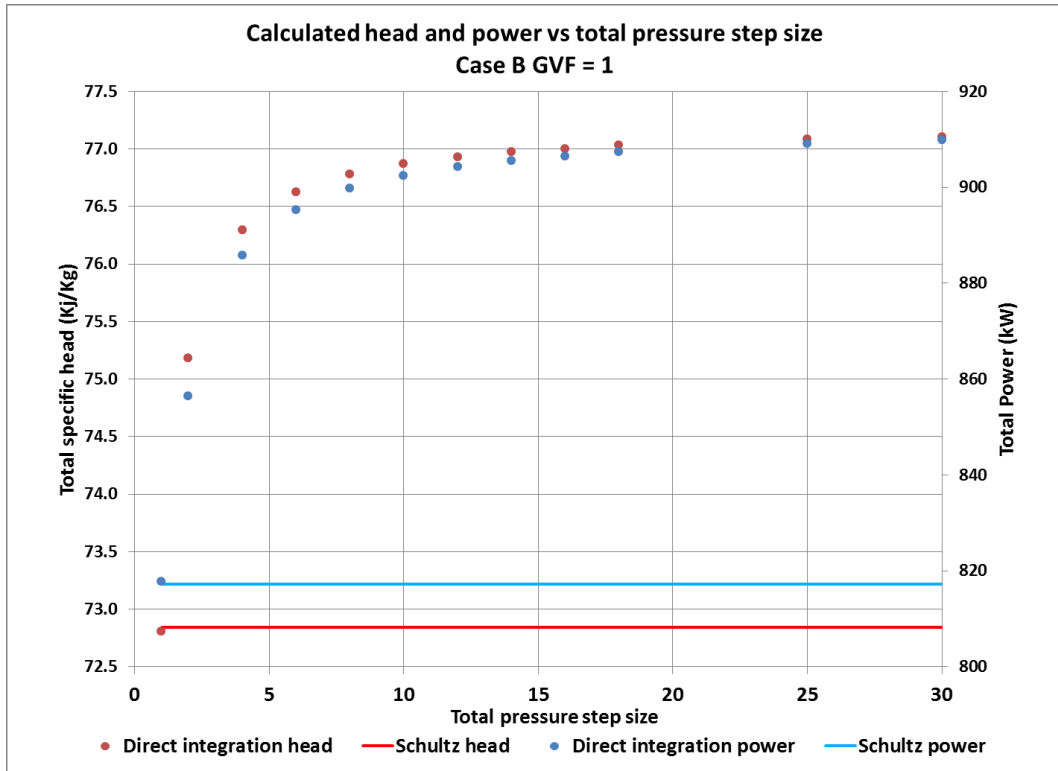
Figure 4.33 Calculated head and power vs total pressure step size, case B GVF = 1
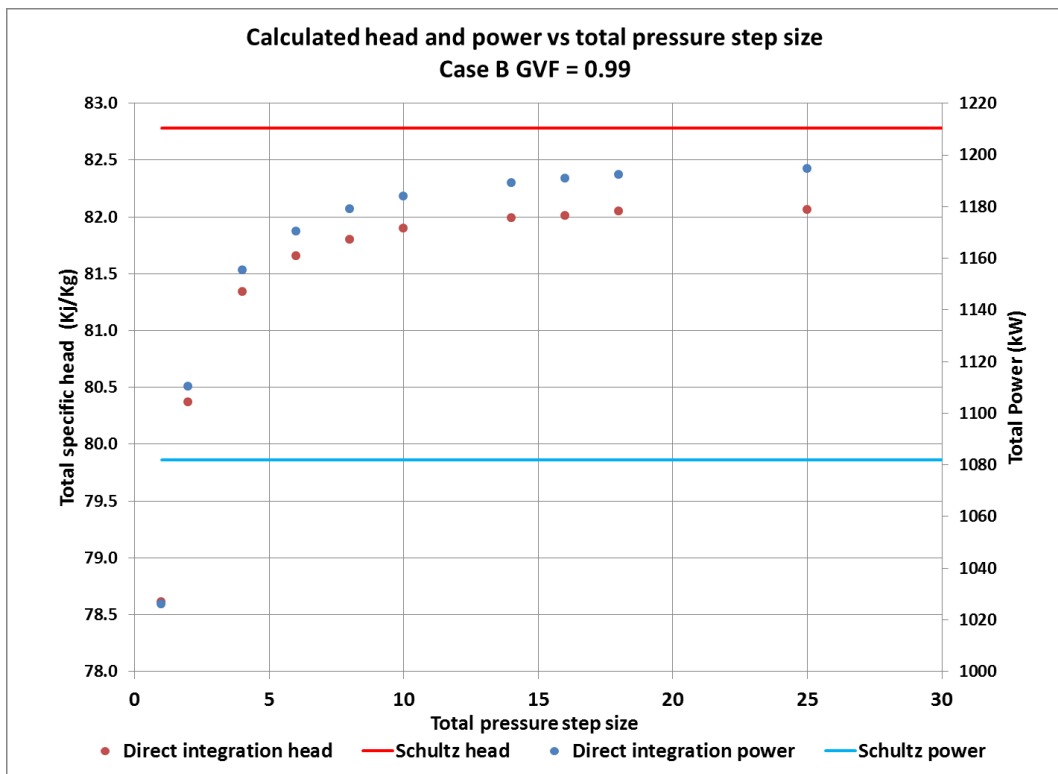
Figure 4.34 Calculated head and power vs total pressure step size, case B GVF = 0.99
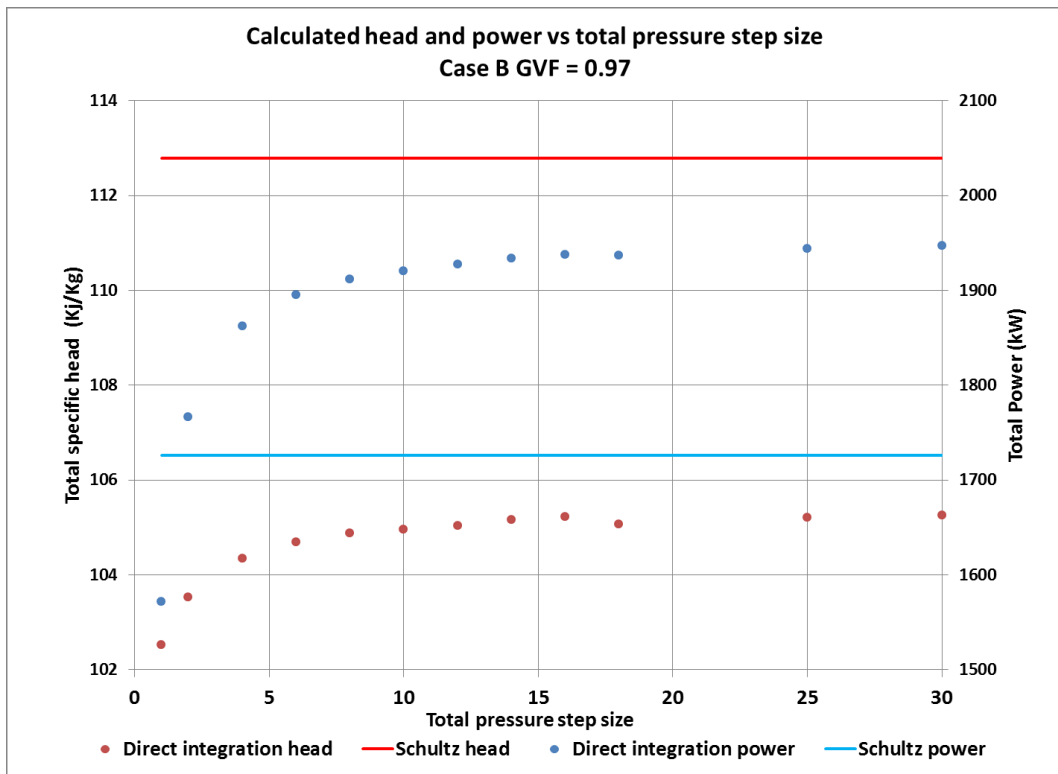
Figure 4.35 Calculated head and power vs total pressure step size, case B GVF = 0.97
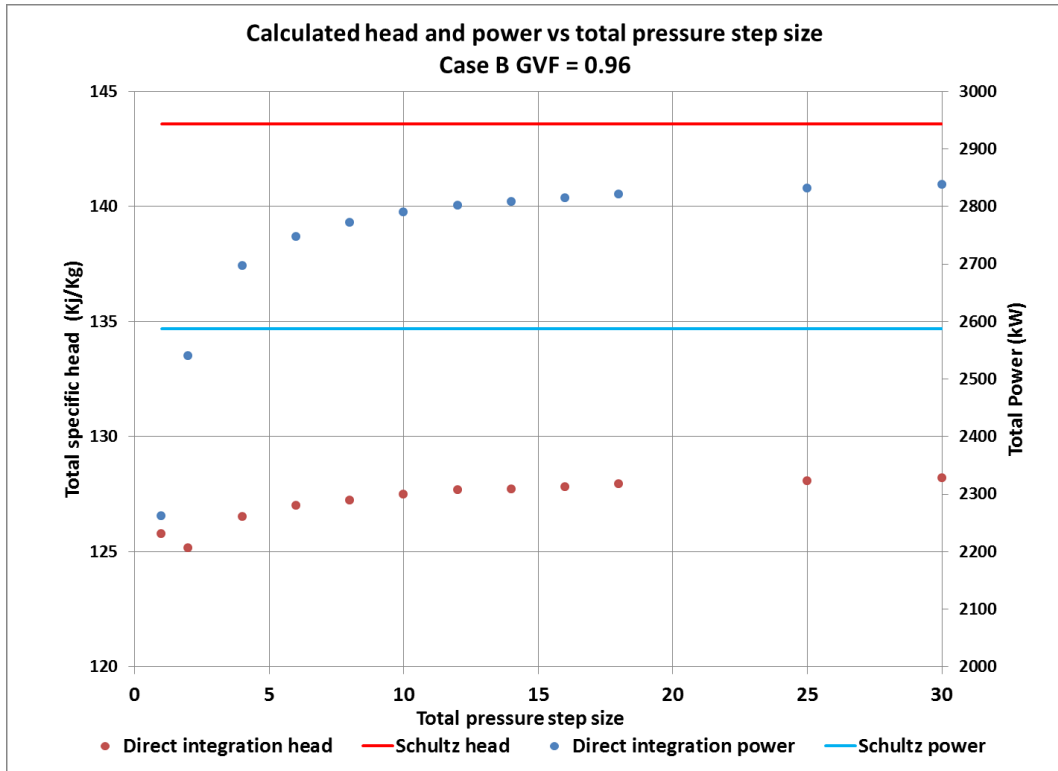
Figure 4.36 Calculated head and power vs total pressure step size, case B GVF = 0.96

Figure 4.37 through Figure 4.40 show head percentage on each step calculated by Equation 67 for various gas volume fraction (GVF=1, GVF=0.99, GVF=0.97, GVF=0.96). Data shown in the figure are calculated from direct integration method with total pressure step size of 6, 8, and 10.
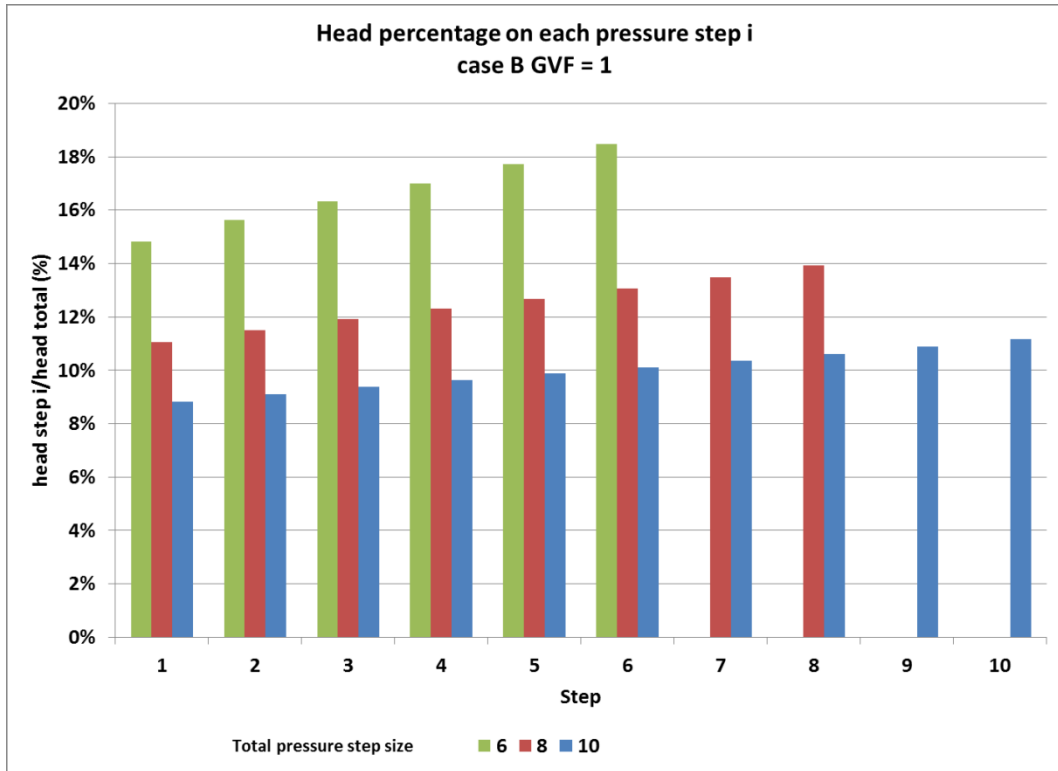
Figure 4.37 Percentage of head on each pressure step i, case B GVF = 1
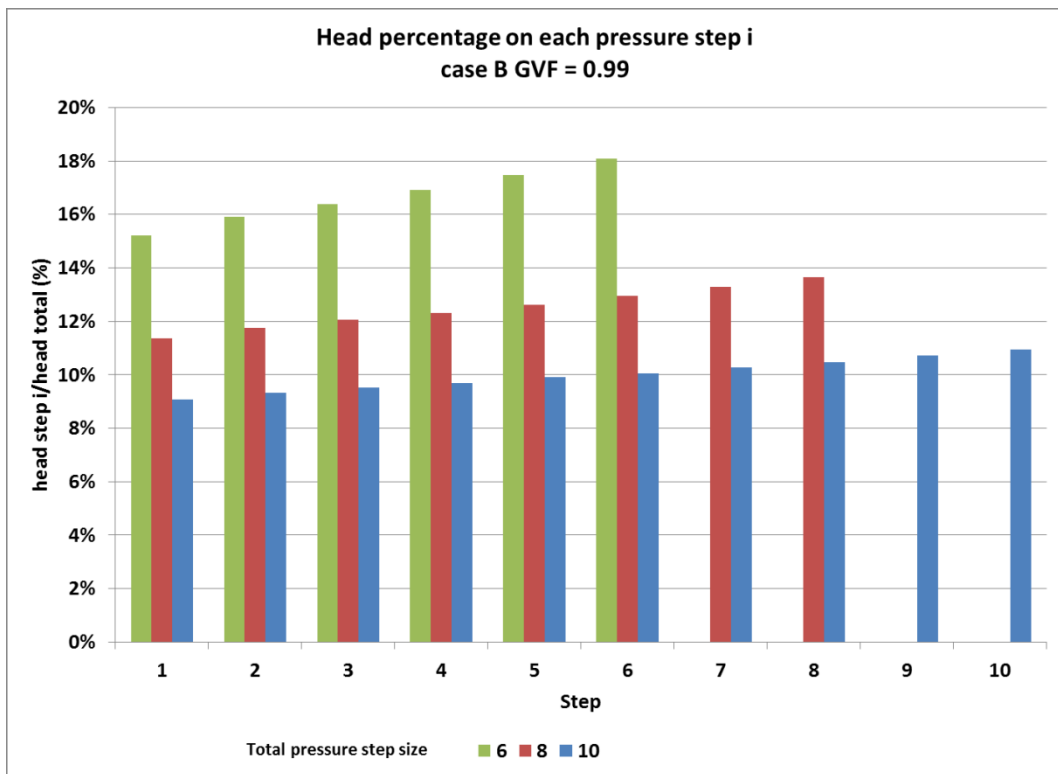
Figure 4.38 Percentage of head on each pressure step i, case B GVF = 0.99
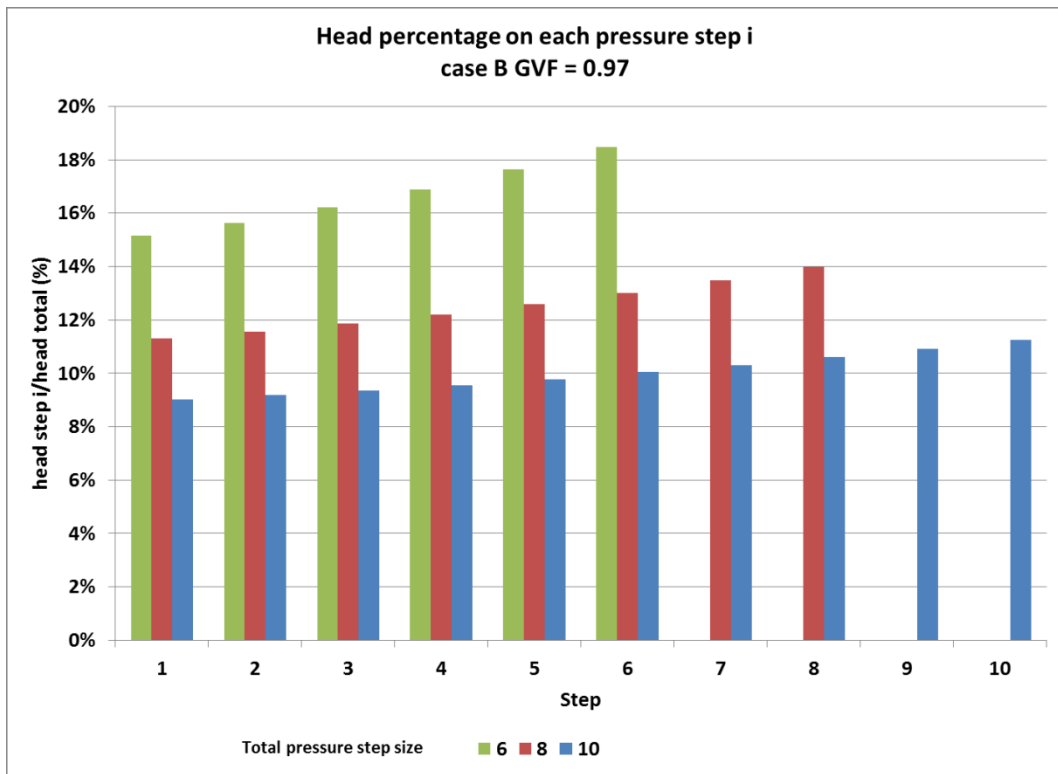
Figure 4.39 Percentage of head on each pressure step i, case B GVF = 0.97
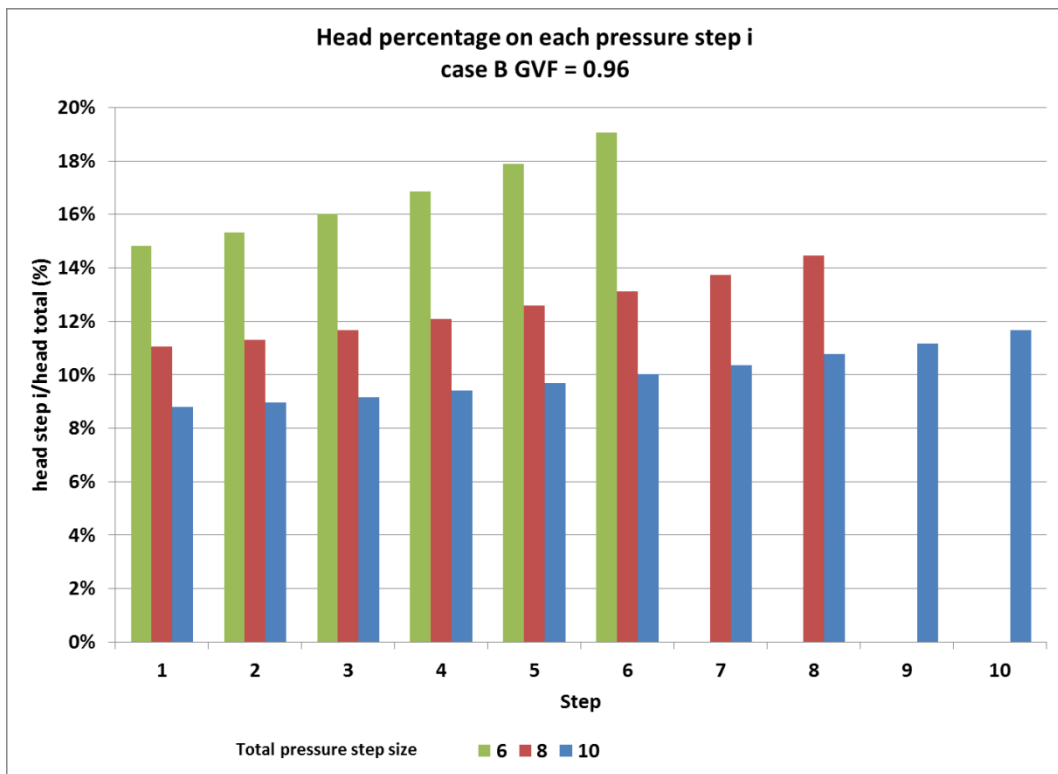
Figure 4.40 Percentage of head on each pressure step i, case B GVF = 0.96

Table 8 and Table 9 show summary of compressor performance for case A and case B. Direct integration method data are shown using total pressure step size of 10. The head and power difference between Schultz method and direct integration method calculated by using the following equations Equation 68 and Equation 69

Equation 68:

$$\Delta_{head\ Schultz-direc\ integration} = \frac{h_{p,S} - \sum_{i=1}^{10} h_{p,r,i}}{\sum_{i=1}^{10} h_{p,r,i}}$$

Equation 69:

$$\Delta_{power\ Schultz-direc\ integration} = \frac{HP - \sum_{i=1}^{10} HP_{r,i}}{\sum_{i=1}^{10} HP_{r,i}}$$

Table 8 Summary case A

Parameter	Method	Total pressure step size (For direct integration method)	Case A			
			GVF=1	GVF=0.99	GVF=0.97	GVF=0.96
Total specific head (Kj/Kg)	Direct integration	10	43.3	35.3	30.0	26.1
	Schultz	-	43.2	35.2	30.1	26.1
Power (kW)	Direct integration	10	157.5	148.3	141.6	135.7
	Schultz	-	157.5	148.2	141.7	135.5
Δ specific head Schultz−direct integration (%)	-	-	-0.02%	-0.19%	0.28%	-0.20%
Δ power Schultz−direct integration (%)	-	-	-0.01%	-0.10%	0.08%	-0.13%

Table 9 Summary case B

Parameter	Method	Total pressure step size (For direct integration method)	Case B			
			GVF=1	GVF=0.99	GVF=0.97	GVF=0.96
Total specific head (Kj/Kg)	Direct integration	10	76.9	81.9	105.0	127.5

	Schultz	-	72.8	82.8	112.8	143.6
Power (kW)	Direct integration	10	902.4	1184.0	1920.7	2789.4
	Schultz	-	817.1	1081.9	1725.8	2587.3
Δ specific head Schultz−direct integration (%)	-	-	-5.24%	1.08%	7.46%	12.63%
Δ power Schultz−direct integration (%)	-	-	-9.45%	-8.63%	-10.15%	-7.24%

Table 10 and Table 11 show result of compression of wet gas using separator and without separator as in Figure 3.5 and Figure 3.6. For case A, the difference between wet gas compression with separator and without separator are calculated by Equation 70 below

Equation 70:

$$\Delta_{power\ with\ separator-without\ separator} = \frac{HP_{without\ separator} - HP_{with\ separator}}{HP_{with\ separator}}$$

Table 10 Comparison of wet gas compression using separator and without separator (case A)

CASE A					
Gas volume fraction			GVF=0.99	GVF=0.97	GVF=0.96
power (kw)	Use separator	Compressor (vapour 100%)	149	141	134
		Pump (liquid 100%)	2	4	6
		Total	151	146	140
	Without separator	Total	148	142	136
Δ power seprator-without separator (%)			-2%	-3%	-3%

Table 11 Comparison of wet gas compression using separator and without separator (case B)

CASE B					
Gas volume fraction			GVF=0.99	GVF=0.97	GVF=0.96
power (kw)	Use separator	Compressor (vapour 100%)	910	1242	1616
		Pump (liquid 100%)	10	20	30
		Total	920	1263	1646
	Without separator	Total	1082	1726	2587
Δ power seprator-without separator (%)			18%	37%	57%

5. DISCUSSION

Figure 4.19 through Figure 4.22 show that as gas volume fraction decrease, corrected head for case B increased and the deviation between dimensional analysis methods with iterative method increasing. As gas volume fraction decrease, molecular weight increase (more liquid present in the mixture). Increasing molecular weight relative to test reference condition will lead to increasing head, which is consistent with Figure 2.12. Correction method using dimensional analysis and iterative method give different result as molecular weight increase. This is because of fluid in test reference condition is using dry gas composition. As gas molecular weight increase, the molecular weight difference between actual and test reference condition become larger. And both methods may not be accurate for large deviation.

From pressure-molar volume graph in Figure 4.1 and Figure 4.23 (case A and B) it can be seen that as gas volume fraction decrease, the compression path move to the left. This is because the presence of hydrocarbon liquid which is heavier (high density) than gas at the same pressure and temperature.

Figure 4.1 also show that there is no visible difference of compression path in case A using different total pressure step size (1, 10, and 60) and Schultz method.

For case B in Figure 4.23, final compressor outlet pressure increases with decreasing gas volume fraction. This is because of in case B, corrected curve head is higher at low gas volume fraction. Thus, it will give higher compressor discharge pressure. The presence of liquid also increase discharge pressure.

As can be seen in Figure 4.2 and Figure 4.24 (case A and B), gas volume fraction (GVF) is decreasing with increasing pressure step size at initial gas volume fraction less than 1. This event can be described in Figure 5.1 and Figure 5.2. The figures show compression process path in a pressure-volume diagram with bubble point and dew point line. It can be seen that as the pressure increase, fluid states move closer to the bubble point line. Therefore, an increase in liquid content is expected.
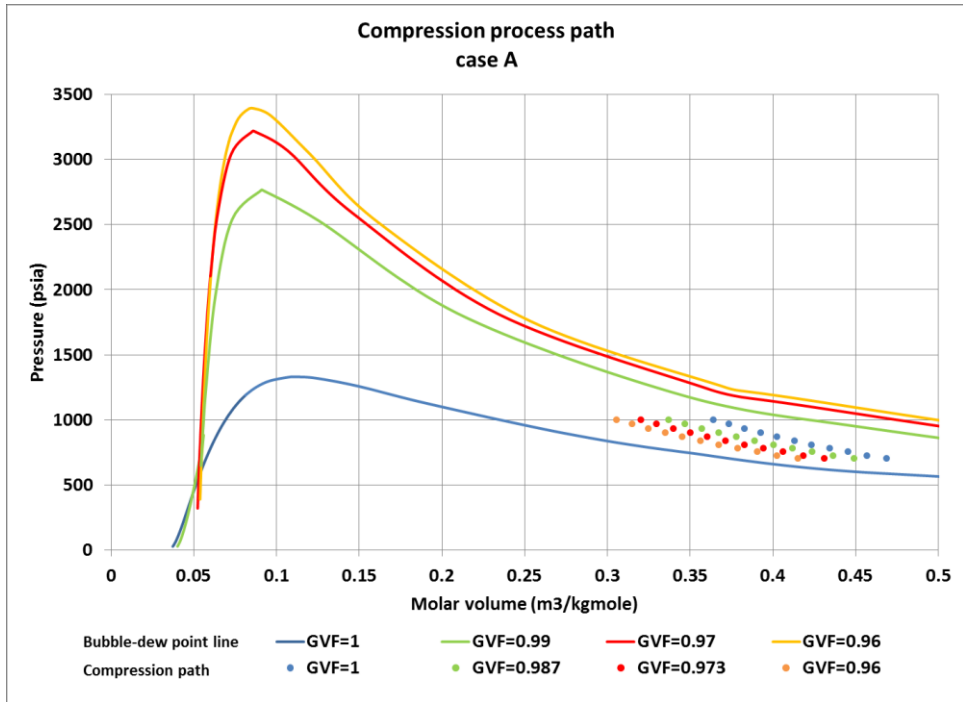
Figure 5.1 Compression process path case A with bubble point and dew point line
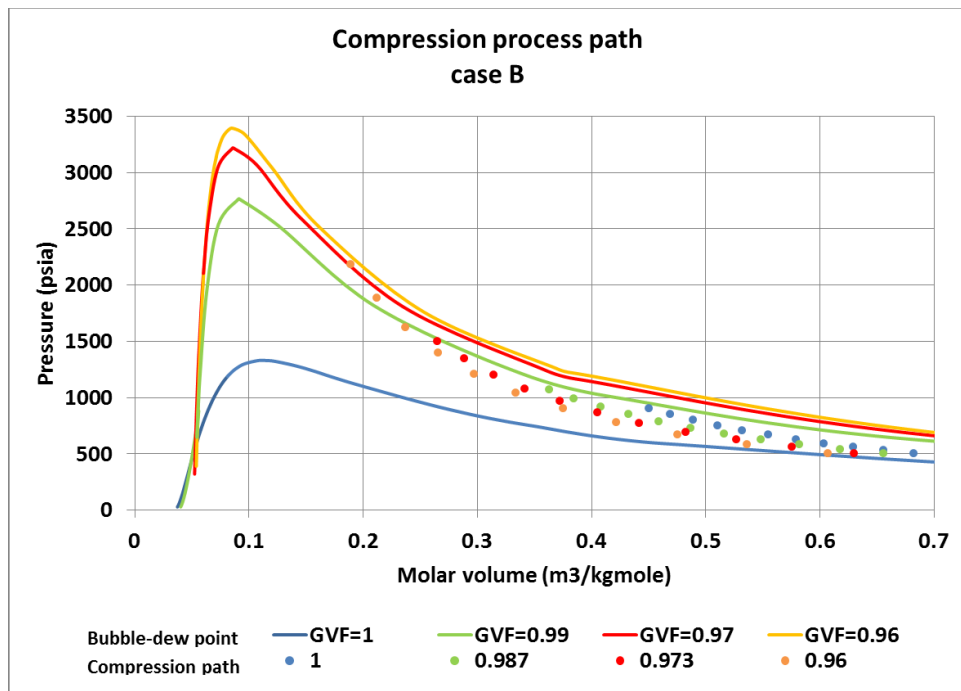
Figure 5.2 Compression process path case B with bubble point and dew point line

Figure 4.2 and Figure 4.24 (case A and B) also shows that the change in gas volume fraction is bigger at lower GVF. At lower gas volume fraction, polytropic exponent values become smaller (See Figure 4.3 through Figure 4.6 for case A and Figure 4.25 through Figure

4.28 for case B). Lower polytropic exponent implies higher molar volume change as pressure change (See Figure 5.3). Accordingly, the fluid state moves faster into bubble point line (lower gas volume fraction/higher liquid content).
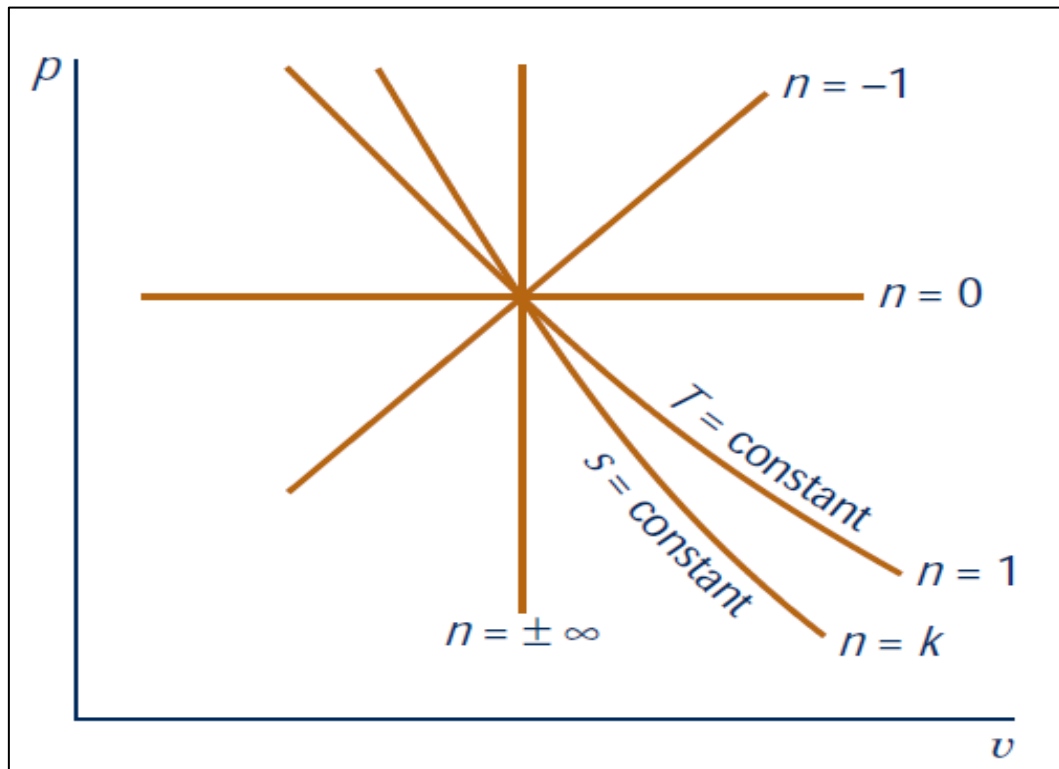
Figure 5.3 Polytropic exponent in a p-v diagram (Courtesy of Moran et al., 2010)

Figure 4.3 through Figure 4.6(case A) and Figure 4.25 through Figure 4.28(case B) show that polytopic exponent increase as pressure step increases. The increase of polytropic exponent was caused by changing property of fluid as pressure and temperature increase. As discussed before, more liquid will form at higher pressure. Properties of gas and liquid are different, thus it will also contribute to the change of polytropic exponent by altering mixture compressibility.

From Figure 4.7 through Figure 4.10(case A) and Figure 4.29 through Figure 4.32 (case B) show that there is an optimum number of total pressure step size in direct integration method. From section 2.3.3 it is described that Equation 37 and Equation 38 must equal, the difference between the equations was calculated from Equation 66. At low total number of pressure step size, the error calculated by Equation 66 is large (up to 1.5%). It is because the small pressure step size cannot take into account change in fluid properties. But at high

number of pressure step size, the calculated head become divergence because of numerical error (for case A only). From the figures, the optimum number of total pressure step size is equal to 10 (calculated error approaching 0%).

Table 8 show that calculated head decreased with increasing gas volume fraction for case A. As described in section 2.5, factors that causing decrease in head with increasing GVF is evaporate cooling and heat transfer. From Figure 4.2 it is clear that evaporate cooling is occurred as gas compressed. The result of evaporate cooling is decreased temperature with more liquid in fluid mixture as can be seen in Figure 5.4.
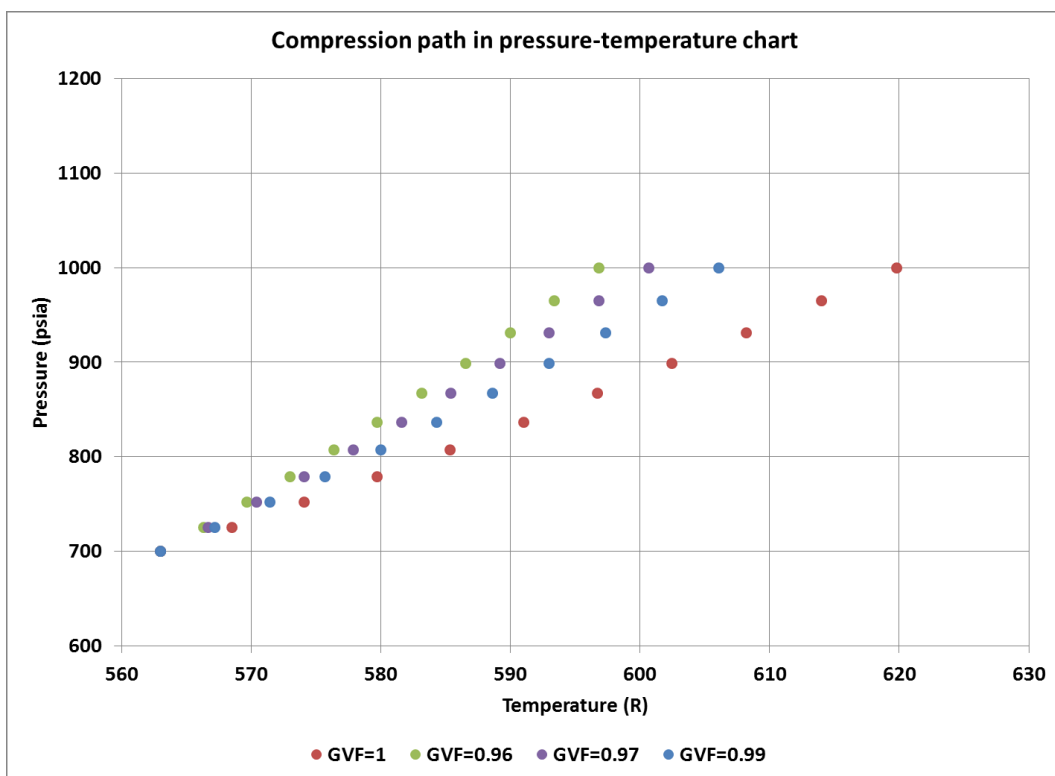
Figure 5.4 Cooling effect in wet gas compression for case A

For case B in Table 9, as gas volume fraction decreased, calculated head is increasing. This is because of in case B, compression ratio becomes higher at low gas volume fraction (see Figure 4.23). Thus it will need more head to compress the fluid.

From Table 8, Table 9, Figure 4.11 through Figure 4.14, and Figure 4.33 through Figure 4.36 show that Schultz method and direct integration head give different results. Schultz method give lower head and power compared to direct integration method except for GVF=0.97. Schultz methods give lower result because polytropic exponent in Schultz is

lower compared to entire direct integration method's polytropic exponent (See Figure 4.3 through Figure 4.6 for case A and Figure 4.25 through Figure 4.28 for case B). But calculated head in Schultz method will be corrected by Schultz correction factor f.

Figure 4.15 through Figure 4.18 (case A) and Figure 4.37 through Figure 4.40 (case B) show that as pressure step increase, calculated head will slightly increase on each pressure step. It is caused by changing fluid properties as pressure and temperature increase. As discussed before, as pressure step increase polytropic exponent will increase. From section 2.2 it is clear that increasing polytropic exponent will increase calculated head.

The results in Table 10 and Table 11 show that HYSYS^{TM} does not calculate wet gas compression where each phase compressed separately using compressor (for vapor) and pump (for liquid) as seen in Figure 3.5. For case A, the difference between compression using separator and without separator is up to -3%. For case B the difference is larger (up to 57%). Therefore, HYSYS^{TM} calculate wet gas compression by considering interaction between liquid and vapor phase.

6. CONCLUSION AND RECOMMENDATION

Compressor performance running at off design condition will have large deviation from original tested performance, therefor it needs correction. The correction can be done by using iterative method or dimensional analysis method. Both methods give the same result if the difference between test condition and actual condition is small. At large difference between actual and reference condition, both method give significantly different result. Accordingly, corrected compressor performance becomes uncertain.

In a wet gas compression, fluid composition is changing as pressure and temperature increase toward discharge pressure. As gas become compressed, more liquid will be presence in the mixture. Gas and liquid have different properties that will affect mixture properties. This condition will alter compressor performance.

The presence of liquid in compressor will reduce specific head of the compressor. Specific head reduced because of liquid having higher density compared to gas. Another factor that reduces compressor specific head is evaporate cooling and heat transfer effect. The presence of liquid will cool off the fluid since it has high heat capacity.

Direct integration method is much more appropriate for application in wet gas compression compared to Schultz. This is due to changing fluid properties as wet gas compressed. The direct integration method calculation will take consideration of changing fluid properties as pressure goes up. In Schultz method, fluid properties change does not completely taken into account. It only uses average fluid properties and add Schultz correction factor.

There is an optimum number of total pressure step size in calculation using direct integration method. If the pressure step size is too low, compressor performance accuracy is low because of changing fluid properties does not well represented in the calculation. If the total pressure step size is too high, there will be numerical error. The optimum number of total pressure step size is when head calculated by enthalpy difference and head calculated by molar volume- pressure is nearly equal.

HYSY^{TM} software calculates wet gas compression performance by considering interaction between liquid and gas phase. This statement proved by separating gas and liquid before fluid compressed. Then the result compared with compression of wet gas without prior

separation. The result between case with separator and without separator gives large difference.

It would be interesting to compare calculated performance using direct integration method with actual wet gas compression experiment. By comparing compressor performance calculation with real data, the accuracy of direct integration method will be discovered. The experiment result will become foundation in wet gas compression calculation.

Another improvement that can be done in wet gas compressor performance calculation is correction for off design operation in wet gas compression condition. In gas condensate field, fluid properties will change significantly with decreasing pressure. Therefore, actual and test reference condition will be different over time and will affect gas condensate field performance. This condition need attention since current off design correction accuracy will be reduced if the deviation is large. Good prediction of wet gas compression performance is required in developing gas condensate field

NOMENCLATURE

a   =   Huntington equation constant

b   =   Huntington equation constant

c   =   Huntington equation constant

f   =   Schultz correction factor

h   =   Specific molar enthalpy, kj/kgmole

HP   =   Power, j/s

k   =   Isentropic exponent

MW   =   Molecular weight

n   =   Polytropic exponent

N   =   Compressor speed of rotation, rpm [1/s]

p   =   Pressure, psi [bar]

q   =   Heat flow, kJ

Q   =   Volume flow, m^3/h [m^3/s]

R   =   Gas constant, 8.3143 kj/kgmole-K

s   =   Specific entropy, kj/kgmole-C

S   =   Entropy, j/K

T   =   Temperature, C [K]

V   =   Volume, m^3

v   =   Molar volume, $m^3/kgmole$

W   =   Work, J

X	=	Compressibility function
Y	=	Compressibility function
z	=	Compressibility factor
η	=	Efficiency, % [fraction]
$\dot{m}$	=	Mass flow, kg/s
Δ	=	Difference

Subscript

1	=	Inlet condition
2	=	Outlet condition
act	=	Actual
avg	=	Average
corr	=	Corrected
h	=	Huntington method
i	=	Pressure step i
m	=	Midpoint
p	=	Polytropic
P	=	Isobar
r	=	Reference/direct integration method
ref	=	Reference condition
s	=	Isentropic
S	=	Schultz method

T   =   Isothermal

t   =   Total

v   =   Volume corrected

superscript

c   =   Corrected

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APPENDIX

VISUAL BASIC SCRIPT FOR DIRECT INTEGRATION METHOD

Public hyApp As HYSYS.Application

Public simCase As SimulationCase

Public inlet As ProcessStream

Public outlet As ProcessStream

Public compressor As CompressOp

Public compcor As CompressOp

Public table As PropertyTable

Public cmprCurves As CompExpCurves, cmprCurvescor As CompExpCurves

Public curve1 As CompExpCurve, curvecor1 As CompExpCurve

Public hyfluid As Fluid

Public RealIsentropicCompression As CompressOp, CorrectedIsentropicCompression As CompressOp, comp As CompressOp

Public Sub calculate_int()

Dim fileName As String

Dim Inletpress As Double, Outletpress As Double

Dim inlettemp As Double, outlettemp As Double

Dim outletenthalpy As Double

Dim molarflow As Double

Dim compositions As Variant

Dim effi As Variant, efficiency As Variant

Dim head As Variant

Dim volflow As Variant

Dim curves As String

Dim N As Integer

```vba
'connect with HYSYS

Set hyApp = CreateObject("HYSYS.Application")

hyApp.Visible = True

    Set simCase = hyApp.ActiveDocument

    If simCase Is Nothing Then

        fileName = Worksheets("Integration").Range("Filename_int")


        If fileName <> "False" And simCase Is Nothing Then

            Set simCase = GetObject(fileName, "HYSYS.SimulationCase")

            simCase.Visible = True

        End If

    End If


'######              CLEAR CALCULATION TABLE CONTENT              ########
    'Clear Content

    Sheets("Integration").Select

    Worksheets("Integration").Range("TopLeft_Calc_Int").Select

    Range(Selection, Selection.End(xlDown)).Select

    Range(Selection, Selection.End(xlToRight)).Select

    Selection.ClearContents

'#######              ROW AND COLUMN TABLE REFERENCE              ####
'topleft of calculation table

rowcalc = Worksheets("Integration").Range("TopLeft_Calc_Int").Row

colcalc = Worksheets("Integration").Range("TopLeft_Calc_Int").Column

'topleft of number of step table

rowstep = Worksheets("Integration").Range("TopLeft_Step_Int").Row

colstep = Worksheets("Integration").Range("TopLeft_Step_Int").Column
```

```vba
'Topleft of result table

rowresult = Worksheets("Integration").Range("Result_Table").Row

colresult = Worksheets("Integration").Range("Result_Table").Column


'top left of compressor curve

Sheets("Integration").Select

Worksheets("Integration").Range("Topleft_Curve_Int_Ref").Select

Sizecurve = Worksheets("Integration").Range(Selection, Selection.End(xlDown)).Count

rowcurve = Worksheets("Integration").Range("Topleft_Curve_Int_Ref").Row

colcurve = Worksheets("Integration").Range("Topleft_Curve_Int_Ref").Column


'topleft of real composition table

Sheets("Integration").Select

Worksheets("Integration").Range("Topleft_Comp_Int").Select

sizecomp = Worksheets("Integration").Range(Selection, Selection.End(xlDown)).Count

rowcomp = Worksheets("Integration").Range("Topleft_Comp_Int").Row

colcomp = Worksheets("Integration").Range("Topleft_Comp_Int").Column


'topleft of reference composition table

Sheets("Integration").Select

Worksheets("Integration").Range("Topleft_Comp_Int_Ref").Select

sizecomp_ref = Worksheets("Integration").Range(Selection, Selection.End(xlDown)).Count

rowcomp_ref = Worksheets("Integration").Range("Topleft_Comp_Int_Ref").Row

colcomp_ref = Worksheets("Integration").Range("Topleft_Comp_Int_Ref").Column


'topleft of curve correction calculation table

rowcalc_curve = Worksheets("Integration").Range("TopLeft_Calc_Curve_Int").Row

colcalc_curve = Worksheets("Integration").Range("TopLeft_Calc_Curve_Int").Column
```

```vba
'Count Column calculation table
Sheets("Integration").Select
Worksheets("Integration").Range("Header_Calc_Table").Select
size_col_calc = Range(Selection, Selection.End(xlToRight)).Count


'step = Loop for step to reach final pressure
'number = loop for each step package
step = Worksheets("Integration").Cells(rowstep, colstep).Value
number = Worksheets("Integration").Range("Number_step_Int").Value


'top left of curve correction result
row_curve_result = Worksheets("Curve correction result").Range("Curve_corr_Result_Int").Row
col_curve_result = Worksheets("Curve correction result").Range("Curve_corr_Result_Int").Column


'top left of curve correction result at step i
row_curve_result_stepi = Worksheets("Integration").Range("TopLeft_Curve_Res_Int").Row
col_curve_result_stepi = Worksheets("Integration").Range("TopLeft_Curve_Res_Int").Column


'Curve_corr_Result_Int
row_curveRPM_result = Worksheets("Curve correction result").Range("RPM_Curve_Res").Row
col_curveRPM_result = Worksheets("Curve correction result").Range("RPM_Curve_Res").Column


'g and h is column in curve correction result
g = 1
h = col_curveRPM_result
```

```vba
'loop for different number of integration step (to the right)
For y = 1 To number
 k = colcalc + ((size_col_calc + 1) * (y - 1))



   'copy molar flow to cells B
   Worksheets("Integration").Range("molarflow_int").Value
=Worksheets("Integration").Range("molarflow_parameter_Int").Value



'#####                    INPUT COMPOSITION TO STREAM                    ########
   'Input real composition to inlet integration condition  hysys
   Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
   compositions = inlet.ComponentMolarFractionValue
      For item = 0 To (sizecomp - 1)
         compositions(item) = Worksheets("Integration").Cells(rowcomp + item, colcomp).Value
      Next item
   inlet.ComponentMolarFraction.Values = compositions



    'Input real composition to outlet integration condition  hysys
   Set inlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration Temp")
   compositions = inlet.ComponentMolarFractionValue
      For item = 0 To (sizecomp - 1)
         compositions(item) = Worksheets("Integration").Cells(rowcomp + item, colcomp).Value
      Next item
   inlet.ComponentMolarFraction.Values = compositions



   'get Molecular weight
   Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
```

Worksheets("Integration").Range("MW_INT").Value = inlet.MolecularWeight.GetValue("")

'copy initial guess of compressor efficiency to calculation table

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 13).Value = Worksheets("Integration").Range("compressor_eff_int").Value

' integration step size

step = Worksheets("Integration").Cells(rowstep, colstep + (y - 1)).Value

'loop for each step (in a integration step)

For z = 1 To step

Sheets("Integration").Select

Worksheets("Integration").Range("TopLeft_Calc_Int").Select

'###### WRITE INLET CONDITION ON CALCULATION TABLE #########

'write step in calculation table

Worksheets("Integration").Cells(rowcalc + (z - 1), k).Value = z

'write initial pressure and temperature in calculation table

Worksheets("Integration").Cells(rowcalc, k + 1).Value = Worksheets("Integration").Range("Press_init_Int").Value

Worksheets("Integration").Cells(rowcalc, k + 2).Value = Worksheets("Integration").Range("Temp_init_int").Value

'write inlet pressure at each step in calculation table

```
Worksheets("Integration").Cells(rowcalc + (z), k + 1).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 1).Value *
Worksheets("Integration").Cells(rowstep + 1, colstep + (y - 1)).Value



'####                    SET INLET CONDITION TO HYSYS          #########


    'set inlet pressure
    Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
    Inletpress = Worksheets("Integration").Cells(rowcalc + (z - 1), k + 1).Value
    inlet.Pressure.SetValue Inletpress, "psia"


    'Input inlet temperature to hysys
    Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
    inlettemp = Worksheets("Integration").Cells(rowcalc + (z - 1), k + 2).Value
    inlet.Temperature.SetValue inlettemp, "R"


     'Input mass flow to hysys
    Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
    molarflow = Worksheets("Integration").Range("molarflow_int").Value
    inlet.molarflow.SetValue molarflow, "kgmole/h"



'######                  GET INLET CONDITION FROM HYSYS              ######


     'get inlet molar enthalpy
    Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")
    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 3).Value =
inlet.MolarEnthalpy.GetValue("kj/kgmole")
```

```vba
'get inlet molar entropy

Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 4).Value = inlet.MolarEntropy.GetValue("kj/kgmole-c")


'get inlet Cp/Cv

Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 5).Value = inlet.CpCv.GetValue("")


'get molar density

Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 6).Value = inlet.MolarDensity.GetValue("kgmole/m3")



'########  SET ISENTROPIC COMPRESSOR PROPERTY ######


 'input expander efficiency

Set compressor = simCase.Flowsheet.Operations.item("Integration")

efficiency = 100

'efficiency = Worksheets("Integration").Cells(rowcalc + (z - 1), k + 7).Value

compressor.CompPolytropicEff.SetValue efficiency


'input outlet pressure (Use pressure ratio)

Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration")

Outletpress = Worksheets("Integration").Cells(rowcalc + (z), k + 1).Value

outlet.Pressure.SetValue Outletpress, "psia"


'##########   GET OUTLET ISENTROPIC COMPRESSION PROPERTY ######
```

```vb
'get outlet isentropic molar enthalpy

Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 7).Value =
outlet.MolarEnthalpy.GetValue("kj/kgmole")


'get outlet isentropic molar entropy

Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 8).Value =
outlet.MolarEntropy.GetValue("kj/kgmole-c")


'get outlet Cp/Cv

Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet integration")

Worksheets("Integration").Cells(rowcalc + (z - 1), k + 9).Value = outlet.CpCv.GetValue("")




'######             GET EFFICIENCY             ######


'input expander efficiency

Set compressor = simCase.Flowsheet.Operations.item("Integration")

efficiency = Worksheets("Integration").Cells(rowcalc + (z - 1), k + 13).Value

compressor.CompPolytropicEff.SetValue efficiency


'Get adiabatic efficiency

Set compressor = simCase.Flowsheet.Operations.item("Integration")
```

```vba
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 14).Value =
compressor.CompAdiabaticEff.GetValue("")
```

```vba
'#######          CALCULATE AVERAGE K          ############
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 11).Value =
(Worksheets("Integration").Cells(rowcalc + (z - 1), k + 9).Value +
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 5).Value) / 2
```

```vba
'######## CALCULATE REAL ENTHALPY CHANGE  ############

'calculate dh isentropic
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 15).Value =
(Worksheets("Integration").Cells(rowcalc + (z - 1), k + 7).Value -
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 3).Value)

'calculate dh isentropic/adiabatic eff
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 16).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 15).Value /
(Worksheets("Integration").Cells(rowcalc + (z - 1), k + 14).Value / 100)

'calculate dh
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 17).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 16).Value *
(Worksheets("Integration").Cells(rowcalc + (z - 1), k + 13).Value / 100)

'polytropic fluid head
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 18).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 17).Value /
Worksheets("Integration").Range("MW_INT").Value

'polytropic head
```

```vba
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 19).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 18).Value * 1000 /
Worksheets("Integration").Range("gravity").Value


    'Calculate outlet enthalpy

    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 21).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 16).Value +
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 3).Value




    '######   GET OUTLET TEMPERATURE KNOWN PRESSURE AND ENTHALPY #######


    'set outlet pressure (find temperature, known pressure and enthalpy)
    Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration Temp")
    Outletpress = Worksheets("Integration").Cells(rowcalc + (z), k + 1).Value
    outlet.Pressure.SetValue Outletpress, "psia"


    'write outlet pressure on excel
    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 23).Value =
Worksheets("Integration").Cells(rowcalc + (z), k + 1).Value


    'set outlet molar enthalpy (find temperature, known pressure and enthalpy)
    Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration Temp")
    outletenthalpy = Worksheets("Integration").Cells(rowcalc + (z - 1), k + 21).Value
    outlet.MolarEnthalpy.SetValue outletenthalpy, "kj/kgmole"


    'get outlet temperature (find temperature, known pressure and enthalpy)
    Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration Temp")
    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 22).Value =
outlet.Temperature.GetValue("R")
```

```vbnet
    'get molar density

    Set outlet = simCase.Flowsheet.MaterialStreams.item("Outlet Integration Temp")

    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 10).Value =
outlet.MolarDensity.GetValue("kgmole/m3")


    'get mass flow rate

    Set inlet = simCase.Flowsheet.MaterialStreams.item("Inlet integration")

    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 24).Value =
inlet.MassFlow.GetValue("kg/h")


    'Calculate Power

    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 25).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 15).Value *
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 24).Value /
(Worksheets("Integration").Range("MW_INT").Value * 3600 *
(Worksheets("Integration").Cells(rowcalc + (z - 1), k + 14).Value / 100))



    '#######  CALCULATE vdp (Polytropic fluid head) ###############
    'calculate average v

    Worksheets("Integration").Cells(rowcalc + (z - 1), k + 12).Value = (1 /
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 10).Value + 1 /
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 6).Value) / 2


    'vdp (polytropic fluid head)

    DeltaP = (Worksheets("Integration").Cells(rowcalc + (z), k + 1).Value -
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 1).Value) * 6.894757 * 1000

    densityaverage = (Worksheets("Integration").Cells(rowcalc + (z - 1), k + 12).Value) /
Worksheets("Integration").Range("MW_INT").Value
```

```vba
        Worksheets("Integration").Cells(rowcalc + (z - 1), k + 20).Value = DeltaP * densityaverage /
1000



    '######  SET EFFICICIENCY SAME AS STEP BEFORE AND USE OUTLET
    TEMPERATURE AS INLET TEMPERATURE ############



        Worksheets("Integration").Cells(rowcalc + (z), k + 2).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 22).Value

        Worksheets("Integration").Cells(rowcalc + (z), k + 13).Value =
Worksheets("Integration").Cells(rowcalc + (z - 1), k + 13).Value



    Next z



    '#########  CALCULATE TOTAL HEAD AND POWER ##########



sum_head = 0

sum_power = 0

vdeltap = 0

i_sum = 1



For i_sum = 1 To z

    sum_head = Worksheets("Integration").Cells(rowcalc + (i_sum - 1), k + 18).Value + sum_head

    sum_power = Worksheets("Integration").Cells(rowcalc + (i_sum - 1), k + 25).Value + sum_power

    vdeltap = Worksheets("Integration").Cells(rowcalc + (i_sum - 1), k + 20).Value + vdeltap

Next i_sum



Worksheets("Integration").Cells(rowresult, colresult + (y - 1)) = sum_head

Worksheets("Integration").Cells(rowresult + 2, colresult + (y - 1)) = vdeltap
```

Worksheets("Integration").Cells(rowresult + 1, colresult + (y - 1)) = sum_power

Worksheets("Integration").Cells(rowresult + 3, colresult + (y - 1)) = (vdeltap - sum_head) / sum_head

Next y

MsgBox "Finish Calculating Result", vbInformation

End Sub