OPTIMAL DESIGN OF MULTI-STAGE NATURAL GAS COMPRESSION WITH INTER- AND AFTER-COOLERS USING THE MOLLIER-TYPE CHARTS

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Abstract

Fundamental operational equations required for design of multi-stage compressor stations equipped with inter- and after-coolers are reviewed. Applications are demonstrated for optimal design of typical compressor stations. Numerical examples are presented to illustrate the application of the theory and methodology for effective design of the compressor stations using the Mollier-type charts.

Introduction

The principles of compressor station design are described by Ikoku (1980, 1984), Manning and Thompson (1991), Arnold and Steward (1999), and Pennybaker (1998). In this paper, a review of the fundamental principles involved in the design of multi-stage compressor stations equipped with inter- and after-coolers is presented.

The construction of the thermodynamic path of the natural gas on the Mollier-type charts, during the gas processing through the system of compressors and coolers, is described. The optimal procedures required for determination of the number of compressors necessary for a prescribed condition, the individual compressor compression ratio, and the cooling load are presented. The effect of irreversible power loss on the design procedure is delineated. The various mechanisms causing the loss of compressor and cooler efficiency are explained and quantified. The practical limitations that must be taken into consideration are emphasized.

Several applications are provided demonstrating the use of the methodology presented in this paper concerning the optimal design of typical compressor stations for practical situations. The numerical examples presented in this paper illustrate the application of the theory and methodology for effective design of compressor stations using the Mollier-type charts.

Multi-Compressors System without Pressure Loss through Intercooler

Consider Fig. 1 showing a series of compressors without pressure loss during intercooling.

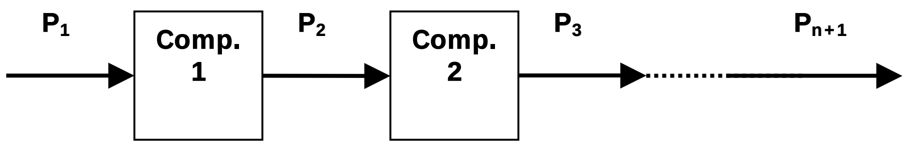

Figure 1- Multi-compressors system without pressure loss through intercooler.

The compression ratio of all the compressors is desired to be the same for all practical purposes. Thus,

$$r_i = P_{i+1}/P_i = r_o : i = 1,2,..,n \tag{1}$$

The overall compression ratio can be expressed by the product of the individual compression ratios as:

$$r = \prod_{i=i}^{n} r_i = r_o^n = P_{n+1}/P_1 \tag{2}$$

Eq.(2) can be solved for the number of compressors as:

$$n = \frac{\log_{10} r}{\log_{10} r_o} \tag{3}$$

The result is rounded-off to the larger integer number because the number of compressors is an integer. For practical reasons n is determined such that $r_o \le 4$. For example if r = 100 and r_o = 4, then, Eq.(3) yields n = 3.3, which should be rounded as n = 4. Consequently, Eq.(2) yields r_o = 3.2 for n = 4 and the pressure values are calculated from Eq.(1) as following:

$$P_2 = r_o P_1 = 3.2 \times 300 = 960\text{psia}, P_3 = r_o P_2 = 3.2 \times 960 = 3{,}000\text{psia} \tag{4}$$

The compressor work for q = 1.0 lb-mole/day of gas processed can be calculated as following:

$$W = \Delta H = \Delta H_2 - \Delta H_1 \left(\frac{Btu}{lbmole} \right) \tag{5}$$

Note

$$\frac{Btu}{day} = 1.637 \times 10^{-5} Hp \tag{6}$$

The heat removed at the gas coolers is given by:

$$\Delta H_{1-2} = Q - W \tag{7}$$

But W = 0 for the coolers. Then,

$$Q = \Delta H_{1-2} = -\left(\Delta H_2 - \Delta H_1 \right) \tag{8}$$

For example, consider the following problem given by Ikoku (1980, 1984) with some modification. A 0.65 gravity natural gas at the initial conditions of 100 psia at 80 ^{o}F will be compressed to a final pressure at 2,700 psia. Intercoolers will be used to remove the excess heat generated by compression to cool the gas to the same temperature of 100^{o}F after each compression. The objectives are to determine the optimum number of compressors that should be considered, gas pressure and temperature that will be attained after each compression, total compressor horsepower that needs to be supplied with 85% efficiency, and heat load involving the intercoolers. The flowing gas will be processed at a rate of 1.0

MMscfd.

The overall compression ration is calculated as:

$$r = \frac{P_2}{P_1} = \frac{2700}{100} = 27 \tag{9}$$

The number of compressors required to accomplish the objectives of the problem is given by (Civan, 2003-2005):

$$n = \frac{\log_{10} 27}{\log_{10} 4} = 2.4 \tag{10}$$

Rounding to the larger integer, n = 3 compressors are required. Therefore, the individual compressor compression ratio is calculated as:

$$r = r_o^{\,n},\ r_o = \sqrt[3]{27} = 3 \tag{11}$$

Note that there is no pressure loss in the intercoolers.

$$\Delta P = 0 \tag{12}$$

Consequently, the outlet pressures of the compressors are calculated, respectively, as:

$$\begin{aligned} &P_2 = r_o P_1 = 3\times 100 = 300\text{psia} \\ &P_4 = 3\times 300 = 900\,psia,\quad P_5 = 2{,}700\text{psia} \end{aligned} \tag{13}$$

The corresponding temperature values can be determined by means of the Mollier chart given in Fig.2. Referring to the beginning and end-point enthalpy values shown on the Mollier chart, the heat load of the intercoolers and work supplied by the compressors are given by the following equations:

$$\begin{aligned} Q_T &= Q_1 + Q_2 + Q_3 \\ W_T &= W_1 + W_2 + W_3 \end{aligned} \tag{14}$$

$$\begin{aligned} W_1 &= \Delta H_{1-2} \\ W_2 &= \Delta H_{3-4} \\ W_3 &= \Delta H_{5-6} \end{aligned} \tag{15}$$

$$\begin{aligned} Q_1 &= -\Delta H_{2-3} \\ Q_2 &= -\Delta H_{4-5} \\ Q_3 &= -\Delta H_{6-7} \end{aligned} \tag{16}$$

Note that

$$\frac{Btu}{day} = 1.637\times 10^{-5}\,HP \tag{17}$$

The total adiabatic horse power requirement is:

$$\begin{aligned} &HP_T = \sum_{i=1}^{n} HP_{comp.i} \\ &W_{total} = -q\Delta H = q\left(\Delta H_{Inlet} - \Delta H_{Outlet}\right) \\ &q = 1.0 MMscfd \end{aligned} \tag{18}$$

The compressor power calculated above is the ideal power. It needs to be divided by 85% efficiency to determine the actual power required.

The total heat removed (load) in intercoolers is:

$$Q = \Delta H = \Delta H_{Outlet} - \Delta H_{Inlet}$$
$$Q_{total} = q\Delta H \,, \quad q = 1.0 MMscfd \tag{19}$$

Fig.2 shows the thermodynamic path followed by the compressed gas on the Mollier chart without pressure loss in the intercooler.

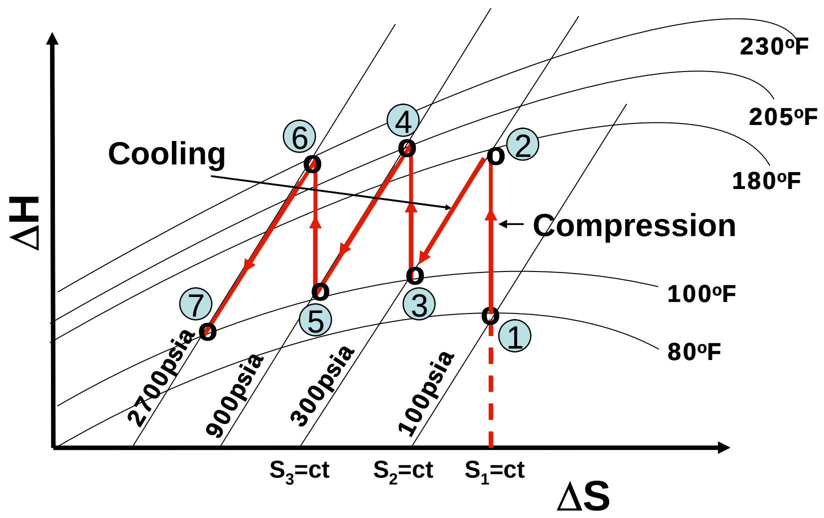

Figure 2- Thermodynamic state of the compressed gas on the Mollier chart without pressure loss in the intercooler.

Multi-Compressors System with Pressure Loss through Intercooler

Consider Fig. 3 showing a series of compressors with pressure loss during intercooling.

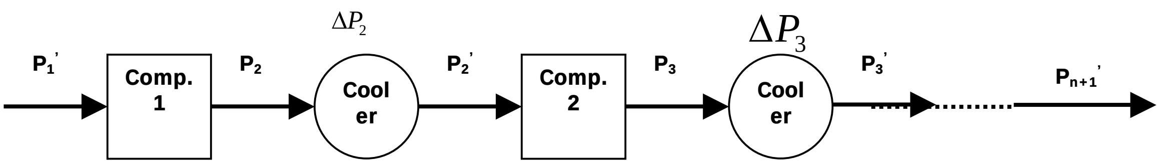

Figure 3- Multi-compressors system with pressure loss through intercooler.

The compression ratio equation for the case of all compressors followed by cooling involving pressure drop is derived as following (Civan, 2003-2005):

$$r_i = P_{i+1} / P_i^{'} = r_o : i = 1, 2, .., n \tag{20}$$

$$r = \prod_{i=i}^{n} r_i = r_o^n = P_{n+1}^{'} / P_1^{'} \tag{21}$$

$$P_2^{'} = P_2 - \Delta P = r_o P_1^{'} - \Delta P \tag{22}$$

$$P_3' = P_3 - \Delta P = r_o P_2' - \Delta P = r_o\left(r_o P_1' - \Delta P\right) - \Delta P \qquad (23)$$

Facilitating these equations, a general formula can be derived for the overall compression ratio as given below:

$$r = r_o^n - \left(\Delta P / P_1'\right)\sum_{i=1}^{n} r_o^{\,i-1} \qquad (24)$$

For example, consider the following problem modified after Ikoku (1980, 1984). A 0.65 gravity natural gas will be compressed from 100 psia to 1,000 psia pressure. Intercoolers, each experiencing a 30 psia pressure loss, will be used in this system. The objective is to calculate the optimum number of compressors that should be considered and the pressure and temperature conditions that will be attained after each compression. Note that

$$P_1' = 100\,\text{psia}, \quad P_{n+1}' = 1,000\,\text{psia} \qquad (25)$$

Therefore, the overall compression ratio is given by:

$$r = \frac{P_{n+1}'}{P_1'} = \frac{1,000}{100} = 10 \qquad (26)$$

Next, consider Eq.(24), which can be expanded as:

$$r = r_o^n - \frac{\Delta P}{P_1'}\left(1 + r_o + r_o^{\,2} + \ldots + r_o^{\,n-1}\right) = 10 \qquad (27)$$

This equation can be solved by a trial-and-error method to obtain a solution such that r_o has the largest value closest to 4, because it is required that $r_o \le 4$. For example, assuming n = 2, Eq.(27) yields:

$$r_o^2 - 0.30 r_o - 10.3 = 0 \qquad (28)$$

Solving the quadratic equation for its positive root yields r_o = 3.363, which satisfies the practical condition of $r_o \le 4$. Therefore, n = 2 compressors are required. Under these conditions, the pressure calculations can be readily carried out as following:

$$\begin{aligned} P_1' &= 100\,psia \\ P_2 &= r_o P_1' = 3.363 \times 100 = 336.3\,psia \\ P_2' &= P_2 - \Delta P = 336.3 - 30 = 306.3\,psia \\ P_3 &= r_o P_2' = 3.363 \times 306.3 = 1030\,psia \\ P_3' &= P_3 - \Delta P = 1030 - 30 = 1000\,psia \end{aligned} \qquad (29)$$

The corresponding temperature values can be determined by means of the Mollier chart given in Fig.4. Next, using the Mollier diagram, the following can be calculated:

$$\begin{aligned} Q_T &= Q_1 + Q_2 \\ W_T &= W_1 + W_2 \end{aligned} \qquad (30)$$

$$\begin{aligned} W_1 &= \Delta H_{1'-2} \\ W_2 &= \Delta H_{2-2'} \end{aligned} \qquad (31)$$

$$\begin{aligned} Q_1 &= -\Delta H_{2-2'} \\ Q_2 &= -\Delta H_{3-3'} \end{aligned} \qquad (32)$$

$$\frac{Btu}{day} = 1.637 \times 10^{-5} HP \qquad (33)$$

Fig.4 shows the thermodynamic path followed by the compressed gas on the Mollier chart with pressure loss in the intercooler. The compressor power calculated above is the ideal power. It needs to be divided by 85% efficiency to determine the actual power required.

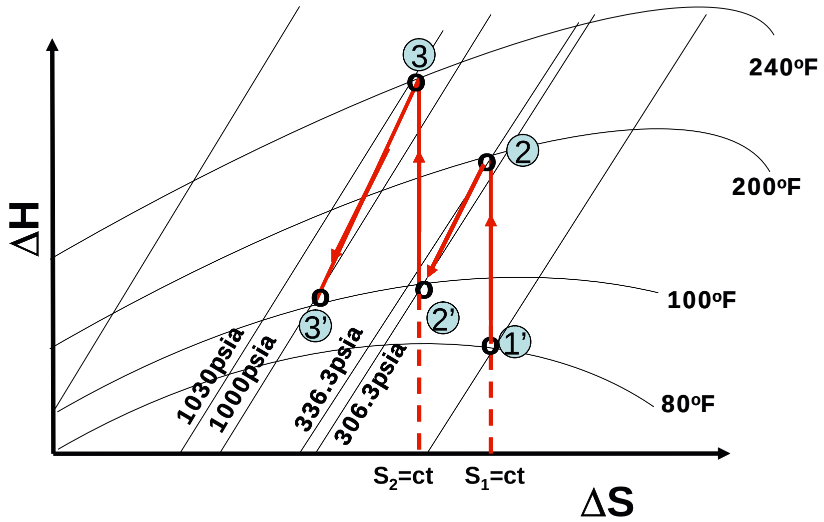

Figure 4- Thermodynamic state of the compressed gas on the Mollier chart with pressure loss in the intercooler.

Conclusions

This paper presented the various useful formulae required for design of compressor stations. Their applications and computational method were illustrated by means of several applications.

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