■ Elliott 15 MB hydrogen recycle compressor at the Valero refinery in Ardmore, Oklahoma, U.S.A. Performance analysis found that cleaning the compressor would bring the unit back to normal operating conditions and a rerate was not necessary. Plans are to install online performance monitoring software to confirm current performance and to aid in scheduling compressor maintenance.

HYDROGEN RECYCLE COMPRESSOR FIELD PERFORMANCE ANALYSIS

Compressor Performance Analysis Prior to Major Overhaul or Intended Rerate Can Reveal Important Cost and Time Saving Measures

By Ted Gresh

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As part of a debottlenecking procedure, management at Valero — an Ardmore, Oklahoma, U.S.A., refinery — were interested in analyzing the plant's hydrogen recycle compressor performance. The compressor string consisted of an Elliott 15 MB barrel compressor driven by an Elliott SBEG-5 condensing steam turbine driver. Of primary concern for data accuracy were the flow meters and obtaining an accurate gas analysis. Accurate data were of special concern because confirmation of calculation results was not available.

Special care was taken to assure accurate data. Pressure differential data from the compressor gas-flow meter were read directly and used to calculate the flow rate to the compressor. The same was done for the turbine flow meter. Multiple gas samples were taken to assure redundancy. The compressor was determined to be operating at about 71% efficiency, about 5% below predicted values. The turbine was operating at about 44% efficiency, about 10% below its predicted value.

While the data showed the equipment needed maintenance to bring it back to design operating condition, the compressor was operating at midrange so that a rerate was not required. It was recommended that the compressor be opened for cleaning and inspection of the internal labyrinth seals. According to Michael Tibbits, Staff Process Engineer, the main reason for having the analysis was to determine the extent of rerate of the compressor to increase its throughput. Because the analysis revealed that only minor maintenance was required, the refinery saved considerable time and expense. Valero was most pleased with the results.

Start-up — Following overhaul, all the piping and vessels were filled with air rather than the process gas. So, when the compressor first started, it compressed air and eventually nitrogen once all the air was purged. For operation, the effects are approximately the same because the molecular weight (MW) for air and nitrogen is 28. However, this is very different than the process gas, which has a MW of 3.6.

First consideration was the power. The power was limited to the available power of the driver. And, even if there was unlimited driver power, the increase in power required for operation on nitrogen would end up in a shaft-end failure if the compressor was operated at the same speed and pressure. To operate the compressor on nitrogen, it was necessary to reduce both speed and pressure. To estimate required speed and pressure, guidelines and formulas were obtained from a book composed by M.T. Gresh, entitled, "Compressor Performance: Aerodynamics for the User." For simplification, these equations are labeled numerically from 1 through 5.

■ **Polytropic gas horsepower is obtained as follows:**

$$GHP_p = \frac{H_p \dot{M}}{\eta_p \, 33{,}000} \quad (1)$$

■ **Mass flow is roughly proportional to MW and pressure as expressed approximately by the formula:**

$$H_1 MW_1 P_1 = H_2 MW_2 P_2 \quad (2)$$

■ **If the compressor is to be operated at 400 psia (27.6 bar) suction pressure while operating on nitrogen:**

$$35{,}000 \text{ x } 3.6 \text{ x } 1700 = H_2 \text{ x } 28 \text{ x } 400$$

$$H_2 = 19{,}125 \text{ ft-lb/lb. } (57{,}165 \text{ Nm/kg})$$

■ **In order to achieve this head, the speed had to be reduced. The fan law equation shows that head is proportional to speed.**

$$H \propto N^2 \quad (3)$$

$$\frac{35{,}000}{19{,}125} = \left(\frac{11{,}289}{N_2}\right)^2 \quad (4)$$

$$N_2 = 8344 \text{ rpm}$$

■ **The compressor was operated on nitrogen at 8344 rpm, 400 psia (27.6 bar) suction pressure and 100°F (38°C). The discharge pressure is estimated using the formula:**

$$P_2 = \left[\frac{H_p}{Z_1 R T_1 [n/(n-1)]} + 1\right]^{n/(n-1)} \times P_1 \quad (5)$$

$$P_2 = \left[\frac{19{,}125}{1.0x55.18x560[1.36/(1.36-1)]} + 1\right]^{1.36/(1.36-1)} \times 400$$

$$P_2 = 710 \text{ psia (49 bar)}$$

Nomenclature:

GHP	= Polytropic Gas Horsepower
H_P	= Polytropic head, ft-lb/lb
$\dot{M}$	= *Mass Flow Rate, lb/min*
MW	= Molecular Weight of Gas Mixture
n	= Polytropic exponent
N	= Equipment speed, rpm
P	= Pressure, psia
R	= Gas constant = (1545) ÷ (molecular weight)
T	= Temperature, degrees Rankine
Z1	= Inlet compressibility factor
n_P	= Efficiency, Polytropic

Subscripts:

1 = Case 1

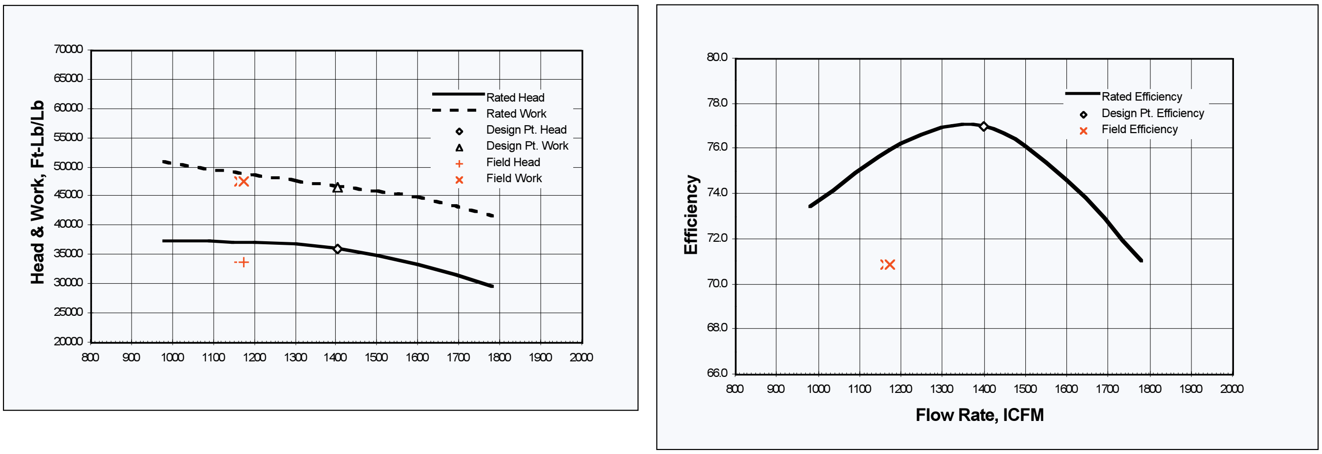
2 = Case 2

P = Polytropic

Another variable to consider is the discharge temperature. We had to be sure the discharge temperature did not exceed guidelines for the compressor. In this case the discharge temperature is relatively low and well within limits (Figure 2).

An accurate operating curve for start-up conditions on nitrogen is necessary and should be obtained from the compressor OEM. The OEM also can confirm if there are other limitations to consider at this off-design operating condition.

Conclusion — A lot can be learned from a field performance test. Knowing where the compressor is operating on the curve is valuable information. In this case, it was found the compressor was not the bottleneck and a rerate was not necessary, although an internal inspection and cleaning was found to be necessary. Routine monitoring of rotating equipment performance should be part of a normal preventative maintenance program to maintain peak plant production rates.



■ **Figure 1. Hydrogen recycle compressor operating data for August 6, 2004. Data has been fan law corrected to design speed, 11,070 rpm.**

Summary of Results

Compressor Data			Gas	Mole Fraction	Formula
Time	7:30 AM	10:30 AM	Hexane	0.0002	C_6H_{14}
Flow, MMSCFD	134	132	Hydrogen	0.92242	H_2
Orifice DP, H_2O	19.65	18.9	Propane	0.00346	C_3H_8
Inlet T, F	112.5	114	i Butane	0.0003	C_4H_{10}
Inlet P, psia	1721	1724	n Butane	0.00051	C_4H_{10}
Disch T, F	143	144	Ethane	0.01788	C_2H_6
Disch P, psia	1962	1961	Nitrogen	0.0064	N_2
Speed, rpm	11,289	11,289	Methane	0.04883	CH_4
			MW =	3.5766	
Compressor Results					
Flow, #/min	1139	1112			
Flow ICFM	1195	1183			
Head, ft-lb/lb	35,118	35,040			
Efficiency	70.9	70.9			
Power, HP	1710	1665			
Turbine Data					
Inlet P, psig	588	589			
Inlet T, F	625	625			
Exh P, Hg Vac	28.5	28.5			
Exh T, F	75	75			
Flow, k#/hr	19.7	19.55			
Orifice DP, “H_2O	10.9	10.55			
Turbine Results					
Flow #/hr	21,568	21,240			
Efficiency	44.3	43.8			
Power, HP	1710	1665			

■ **Table 1. Hydrogen recycle operating data for August 6, 2004. Note that the compressor power is identical to the steam turbine power. The compressor power was used as input data for the steam turbine calculation to determine the exhaust conditions of the condensing steam turbine.**

Gas Flex Straight Through Compressor Estimation

Inlet Flange	Units	Inlet	Gas Composition	
Pressure	PSIA	400.000		
Temperature	F	100.0		
Given Flow	ICFM	1,200	N2	1
Volume Flow	Ft^3/Min	1,200.	Total Mole Weight	28.0130
Mass Flow	Lb/Min	2,255.8		
Compressibility		0.9927		
Min. Flange Dia	Inches	5.1		
Flange Velocity	Ft/Sec	140.0		
Discharge Flange Data				
Pressure	PSIA	697.		
Temperature	F	239.6		
Volume Flow	Ft^3/Min	870		
Compressibility		1.0039		
Min. Flange Dia	Inches	4.4		
Flange Velocity	Ft/Sec	140.0		
Total Head Data				
Head	Ft-Lb/Lb	19,158		
Efficiency		71.00		
Gas Power	HP	1,845		

■ **Figure 2. Operation on nitrogen at reduced pressure and speed.**

Gas Flex Straight Through Compressor Test Results

Inlet Flange	Units	Inlet
Pressure	PSIA	1,724.
Temperature	F	114.0
Compressibility		1.0660
Enthalpy	BTU/Lb	971.6
Entropy	BTU/Lb-R	3.7604
Specific Volume	ft^3/lb	1.0641
K(Cp/Cv)		1.3677
K(temp exp)		1.3867
K(vol exp)		1.5080
Specific heat (Cp)	BTU/mol-R	2.0642
Dynamic viscosity	Lb/Ft-Sec	6.91E-06
Sonic velocity	Ft/Sec	3,580.1
Given Flow	Lb/Min	1,112.0
Mass Flow	Lb/Min	1,112.0
Volume Flow	Ft^3/Min	1,183.3
Discharge Flange Data		
Pressure	PSIA	1,961.
Temperature	F	144.0
Compressibility		1.0738
Enthalpy	BTU/Lb	1035.1
Entropy	BTU/Lb-R	3.7918
Specific Volume	ft^3/lb	0.9917
K(Cp/Cv)		1.3651
K(temp exp)		1.3838
K (vol exp)		1.5159
Specific Heat (Cp)	BTU/mol-R	2.0751
Dynamic Viscosity	Lb/Ft-Sec	7.16E-06
Sonic velocity	Ft/Sec	3,695.7
Volume Flow	Ft^3/Min	1102.7
Total Polytropic Data		
Head	Ft-Lb/Lb	35,040.0
Efficiency		70.93
Gas Power	HP	1,664.6

Gas Composition

HEXA	0.0002
H2	0.92242
C3H8	0.00346
IBUT	0.0003
BUTA	0.00051
C2H6	0.01788
N2	0.0064
CH4	0.04883
Total Mole Weight	3.5766

■ **Figure 3. Compressor calculation results.**