UDC 629.179.13

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SOFTWARE PACKAGE FOR MONITORING AND PREDICTION OF THE COMPRESSOR PERFORMANCE DEGRADATION

The Software package outlines the details of identifying potential process compressor performance degradation. Based on the data received from the compressor manufacturer or a performance test, the software will generate baseline performance curves that are invariant to compressor suction conditions, rotating speed and gas composition. The generated performance curves will be valid for a clean, undamaged compressor only. Performance of compressor will change over time due to fouling, mechanical deterioration from factors such as erosion, rubbing wear resulting in increased tip clearance, seal damage etc. The software will recalculate the compressor map for current inlet condition including current gas composition utilizing the real gas BWRS equation and monitor any changes in the performance of the process compressor with respect to the base line data. On – line calculation of several key variables will be performed for the compressor. Operator will be notified of any changes in compressor performance as part of advisory information. A trend plot will be provided to show deviations of output, polytropic efficiency, power, and other variables (from base line) over time.

Key words: *compressor, performance degradation, power, efficiency, polytrophic head, compression ratio, monitoring, prediction, deviation.*

Introduction

Determination of the compressor performances for the purpose of assessing the health of current compressor condition and prediction performances degradation is an important part of the gas compression industry. It is common practice to measure inlet and discharge pressures, temperatures, mass flow rate and speed for compressor condition evaluation.

Combined with gas mixture properties and run – time data from CCC control system Compressor Performance Adviser (CPA) determines overall compressor productivity, power, efficiency and polytrophic head.

However during an operation the design characteristics are slowly deteriorated. That degradation can be quantified by comparing the relationships between various process characteristics to those that existed when the compressor was in healthy condition.

If a compressor is operated at a constant compression ratio, for example, blade fouling will decrease the flow rate and efficiency at any given speed. Such degradation CPA quantifies by comparing the current flow rate and efficiency to those a healthy compressor would produce at the same speed.

In order to verify the compressor current performances and correctly predict their deterioration it is necessary to take into consideration that different gas mixture compressed by the same compressor produced different output. Therefore CPA is utilizing the variables normalization and the real gas equation of state (EOS) in compliance with the ASME PTC – 10 standard for compressor performance baseline generation that is invariant to compressor suction conditions, and gas composition.

Nomenclature

GC	gas composition
p	pressure
T	temperature
Z	gas compressibility factor
R	gas constant
Rc	compressor pressure ratio
i	enthalpy
Q	volumetric flow rate
N	rotation speed
n_r	reduced speed
H_p	polytropic head
$\sigma_{v.0}$	volumetric polytropic exponent factor
J	compressor power
η_p	polytropic efficiency
n_p	polytropic exponent
k	adiabatic exponent
A_k	flow measurement device (FMD) coefficient

Subscripts

s	suction side
d	discharge side
0	base line (specified) value
r	reduced value
p	polytropic

Calculation procedure

Symbol	Gas property calculation
$Z(GC,p,T)$	Compressibility factor for real gas composition mixture
$i(GC,p,T)$	Enthalpy for real gas composition mixture
$R(GC)$	Gas constant for real gas composition mixture

Notice: All calculations are realized in equation of state by BWRS method (Benedict Webb Rubin Sterling equation).

1. Input data description

The base line input data can be conventionally distinguished in the following way:

– data includes base line performance and efficiency maps and process parameters;

– additional data includes constants and parameters determining properties of the base line working medium from BWRS real gas solution.

The base line data can be obtained from customer (manufacturer) or as measured parameters from designated performance test.

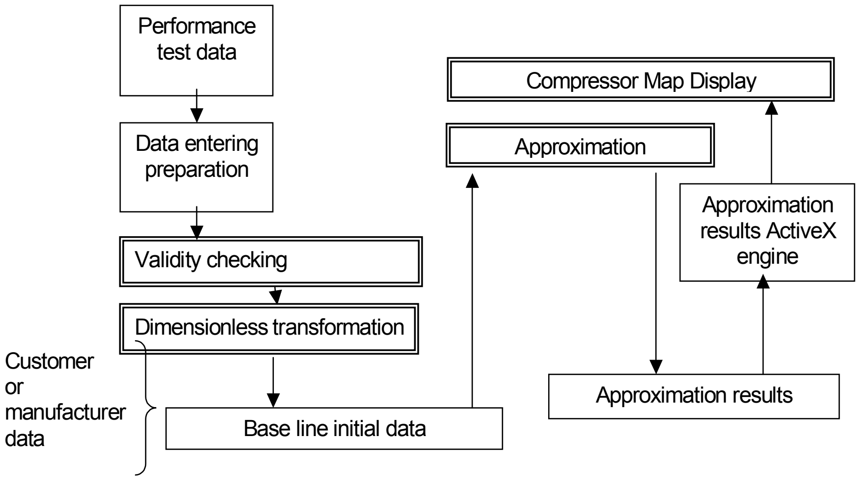

Fig. 1. Structure of Generalize Compressor map formation

2. Principles Description

The performances are as the follow:

$$Rc = f(Q_s, N);$$

$$\eta_p = f(Q_s, N);$$

$$H_p = f(Q_s, N);$$

$$J = f(Q_s, N)$$

for operational GC, P_s, T_s. (1)

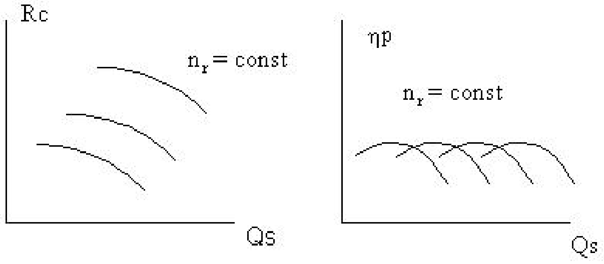

Fig. 2. Compressor performance

Thermodynamic property calculation software is used to provide gas properties of compressed gas mixture based on gas analyzer signal to control system or manually entered by operator.

This methodology consists from two stages: preparatory and operational.

In the preparatory stage the initial performances as a base line initial data are used the manufacturer compressor performance map supplied by end user or to map out the existing machinery characteristics capturing data during Performance Test under specified real gas composition.

These performances are as the follow:

$$Rc_0 = f(Q_{s.0}, N_0)$$

and/or

$$h_{p.r.0} = f(Q_{s.0}, N_0),$$

$$\eta_{p.0} = f(Q_{s.0}, N_0) \qquad (2)$$

under specified (base line)

$$GC_0, P_{s.0}, T_{s.0}, N_0,$$

where $h_{p.r} = Hp/(Z_{s.0} R_0 T_{s.0})$.

The gas composition and operating condition can be significantly different from specified base line conditions $Rc_0 = f(Q_{s.0}, N_0)$ and/or $h_{p.r.0} = f(Q_{s.0}, N_0)$, $\eta_{p.0} = f(Q_{s.0}, N_0)$ under specified $GC_0, p_{s.0}, T_{s.0}, n_{r.0}$ are used for performances normalization (reduction).

These global compressor characteristics are invariant to the compressed gas mixture and inlet gas operational condition.

$$Rc_r = f(q2, n_r),$$
$$\eta_p = f(q2, n_r), \tag{3}$$

where $q2 = \left(\frac{Q_s}{A_k}\right)^2 \frac{1}{Z_s\, R\, T_{s.0}}$; $n_r = \frac{N}{\sqrt{Z_{s.0}\, R\, T_{s.0}}}$, (4)

but only $n_{r.0}$(min) and $n_{r.0}$(max) range identified these characteristics.

In order to get initial data from performance test for base line compressor map generation all data has to be taken during entire range of compressor operation under base gas composition and inlet gas condition.

In the operational stage the normalized compressor performances (3) are used to regenerate the actual compressor performances for current operational gas composition and inlet compressor conditions utilizing the generated in the preparatory stage base line compressor map.

2.1. Normalized Compressor Performance

For the task solution an each point of the specified initial characteristics (parameters Rc, η_p, Q_s, n_r) has to be utilized for current operational η_p and Rc_r calculation.

The findings of Rc_r and η_p are approximated (for instance, polynomials or two dimensional splines) as a function of volumetric flow Q_s (or as a dimensionless representation of flow rate q2) and dimensionless (reduced) speed n_r

$$q2 = \frac{dPo}{Ps}$$

or

$$q2 = \frac{dPo_d\, Rc T_s\, Z_s}{T_d\, Z_d}, \tag{5}$$

where dPo – pressure difference on the flow measuring device at compressor suction; dPo_d – pressure difference on the flow measuring device at compressor discharge; Z_s – gas mix compressibility at suction; Z_d – gas mix compressibility at discharge.

The flow rate calculated as:

$$Q_s = A_k \sqrt{\frac{dP_o Z_s R T_s}{P_s}}. \tag{6}$$

For Rc_r normalization is used the following thermodynamic relations:

Polytropic efficiency calculation utilizing “enthalpy method”:

$$\eta_p = \frac{H_{p.0}}{i(GC_0, p_{d.0}, T_{d.0}) - i(GC_0, p_{s.0}, T_{s.0})}, \tag{7}$$

where $P_{d.0} = P_{s.0}\, Rc$; $T_{d.0}$ – discharge variable corresponding to suction data $p_{s.0}$, $T_{s.0}$, Rc and GC_0 at initial base condition.

Relation between polytropic head and compressor ratio is:

$$H_{p.0} = \frac{Z_{s.0} R_0 T_{s.0}}{\sigma_{v.0}} (Rc^{\sigma_{v.0}} - 1). \tag{8}$$

Volumetric polytropic exponent factor is:

$$\sigma_{v.0} = \frac{\eta_p - 1}{\eta_p};$$

$$\sigma_{v.0} = \frac{\ln \frac{Z_{d.0} T_{d.0}}{Z_{s.0} T_{s.0}}}{\ln Rc}. \tag{9}$$

Normalized polytropic head is:

$$H_{p.r} = H_{p.r.0} \tag{10}$$

Normalized compressor ratio is:

$$Rc_r = \left(\frac{\sigma_{v.0}}{Z_{s.0}\, R_0\, T_{s.0}} H_{p.r.0} + 1\right)^{\frac{1}{\sigma_{v.0}}}. \tag{11}$$

Under specified Rc, η_p, $P_{s.0}$, and GC_0 equations (7) – (9) have 3 unknowns: $H_{p.0}$, $T_{d.0}$, $\sigma_{v.0}$.
So this is a close – loop control of equation system.

To put (9) in the (8), and (8) – in the (7), it is just one equation with one unknown $\sigma_{v.0}(T_{d.0})$.

To designate (9) as $\sigma_{v.0}$ $(T_{d.0})$, (7) can be rewrite as:

$$\left[i(GC_0, p_{d.0}, T_{d.0}) - i_{s.0})\right]\eta_p = \\ = \frac{Z_{s.0} R_0 T_{s.0}}{\sigma_{v.0}(T_{d.0})}\left(Rc^{\sigma_{v.0}(T_{d.0})} - 1\right), \tag{12}$$

where $i_{s.0} = i(GC_0, p_{s.0}, T_{s.0})$; $i_{d.0} = i(GC_0, p_{d.0}, T_{d.0})$ – gas mix enthalpy in suction and discharge accordingly at the base condition; $Z_{s.0} = Z(GC_0, p_{s.0}, T_{s.0})$; $Z_{d.0} = Z(GC_0, p_{d.0}, T_{d.0})$ – gas mix compressibility in suction and discharge accordingly at the base condition; $R_0 = R(GC_0)$ – gas constant for the base gas mixture.

Solution of equation (12) to find $T_{d.0}$.

This is a nonlinear algebraic equation. To solve it can be utilized iteration procedure (for example Newton – Raphson method). As initial approach for unknown variable $T_{d.0}$ could be used value of $\sigma_{v.0}$ ignoring the gas compressibility change during compression process as

$$\sigma_{v.0.init} = \frac{k-1}{k\, \eta};$$

$$T_{d.init} = T_{s.0}\, Rc^{\sigma_{v.0.init}} . \qquad (13)$$

Equation (9) to define $\sigma_{v.0}$

Equation (8) to define polytropic head $H_{p.0}$.

Equation (11) for reduced Rc calculation.

2.2. Generalized compressor performance building algorithm

a) Selection of the compression performance lines for the generalization. Point selection on the performance lines.

b) For each point:

- define value of n_r , Q_s , Rc and η_p ;
- define value of q2 as:

$$q2 = \left(\frac{Q_s}{A_k}\right)^2 \frac{1}{Z_s\, R\, T_s} ;$$

- define Rc_r under describe in section 2.1 methodology.

c) Utilizing as initial data the values of n_r , q2, Rc_r and η_p for entire set of points make approximation in order to get mathematical dependence $Rc = f(q2, n_r)$ and η_p =f(q2,nr) (for example two arguments squared polynomial relationship).

3. Compressor Map Generation Under Operational Condition Utilizing Compressor Generalized Performance

In order to solve this problem each point of initial performance curve (variables $Q_{s.r}$, Rc_r , η_p , $n_{r.0}$) has to be used for η_p and Rc calculation under specified n_r , current inlet condition of p_s , T_s and gas composition.

3.1. Calculation formulas

For algorithm formation:

$$\eta_p = \frac{H_p}{i(GC, p_d, T_d) - i(GC, p_s, T_s)} ; \qquad (14)$$

$$H_p = H_{p.r} \qquad (15)$$

$$H_{p.r} = \frac{Z_s\, R\, T_s}{\sigma_v}\left(Rc_r^{\sigma_v} - 1\right) ; \qquad (16)$$

$$Rc = \left(\frac{\sigma_v}{Z_s R T_s} H_p + 1\right)^{\frac{1}{\sigma_v}} ; \qquad (17)$$

$$\sigma_v = \frac{\ln \frac{Z_d T_{d.}}{Z_s T_s}}{\ln R_c} . \qquad (18)$$

If $H_p = f(Q_s, N)$, $H_p = H_{p.r}$.

Under specified n_r , Rc_r , η_p and operational GC , p_s , T_s equation set (14) – (18) contains 4 unknown: H_p , σ_v , and Rc (variable p_d can be ignored because $p_d = p_s\, Rc$).

Equation set reorganization for a number of the unknown's reduction:

Denote $Z_d = Z(Rc, T_d)$: $i(GC, p_d, T_d) = i(Rc, T_d)$, and function (18) – as $\sigma_v(Rc, T_d)$, from (16) and (17) we get:

$$H_p = \frac{Z_s R T_s}{\sigma_v(Rc, T_d)}\left[Rc_r^{\sigma_v(Rc,T_d)} - 1\right] . \qquad (19)$$

Substitute H_p from (19) to (14) and (17):

$$\begin{aligned} &\frac{Z_s R T_s}{\sigma_v(Rc, T_d)}\left[Rc_r^{\sigma_v(Rc,T_d)} - 1\right] = \\ &= \eta_p\left[i(Rc, T_d) - i_s\right] \end{aligned} ; \qquad (20)$$

$$Rc = \left\{\left[Rc_r^{\sigma_v(Rc,T_d)} - 1\right] + 1\right\}^{\frac{1}{\sigma_v(Rc,T_d)}} . \qquad (21)$$

Equation set (20), (21) contain 2 unknowns: R_c and T_d.

Equation set (20), (21) solution in order to define Rc and T_d .

3.2. Compressor map current performance curve formation algorithm

1. Select specified reduce compressor speeds for the performance curves creation.
2. Specified the values of the dimensionless flow rate q2 for curve point set selection
3. For each point of the performance curve utilizing selected value of n_r and values of q2 :
   - Under compressor generalized performance define Rc_r and η_p ;
   - Utilizing (5), (6), calculate value of q2 if any;
   - Utilizing 3.1 define value of Rc .
4. For entire set of performance curve points of q2 and Rc , display it.

Repeat pp 3 and 4 for the rest of performance curves

5. Utilizing 3.1 (14) define value of η_p .

4. Methodology of deviation analysis

In order to avoid an influence of the compressor operating mode on the performance degradation the performance deviation between current and base line condition are computed and analyzed instead monitored performance itself. The deviation can be defined for a monitored variable Y as a relative discrepancy between a operational calculated value Y^* and a baseline (reference) value $Y_0(\vec{U}_m)$:

$$\delta Y^* = \frac{Y^* - Y_0(\vec{U}_m)}{Y_0(\vec{U}_m)}, \qquad (22)$$

where the value Y_0 is a function of a vector $\vec{U}_m$ of the operating conditions chosen as arguments.

Deviations (22) computed for all monitored characteristics create a deviation vector $\delta \vec{Y}^*$ that presents input information for the stages of compressor degradation and performance deviation prediction.

In [8] noted that a second order full polynomial adequately describes a healthy condition of the analyzed a natural gas compressor unit.

Therefore this polynomial technique selected to create the function of $\vec{Y}_0(\vec{U}_m)$.

5. Performance Monitoring

The difference of the compressor actual operating point performance and the expected value indicates some degree of OEM conditions discrepancy. The operating point representing the actual compressor performance as Hp, Rc, Power and Efficiency against their functions versus suction volumetric flow.

Based of the compressor operating point position on the performance maps adjusting the flow rate for more efficiency can be optimized compressor operation.

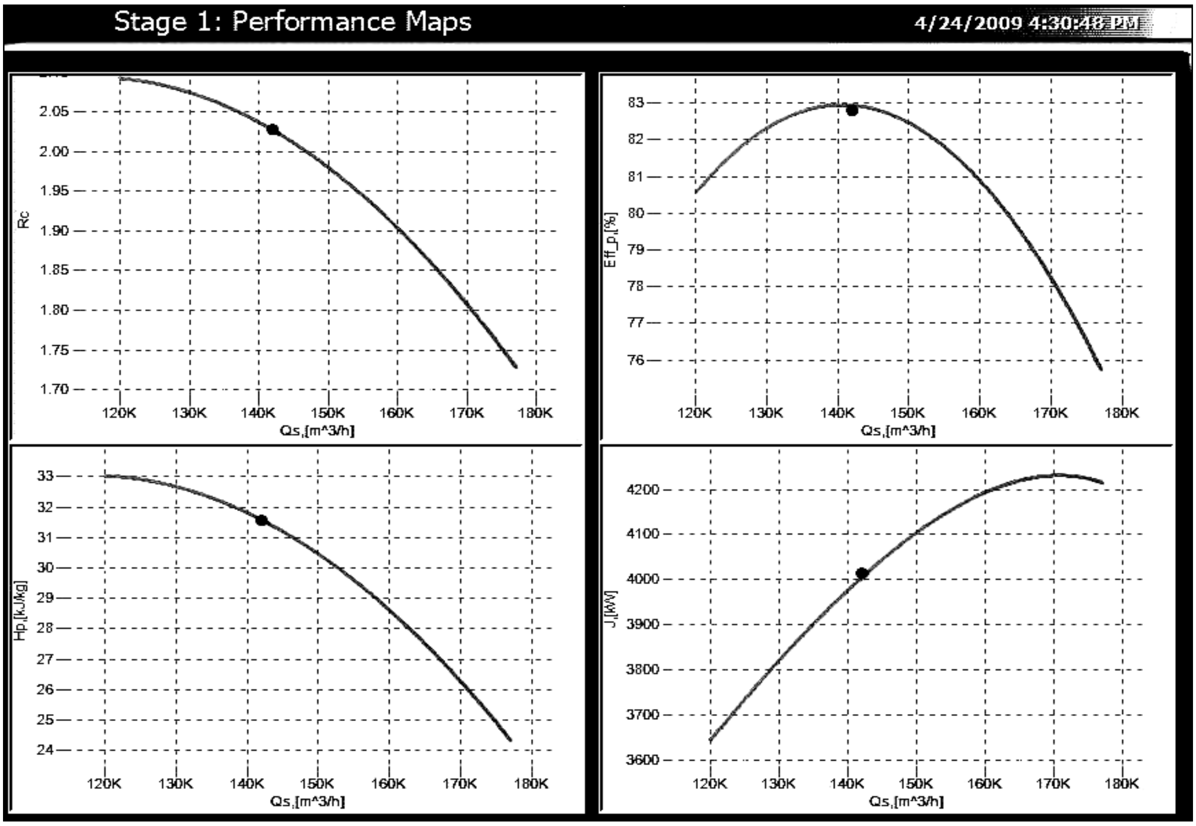

Fig. 3. Operational performance monitoring

The historical compressor performance deviation trends of the H_p, Rc,

Power and Efficiency indicate compressor degradation as function of time. CPA makes prediction based on the performance degradation rate (dotted lines).

There are also configurable degradation thresholds representing the acceptable level (%) of compressor performance degradation.

Alarms will be initiated if:

– compressor performance degradation exceeds the acceptable level threshold;

– predicted performance degradation exceeds the acceptable level threshold.

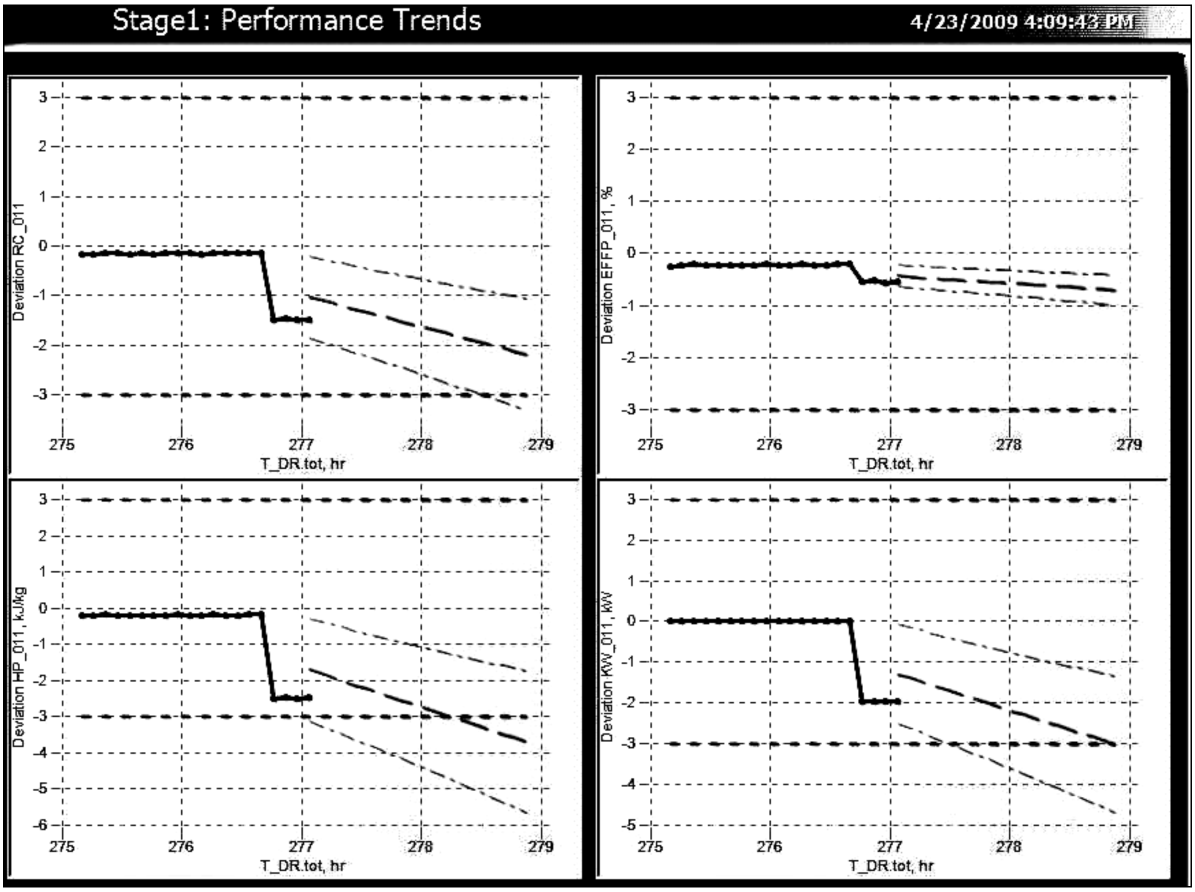

Fig. 4. Performance degradation trend

Conclusions

Compressor performance will change over time due to fouling, mechanical deterioration from factors such as erosion, rubbing wear resulting in increase tip clearance, seal damage etc. That faultiness can be recognized by long – term deviation trend of compressor characteristics against their baseline value. The trend of performance deviation is provided.

If over defined period of time the operating value of compressor characteristics differs from the baseline value by a configurable margin, an alarm is generated.

Sometimes compressor performance OEM data is not available or compressor performance significantly deviates from the OEM data. In both cases Performance Test Data could substitute OEM data.

Software package is capable to build the compressor model using Performance Test data instead of OEM data for expected base line compressor performance.

Some technological processes dealing with variable gas composition when gas properties periodically change. For compressor performance calculations Software package uses the thermodynamic gas property calculation software for gas composition data updated manually or coming to control system from gas analyzer.

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Поступила в редакцию 12.05.2012

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ПАКЕТ ПРОГРАММНОГО ЗАБЕЗПЕЧЕННЯ ДЛЯ МОНІТОРИНГУ ТА ПРОГНОЗУВАННЯ ЗМЕНШЕННЯ ПРОДУКТИВНОСТІ КОМПРЕСОРА

Я. Фельдштейн, А.П. Мазурков

Пакет програмного забезпечення виявляє деталі процесу зниження продуктивності компресора. На підставі даних, отриманих від виробника компресора або тестування продуктивності, програмне забезпечення буде генерує базові криві продуктивності, інваріантні до умов всмоктування компресора, швидкості обертання і складу газу. Створені криві продуктивності дійсні тільки для справного компресора. Продуктивність компресора змінюється з плином часу через забруднення, механічні пошкодження від таких факторів, як ерозія, фрикційний знос, що веде до підвищення зазору, ушкодження ущільнень і т.д. Програмне забезпечення перераховує характеристику компресора для поточного стану на вході, в тому числі для поточного складу реального газу з використанням рівнянь BWRS, і контролює зміни продуктивності компресора по відношенню до базової характеристики. Поточні параметри компресора розраховуються в реальному часі. Оператор одержує інформацію про зміни продуктивності компресора. Графік тренду показує відхилення у часі від базових значень продуктивності, політропного напору, політропного ККД, потужності та інших параметрів.

Ключові слова: компресор, зменшення продуктивності, потужність, політропний ККД, політропна робота, ступінь підвищення тиску, моніторинг, прогнозування, відхилення.

ПАКЕТ ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ ДЛЯ МОНИТОРИНГА И ПРОГНОЗИРОВАНИЯ СНИЖЕНИЯ ПРОИЗВОДИТЕЛЬНОСТИ КОМПРЕССОРА

Я. Фельдштейн, А.П. Мазурков

Пакет программного обеспечения выявляет детали снижения производительности компрессора. На основании данных, полученных от производителя компрессора или тестирования производительности, программное обеспечение генерирует базовые кривые производительности, инвариантные к условиям всасывания компрессора, скорости вращения и составу газа. Созданные кривые производительности действительны только для исправного компрессора. Производительность компрессора изменяется с течением времени из – за загрязнения, механических повреждений от таких факторов как эрозия, фрикционный износ, в результате чего происходит увеличение зазора, износ уплотнений и т.д. Программное обеспечение пересчитывает характеристику компрессора для текущих условий на входе, в том числе для текущего состава реального газа с использованием уравнений BWRS, и контролирует изменения в производительности процесса компрессора по отношению к базовой характеристике. Текущие параметры компрессора вычисляются в реальном времени. Оператор получает информацию об изменениях производительности компрессора. График тренда указывает на отклонения с течением времени от базовых значений производительности, политропного напора, политропного КПД, мощности и других параметров.

Ключевые слова: компрессор, снижение производительности, мощность, политропный КПД, политропная работа, степень повышения давления, мониторинг, прогнозирование, отклонение.

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