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Technology's present situation and the development prospects of energy efficiency monitoring as well as performance testing & analysis for process flow compressors

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Abstract. In this paper, the background of performance testing of in-service process flow compressors set in user field are introduced, the main technique barriers faced in the field test are summarized, and the factors that result in real efficiencies of most process flow compressors being lower than the guaranteed by manufacturer are analysed. The authors investigated the present operational situation of process flow compressors in China and found that low efficiency operation of flow compressors is because the compressed gas is generally forced to flow back into the inlet pipe for adapting to the process parameters variety. For example, the anti-surge valve is always opened for centrifugal compressor. To improve the operation efficiency of process compressors the energy efficiency monitoring technology was overviewed and some suggestions are proposed in the paper, which is the basis of research on energy efficiency evaluation and/or labelling of process compressors.

Key words： Process flow compressor; performance test; energy efficiency monitoring; situation and perspectives

1. Introduction

Process flow compressors are key equipment of processing industries such as petrochemical engineering, coal chemical engineering, etc., and have huge shaft power and flux, complex pipe net and variable working conditions and gas components, which result in much difficulty in the performance testing before ex-factory and energy efficiency evaluating at user field. Processing compressors in petrochemical, coal chemical and metallurgical industries, for examples, the hydrogen compressor in oil refining, the cracking gas, propylene and ethylene compressors in ethylene production, the blower in blast-furnace and the large scale of axial compressor in air-separation system, consume huge energy and have lower operation efficiency [1].

Four types of compressor, reciprocating, screw, axial and centrifugal, are mainly used in the processing industry, and their routine tests in the manufacture's factory are very difficult because of the larger rate of flow and shaft power, complex pipe line, multiple gas constituents and their feature of inflammable, easy explosion and the toxicity. Normally the delivery test only include mechanical running, impeller accelerating and seal trial [2]. So, the compressor performance curve from manufacturer do not reflect their real quality.

However, users need real performances of processing compressors to meet the demand of flow parameter variety. Reliability, higher efficiency and long term running are basic demands of user to processing compressor, but in real operation more attentions are paid to its safety. For an example, in the surge control system of centrifugal compressor the anti-surge valve is generally opened in advance and the compressed gas is forced to flow back to inlet pipe so that the operation efficiency of compressor set is decreased. On the premise of safe and reliability how to keep the compressors operating at higher efficiency at wider range of working conditions is main developing direction of process compressor technologies, to rate real efficiency of process compressor, to grade compressors and to constantly monitor their performances for energy saving operation are also the key point of development.

In this paper it will be introduced that the present situation and development trend of performance worksite test and energy efficiency monitor technique of processing compressors. Take centrifugal compressor as example, the reasons of performances difference between user field and manufacturer factory, surge control and energy consume increase are analyzed. Relative technologies of process compressor will be discussed in the paper too.

2. Performance curves and background of user field test of process compressor as well the results analysis

Energy efficiency evaluation of compressor is basis of energy saving and carbon emission reduction, and also an effect method of impartial assessment of real operation efficiency of compressor set. For general power and refrigeration compressor, the manufacturer and/or the third part can test their real performances at varies operation conditions with different working fluids by setting up test rig because of smaller compressor power, easier operation condition adjustment and simpler gas component. So, similar to the energy efficiency standards of power and refrigeration compressor of Japan, EU and US [3], China also drawn herself energy efficiency standards and began energy efficiency identification of product [4].

For process compressor, so far, there is no complete energy efficiency identification standard in the world because exist many indeterminacy factors in the performance test. The match of compressor performances with parameter change of the process system is a big problem, which results in lower operation efficiency of compressor set. So, it is significant to research performance test and energy efficiency monitoring technique, and to draw energy efficiency standards of process compressor.

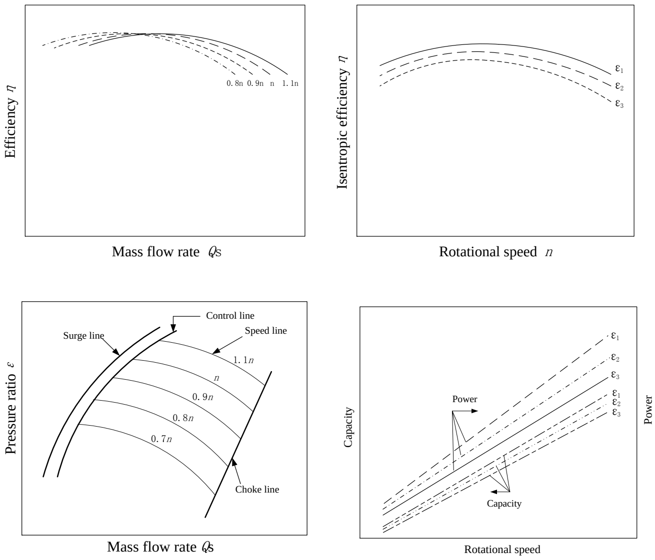
2.1. Theoretical performance curves of centrifugal compressor

Delivery quantity, discharge pressure (pressure ratio), power and so on, are characteristic performance parameters of compressor, and are also the design basis of product. Performance curve of centrifugal compressor depend on four relative parameters, the inlet flow rate *Q*s、the inlet pressure *p*s, the inlet temperature *T*s and the rotation speed of compressor *n*. At constant inlet states (*p*s, *T*s) and *n*, the stage pressure ratio ε and polytrophic efficiency η_{pol} of centrifugal compressor vary with *Q*s, $\varepsilon = f_{\varepsilon}\left(Q_s\right)$ and $\eta_{pol} = f_n(Q_s)$,which can be gotten by numerical analysis and/or theory calculation. The polytrophic efficiency η_{pol} is calculated using equation (1) below [5].

$$\eta_{pol} = \frac{\varepsilon^{(k-1/k)} - 1}{\varepsilon^{(m-1/m)} - 1} \tag{1}$$

Where *k* and *m* are isentropic index and polytrophic exponent respectively, and ε is pressure ratio.

Change trend of theoretical performance curves of centrifugal compressor is shown in figure 1(a). Vary of pressure ratio and efficiency at certain rotation speed with inlet flow rate can be gotten. At certain rotation speed to decrease inlet flow rate the pressure ratio gets large, and as the inlet flow rate is reduced to some value the surge condition of compressor set occurs. Conversely, at certain rotation speed to decrease pressure ratio the inlet flow rate gets large, and as the pressure ratio is reduced to some value the blocking condition of compressor set occurs. The conditions between surge and blocking make sure safety operation of centrifugal compressor.



(a) (b)

Figure 1. Performance curve of compressor(a) centrifugal (b) piston and screw

For positive displacement compressor, for example, the piston and screw compressors, whose theoretical efficiency is expressed as isentropic efficiency. The efficiency, power and delivery quantity (inlet flow rate) of piston and screw compressors also vary with rotation speed of compressor, see figure 1(b). At certain pressure ratio the maximum efficiencies of piston and screw compressors correspond to some rotation speed, but nothing to do with delivery quantity, so, the surge and blocking conditions do not occur for positive displacement compressor.

2.2. User field test and results analysis of process compressor

User field test of process compressor not only may get their real operation performance datum to resolve conflict between users and manufacturers or vendors, but provides references for manufacturer to improve product design to adapt real high efficiency and reliability operation demand of compressor.

M Sib Akhtar introduced a Joint Industry Project entitled “Pointing to the optimum performance of centrifugal compressors for oil & gas”[6]. In the project, design and operating data of more than 50 compressors and drivers were obtained, performance and history of the machine was analyzed over an 18-month period, and real performances varying with working conditions was gotten. For simplicity, the pointes expressing efficiency at different operation conditions in Ref. 6 were deleted, only fitted curves were retained, see figure 2.

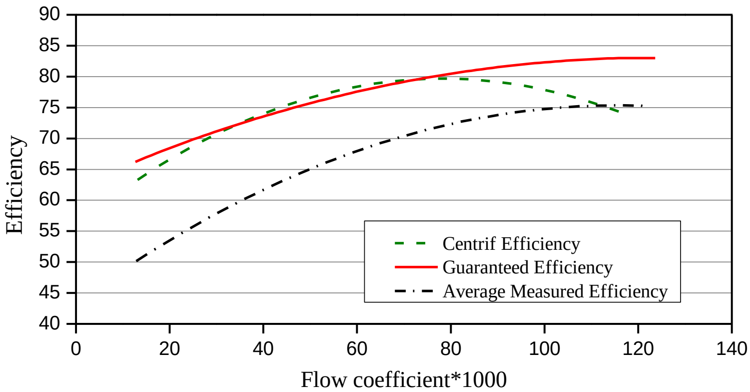


Figure 2. Comparison of compressor performance between operating and guaranteed

From figure 2 we can see that the real efficiencies of compressors are always lower than the values provided or guaranteed by manufacturer, the deviation becomes greater at small flow coefficient. The user field test results prove the significance and difficulty of design and manufacture of centrifugal compressors at small flow coefficient.

Change trends of theoretical efficiency curve of centrifugal compressor in figure 1(a) and figure 2 are alike, which have a little better coincidence with the efficiency change guaranteed by manufacturers especially at large flow coefficient. In other words, it is impossible for manufacturers to provide real operation efficiency of compressor sets because their test in factories are difficult.

Authors of this paper investigated several of petrochemical enterprises in China such as oil refining factory, where there are also performance deviation between compressor real operation and manufacturer's guarantee. To let compressor run safely real working conditions of compressor are usually far away the surge line. Running chart of compressor of an 800 thousand t/a ethylene plant in Shandong is shown in Figure 3, in which red line and blue line are separately the surge line and surge control line of pyrolysis gas centrifugal compressor. Because real operation point of compressor set, the black point in the figure, always keeps away from the surge control line by opening anti-surge valve the operation reliability of compressor is improved but much power be consumed owing to the compressed gas flowing back into inlet pipe.

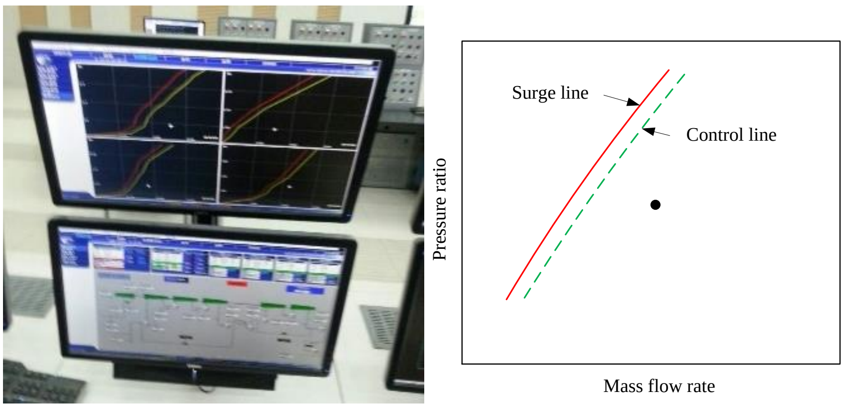


Figure 3. Running chart of compressor of 800 thousand t/a ethylene plant in China

Real operation performance curves of centrifugal compressor not only influence operation reliability of compressor set, for an example, the surge working condition will occur in advance as real flow rate is less than its demand at design conditions, but have a big effect on the energy consumption of compressor set, for instance, much more power is needed because real operation efficiency is lower than the designed value. Data from China petroleum and petrochemical energy saving monitoring centre is shown in table 1.

Table 1. Design efficiency and real operation efficiency of process compressor.

Flow Compressor name & model	Equipment	Design efficiency (%)	Operation efficiency (%)	Main reason
Turbo compressor CT5102	hydrofining	70	32.22	Lower compressor operation load, for instance, the flow rate of C1101 is 61%, the C5102 is lower.
Compressor C5102		75	55.98	
Turbo compressor CT1101	hydrocracking	70	64.71	
Compressor C1101		75	60.09	

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2.3. Difficult points of user field test of process compressor and discuss of energy efficiency labeling

The direct object of user field test of process compressor is to verify if the compressor performances guaranteed by manufacturers could be reached at design working condition and real gas operation, moreover, to provide users the actual performances curve of centrifugal compressor including curve trend, working condition points corresponding to smallest and largest flow rate for operation control and adjustment.

User field test of process compressor is different from lab or factory workshop test, field test is difficult and test result is uncertainty. Firstly, design of test system placing is subject to field environment, system parameters selection like that in laboratory is impossible. Pipe placing, operation condition change and gas compositions and so on will influence the accuracy of instrument installment and test, so, the special test plan for particular user field is essential. Secondly, it is difficult to choose the test instrument suited to the variable operation conditions. In addition, severe field environment and maintenance & calibration measure let measuring apparatus being damaged more easily, which influence test precision accuracy.

Field performances test is basis of efficiency evaluation and energy rating label of process compressor. The third part is responsible for the test and needs wide consultation on test plan from manufacturers, users and designing institute, on which typical compressor sets from petrochemical and metallurgy flow equipment can be selected for test, for examples, centrifugal and reciprocating compressor in oil refining factory, the axial compressor in the blast furnace, etc. The performances of the elected compressor sets can be tested according to ASME PTC 10 Performance Test Code on Compressors and Exhausters[7], the main parameters include inlet and outlet pressure and temperature, flow rate, gas compositions, speed, power and so on.

Main thermal parameters of process compressors can be gotten by field test and the performance parameters such as pressure ratio and efficiency of centrifugal compressor can be calculated, on which the curves of Qs-ε and η_{pol}-Qs at given speed can be plotted. At same time, about one year operation data of the compressor sets were recorded and sorted out, which is reference value of efficiency evaluation and energy rating label, see figure 4.

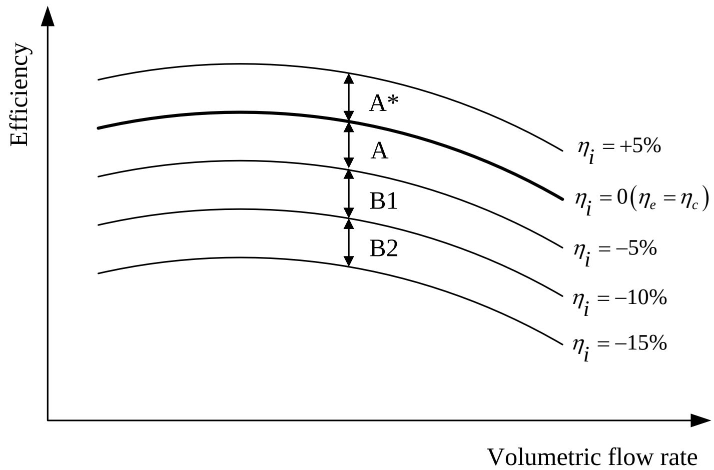

Figure4. Grading of energy efficiency of process gas compressor

For the grading of energy efficiency of process gas compressor shown in figure 4, the fundamental performances curve should be confirmed and approved by vast majority of users and manufacturers first, then energy efficiency grad is formulated according to the deviation between real performance and fundamental performance, which is expressed in equation (2).

$$\eta_i = \left(\frac{\eta_e - \eta_c}{\eta_c}\right) \times 100\% \qquad (2)$$

Where, η_i is the efficiency corresponding to the energy efficiency grad of compressor set, η_c is fundamental efficiency, and η_e is real operation efficiency. The percentage of η_e deviated from η_c can be calculated by equation (2), on which the energy efficiency grading could be done, for examples, -5% $\leqslant \eta_i < 0$, labeling as A; -10%$\leqslant \eta_i <$-5%, labeling as B1; -15%$\leqslant \eta_i <$-10%, labeling as B2, etc., If 0 %$\leqslant \eta_i <$10%, labeling as A*.

In the long run, as the development of networking and intellectualization technique it is possible to do efficiency evaluation and energy rating label on the basis of on line monitoring of real operation performances of process compressor set.

3. Energy efficiency monitoring technique of process compressor

3.1. Present situation of energy efficiency monitoring

Compressor Controls Corporation developed a kind of instantaneous monitoring software CPA [8], the monitoring results on trend of performances change and deterioration of compressors can be displayed in the remote monitoring station window connected to CCC server. CPA may monitor gas pressure and temperature in inlet and outlet of compressors, flow rate and velocity, gas compositions and so on, create models of pressure ratio ε、energy head H_{pol}、efficiency η_{pol} and energy J with flow rate Q_s、speed n and gas compositions, for instance, $\varepsilon = f\left(Q_s, n\right)$、$H_{pol} = f\left(Q_s, n\right)$、$\eta_{pol} = f\left(Q_s, n\right)$、$J = f\left(Q_s, n\right)$, calculate, monitor and record production capacity and efficiency that reflect performance parameters of compressor operation, and track the deviation situation and trend between real performances and the date from health state model and if it reaches the set threshold alarm will sound.

US OnSet Corporation summarized the defects of now available control system for compressor set [9], the efficiency control problem of application together of positive displacement and turbo compressors, the effect integration of different bands of compressor products, the advanced algorithm for best compressors combination, the complete performance monitoring, and the accurate surge condition forecast. For process compressor the indirect monitoring of power can be realized by direct testing of electric current, but more precise power calculation is necessary.

Ted Gresh introduced an on-line performance monitoring system [10], by which the health condition of compressor can be evaluated by comparing instant performance data with the parameters from factory. The performance calculation software they developed can be used to calculate the input power by using the original parameters such as pressure, temperature, speed, and flow rate of compressor. Operation state change of compressor could be monitored by the records for some time, which is used for specified maintenance and trouble founding, see figure 5.

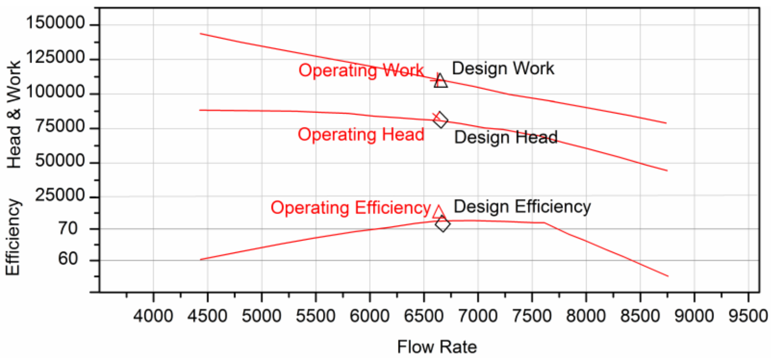

Figure5. Comparison of compressor performance between design and actual in Flexware company

A. Suomilammi and J. Leppäkoski [11] introduced another on-line performance monitor system with fuzzy classification and merging technology. System can show the desired value by using fuzzy clustering prediction model as well acquisition of history data of outlet pressure, temperature and speed of compressor, and as the performance of compressor set seriously deviates from the desired value the maintenance order will be touched off.

ITCC, Integrated Turbine Compressor Control, is a new technique based on advanced technologies such as electronic, communication, control algorithm, and so on. Nowadays, the main functions of integrated control systems for large scale of process compressors include unit interlock ESD (Emergency Shutdown Device), SOE(Sequence of Events) recording, unit control PID (for examples, anti-surge control and speed adjustment control), and routine instruction record, fault diagnosis, etc. Widely used control system in the world include Micro Net TMR of Woodward Corp., Tricon of Triconex Corp., TMR of CCC, FSC of Honeywell, GMR of GE, Trusted of ICS Triplex, and H41/H51 of Hima. Speed adjustment control, process control and compressor control in conventional control system are separate and provided by different venders, while three function control modules and their interrelationship are utilized thoroughly in the ITCC, the positive actions are enhanced and negative actions are eliminated, on which the performance integrated control of increasing operation efficiency and reliability of compressor sets, saving energy consume and fund and minimizing operation and maintenance cost can be realized to the greatest extent. ITCC can decouple anti-surge control returns, and an application case of ITCC in propylene compressor is shown in figure 6 [12]. From it we can see that the compression process of compressor comprises of six sections with each anti-surge control return and share a shaft, and scope of stable operation working conditions can be widened by move left of the new surge curve.

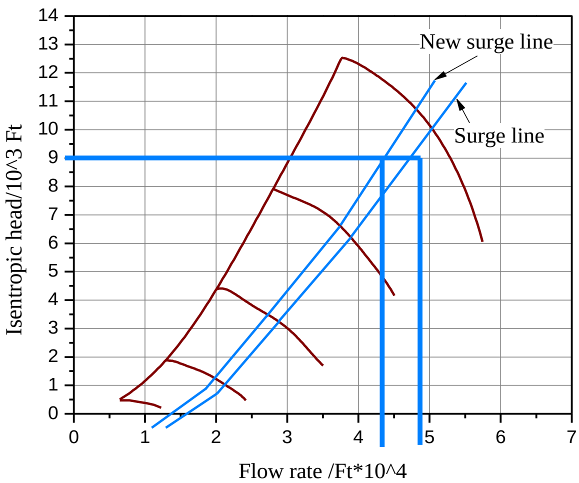

Figure 6. The surge line control of propylene compressor

Irwin Stambler [13] introduced a complex array intelligent tools by which the general health situation of gas turbo system with single cycle and combination cycle can be inspected from points of mechanics and thermodynamics. For compressor performances the operation condition can be assessed by comparison of real data with desired one.

Under the assistance of fund from Chinese Academic of Engineering and National Nature Science Foundation of China authors participate in the present operation situation investigation of compressor sets in petrochemical and metallurgy industries, and mainly focus on sets heath operation and energy efficiency monitoring [14]. Most of large scale of centrifugal compressor and piston compressor sets in the process device in China have been installed on-line operation state monitoring system but no energy efficiency monitoring system.

3.2. Development prospects of Energy Efficiency Monitoring

Energy efficiency monitoring is an important measure to ensure high efficiency operation of compressor sets. The technique development trends of energy efficiency monitor system include: (1) to synchronously test much more parameters, to set reference data base, to create real performance curves of process compressors on the basis of history operation data, and to realize the function parameters such as the power visible and adjustable; (2) to centrally regulate and control a group of compressor sets, to distribute load utilizing intelligent algorithm to ensure all compressor sets in optimum operating condition. To improve operation efficiency of compressor sets and to achieve energy efficiency maximization by depth integration optimization of compressor sets and process system; (3) to increase system efficiency of compressor set by regulating and controlling its auxiliary system, for instance, to adapt the effect of process parameters change on the operation condition by adjusting and controlling intercooler, shaft seal, and so on; (4) to keep compressor sets always run nearby the operation condition with highest efficiency by accurate predict, for an example, to push the surge control line outward the small flow interval by taking different monitoring methods so that stability margin can be widened and energy save operation can be realized for the process compressor sets.

Besides the key points mentioned above, the technique development of energy efficiency monitor of process compressors should consider these factors: (1) the compressed gas leakage result in direct power loss and leakage of process gas probably can cause emergent fatal accident such as explosion, fire, etc., so, to monitor leakage and prevent leak are not only for energy saving but for safe; (2) for noisy working environment it is exigent for developing intelligence detection apparatus to detect leakage point. To accurately fast find the leaking place it is necessary to rationally plan the exploration path and to clearly record the detection place.

4. Conclusions

(1) Full performances test of process compressor in manufacturer workshop is difficult because of variety of the real operation conditions and gas compositions, which results in performance deviation between real operation and the guaranteed data by manufacturers. For centrifugal compressor the performance deviation at small flow rate is large, so manufactures should pay more attention to the design and improvement of its prediction at small flow rate.

(2) Real performances curves of process compressor with operation condition and gas composition can be gotten by the user field test. On basis of test data energy efficiency labeling system can be planned, which is also used by manufacturers to improve compressor set performances and to better meet the need of flow parameters and users.

(3) Energy efficiency monitoring is an effective supplement of safe monitoring of process device. The regulation and control level of process compressor sets operating at full working conditions can be increased by energy efficiency and operation state monitoring so that the compressor operation nearby surge line is also reliable and the power loss owing to anti-surge valve open can be greatly decreased.

5. Appendices

H_{pol}	Energy head	J	Energy，W
k	Isentropic index	m	Polytropic exponent
n	Speed，r/min	ps	Inlet pressure，kPa
Q_s	Flow rate，m^3/min	Ts	Inlet temperature，°C
ε	Pressure ratio	η_{pol}	Polytropicefficiency，%

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