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حساب الكفاءة والاختبار التجريبي لضاغط الغاز الطبيعي الترددي

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الخـــلاصـــة

اقترحت في هذه المقالة طريقة حساب الكفاءة لضاغط الغاز الطبيعي الترددي. واستنادا إلى معادلة توازن الطاقة، استخلصت في هذه المقالة صيغة حساب الطاقة المختلفة والكفاءة لضاغط الغاز الطبيعي الترددي. وأعطيت هذه المقالة التخطيطات التجريبية والمعلمات المطلوبة لاختبار كفاءة الضاغط. قامت عشوائية باختبار كفاءة واحد وثلاثون ضاغط كامل وعشرون ضاغط علي شكل منقسم، وعلى مبادئ 4D ومبادئ متوسطة. وقدمت هذه المقالة أدنى قيمة للكفاءة المسموحة بها للضاغط الترددي. وأظهرت النتائج أن: طريقة التوازن الإيجابي وطريقة التوازن العكسي يمكن أن تستخدمها لحساب الكفاءة العامة للضاغط. وتكون الكفاءة للضاغط الكامل منخفضة وسببها الرئيسي من فقدان غاز المداخن كبيرة جدا، وتكون الكفاءة للضاغط المنقسم وسببها الرئيسي من كفاءة المحرك مرتفعة جدا. وتكون قيمة الحد الأدنى المسموح بها من محرك الاحتراق الداخلي نسبة 25٪، وتكون قيمة الحد الأدنى المسموح بها من وحدة الضاغط نسبة 85٪، وتكون قيمة الحد الأدنى المسموح بها من المحرك نسبة 60٪، وتكون قيمة الحد الأدنى المسموح بها من المحرك الكامل نسبة 16٪، وتكون قيمة الحد الأدنى المسموح بها من المحرك المنقسم نسبة 45٪.

Efficiency Evaluation and Experiment of Natural Gas Reciprocating Compressor

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ABSTRACT

This paper proposes a method of evaluating the performance of natural gas reciprocating compressor. The analytical formulas of various energy and efficiencies for integral engine compressor and separable compressor are presented on basis of their energy balance equations. The experiment setup and required parameters for calculating the energy efficiencies are stated. Experimental tests on integral engine compressor and separable compressor under various operating conditions were conducted to verify the correctness of the method. According to the 4D rule and the principal of average, the minimum allowable efficiencies of natural gas reciprocating compressor are recommended by testing thirty-one integral engine compressors and twenty separable compressors selected randomly. The results show that both the direct procedure and indirect procedure are applicable to obtaining the various efficiencies of integral engine compressor owing to their slight relative errors. Integral engine compressor efficiency is low due to large exhaust loss and heat rejection on gas engine, separable compressor efficiency is high owing to an efficient electric motor. The minimum allowable efficiency of gas engine is 25%, compressor unit 85%, electric motor 60%, integral engine compressor 16% and separable compressor 45%.

Keywords: Energy balance; gas engine; natural gas; performance evaluation; reciprocating compressor.

INTRODUCTION

Natural gas reciprocating compressor is widely utilized because of its flexibility in throughput capacity and discharge pressure in gas gathering, gas processing, gas pipeline transportation and other different industries, but suffers from a certain amount of drawbacks such as its complicated structure, high power demanded, high energy consumption and low efficiency. It is well-known that efficiency is a key indicator of reciprocating compressor performance. A major focus of efficiency improvement in reciprocating compressor is thermodynamic analysis and operating parameters optimization. Different theoretical methods for modeling reciprocating compressor have been investigated based on the energy analysis (according to the first law of thermodynamics) and exergy analysis (according to the first and second laws of thermodynamics). The difference between the energy and exergy balances was stated when considering heat recovery in an internal combustion engine (Bourhis & Leduc, 2010). The energy balance at different speed and load of engine was studied, results of which showed that the thermal efficiency of engine largely depends on the heat rejection due to exhaust gas (Taymaz, 2006). The energy utilization efficiency of engine and heat recovery potential were investigated based on the energy and exergy analysis of engine (Fu et al.,2013). An analysis of heat transfer affecting the efficiency of reciprocating compressor was performed by numerical models or integral correlations

(Tuhovcak et al., 2016). A detailed computational-fluid-dynamic study of the thermodynamic losses associated with heat transfer in reciprocating device was presented, which shows thermal loss is significant in the context of high-efficiency compressors (Willich et al., 2017). The energy efficiencies and exergy efficiencies of an internal combustion engine were evaluated by analytical assessment and experimental measurements (Ameri et al.,2010). A semi-empirical mathematical model was presented to predict the power of compressors on the basis of the thermodynamic equations fitted to manufacturer data by utilizing linear correlation, which was validated by two types of transient experimental tests (Negrao et al., 2011). A mathematical modeling of reciprocating compressor was researched based on its energy equation, piston motion equation, continuity equation and valve movement equation (Faezaneh-Gord et al., 2013). A new phenomenological model for analyzing the performance of reciprocating compressor, when considering its isoenthalpic pressure, leakages and mechanical loss was studied, which can predict the compressor and volumetric efficiencies with an error lower than 3% (Navarro et al., 2007). The effects of gas fuel composition on combustion and emission characteristics of gas engine with two different fuel compositions under different initial temperature and engine speeds was numerically studied (Kakaee et al., 2015). A new simulation approach for hermetic reciprocating compressor including electrical motor was developed, which can predict the compressor efficiency, temperature distribution and motor performance (Dutra & Deschamps, 2015). Thermal performance of reciprocating compressor was analyzed through its equations for the process of suction, compression, discharge and expansion of clearance gas (Bin et al., 2013). To study the effects of angular speed, clearance, compression ratio, natural gas compositions, cylinder geometry, piston speed and discharge to suction valve area on the performance of compressor, some theoretical models and numerical simulations of compressor were presented based on the first law of thermodynamics and real and ideal gas models (Farzaneh-Gord et al., 2015; Mutlu & Kilic, 2014; Ibrahim & Rahman, 2012).

As we know, natural gas reciprocating compressor can be classified as either “integral engine compressor” or “separable compressor” according to the connection between crankshaft and drive. Integral engine compressor is usually driven by gas engine, and separable compressor driven by electric motor (Giampaolo, 2010). For the literatures available to the authors, the peer engineers and researchers mainly focused on either gas engine or compressor cylinder efficiency. Rare work has addressed the efficiency calculation methods of the gas engine (electric motor) and compressor as a whole, though natural gas reciprocating compressor consists of compressor and gas engine (or electric motor). Furthermore, to the authors’ knowledge, the main reference standard on compressor efficiency analysis is “Monitoring and testing method for energy saving of air compressor unit and air distribution system” (Tian et al., 2013). However, air compressor is distinct from natural gas reciprocating compressor in working process and structure. The efficiency calculation methods of air compressor are not fully applicable to natural gas reciprocating compressor. Hence, a new method for evaluating the performance of natural gas reciprocating compressor is essential. The paper presents a research on calculation method of the various energy and efficiencies of integral engine compressor and separable compressor on the basis of its own energy balance equations, performs several experimental setup and field tests to verify the correctness of the method, and then gives the recommended minimum allowable efficiencies of natural gas reciprocating compressor by measuring some integral engine compressors and separable compressors selected randomly.

EFFICIENCY ANALYSIS AND CALCULATION

Integral engine compressor

The integral engine compressor driven by gas engine, where crankshaft connects to both the power cylinder and the compressor cylinder, mainly includes gas engine, compressor unit and cooling unit, as illustrated in Figure 1.

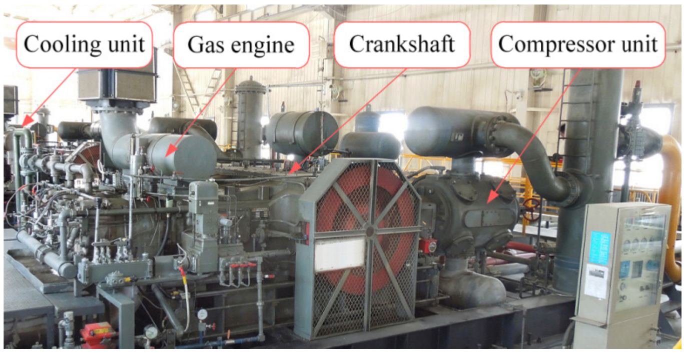

Fig. 1. Integral engine compressor driven by gas engine

The energy balance of integral engine compressor is analyzed first to obtain the efficiency calculation formulas, which indicates that the thermal energy of the fuel in gas engine is divided into four parts: energy converted to useful power, heat rejection transferred to coolant, energy loss due to exhaust gas, and other miscellaneous heat rejection, as shown in Figure 2.

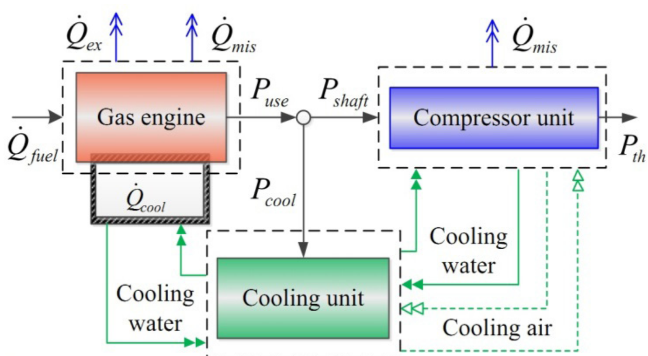

Fig. 2. Energy balance of integral engine compressor

The steady-state energy balance of integral engine compressor gives the relationship among the various kinds of energy is as follows (Abedin et al., 2013).

$$\dot{Q}_{fuel} = P_{use} + \dot{Q}_{cool} + \dot{Q}_{ex} + \dot{Q}_{mis} \tag{1}$$

The total thermal energy of fuel in gas engine $\dot{Q}_{fuel}$ in Equation (1) can be calculated by

$$\dot{Q}_{fuel} = q_{fuel} \sum x_i \cdot \mathrm{LHV}_i \tag{2}$$

where q_{fuel} is the volume flow rate of fuel in gas engine [m^3/s], x_i is the mole fraction of component in the fuel[%], is the lower heating value of the component in the fuel[kJ/m^3].

The useful power of gas engine P_{use} in Equation (1) includes the shaft power driving compressor cylinder (P_{shaft}) and cooling power driving cooling unit (P_{cool}), which can be obtained as follows.

$$P_{use} = \frac{T_{crank} \times N_{crank}}{9550} \tag{3}$$

Or

$$P_{use} = P_{cool} + P_{shaft} \tag{4}$$

$$P_{cool} = \frac{T_{cool} \times N_{cool}}{9550} \tag{5}$$

$$P_{shaft} = \sum \frac{P_{thj}}{\eta_{mej}} \tag{6}$$

$$P_{thj} = 16.745 \sum_{j=1} p_{1j} q_{gas} \frac{k}{k-1} [(\frac{p_{2j}}{p_{1j}})^{\frac{k-1}{k}} - 1] \frac{Z_{1j} + Z_{2j}}{2Z_{1j}} \tag{7}$$

$$\eta_{mej} = \frac{T_{1j}}{T_{2j} - T_{1j}} [(\frac{p_{2j}}{p_{1j}})^{\frac{k-1}{k}} - 1] \times 100\% \tag{8}$$

where T_{crank} and T_{cool} are the torque of crankshaft and cooling unit respectively [$\mathrm{N \cdot m}$], N_{crank} and N_{cool} are the rotational speed of crankshaft and cooling unit respectively [r/min], P_{thj} is the theoretical indicated power of the jth stage compressor cylinder [kW], η_{mej} is the mechanical efficiency of the jth stage compressor cylinder [%], p_{1j} is the inlet pressure of the jth stage compressor cylinder [MPa], p_{2j} is the outlet pressure of the jth stage compressor cylinder [MPa], q_{gas} is the volume flow rate of natural gas in compressor unit[m^3/s], k is the specific heat ratio of natural gas, Z_{1j} is the compressibility factor of the jth stage inlet gas, Z_{2j} is the compressibility factor of the jth stage outlet gas.

The overall heat rejection carried away by the cooling water $\dot{Q}_{cool}$ in Equation (1) can be expressed by

$$\dot{Q}_{cool} = c_{pw}\rho_w V_w (T_{w2} - T_{w1}) \tag{9}$$

where c_{pw} is the specific heat capacity of cooling water [kJ /(kg·°C)], ρ_w is the density of cooling water [kg/m^3], V_w is the actual volume flow rate of cooling water [m^3/s], T_{w2} and T_{w1} are the outlet and inlet temperature of cooling water on gas engine respectively [°C].

The energy loss due to the exhaust gas $\dot{Q}_{ex}$ in Equation (1) can be calculated by

$$\dot{Q}_{ex} = q_{fuel} V_{ex} (c_{pex} t_{ex} - 27.18) \tag{10}$$

$$V_{ex} = 0.01 \times \begin{bmatrix} \varphi(CO_2) + \varphi(CO) + \varphi(H_2) + 2\varphi(H_2S) + \\ \varphi(N_2) + \sum (m + 0.5n)\varphi(C_m H_n) + 0.124\varphi(H_2O) \end{bmatrix} + (1.016\alpha_{ex} - 0.21)V_{air} \tag{11}$$

$$\alpha_{ex} = \frac{21}{21 - 79 \times \dfrac{\varphi'(O_2) - [0.5\varphi'(CO) + 0.5\varphi'(H_2) + 2\varphi'(C_m H_n)]}{100 - [\varphi'(RO_2) + \varphi'(O_2) + \varphi'(CO) + \varphi'(H_2) + \varphi'(C_m H_n)]}} \tag{12}$$

$$V_{air} = 0.0476 \times \begin{bmatrix} 0.5\varphi(CO) + 0.5\varphi(H_2) + 1.5\varphi(H_2S) + 2\varphi(CH_4) \\ + \sum (m + 0.25n)\varphi(C_m H_n) - \varphi(O_2) \end{bmatrix} \tag{13}$$

where V_{ex} is the volumetric coefficient of exhaust gas, c_{pex} is the mean specific heat capacity of exhaust gas[kJ /(kg·°C)], t_{ex} is the mean temperature of exhaust gas [K], φ is the volume fraction of the component in fuel[%], α_{ex} is the excess air coefficient of exhaust gas, V_{air} is the amount of theory air under standard state [m^3], φ' volume fraction of component in exhaust gas, [%].

The miscellaneous heat rejection $\dot{Q}_{mis}$ in Equation (1) consists of unburned fuel energy and heat transfer loss due to convection and radiation on the surface of reciprocating compressor, etc. It is often difficult to measure miscellaneous heat rejection in practice, which can be calculated by subtraction rule as follows.

$$\dot{Q}_{mis} = \dot{Q}_{fuel} - (P_{use} + \dot{Q}_{cool} + \dot{Q}_{ex}) \tag{14}$$

Hence, there are two ways of calculating the various efficiencies of integral engine compressor based on its energy balance: one is direct procedure and the other indirect procedure. Direct procedure is also known as input-output method, the efficiency of reciprocating compressor can be acquired by calculating the input and output energy with this method. Indirect procedure is called heat loss method, the efficiency of reciprocating compressor with this method can be obtained by calculating the input energy and heat loss due to exhaust gas, convection and radiation, etc. As a result, the various kinds of efficiencies of integral engine compressor are calculated as follows:

For the direct procedure:

$$\eta_{heat} = \frac{P_{cool} + P_{shaft}}{\dot{Q}_{fuel}} \times 100\% \tag{15}$$

$$\eta_{me} = \frac{P_{th}}{P_{shaft}} \times 100\% \tag{16}$$

For the indirect procedure:

$$\eta'_{heat} = (1 - \frac{\dot{Q}_{cool} + \dot{Q}_{ex}}{\dot{Q}_{fuel}} - q'_{mis}) \times 100\% \tag{17}$$

$$\eta'_{me} = \frac{P_{th}}{\eta'_{heat}\dot{Q}_{fuel} - P_{cool}} \times 100\% \tag{18}$$

where η_{heat} is the heat efficiency of gas engine calculated by direct procedure, η_{me} is the mechanical efficiency of compressor unit obtained by direct procedure, η'_{heat} is the heat efficiency of gas engine calculated by indirect procedure, η'_{me} is the mechanical efficiency of compressor unit obtained by indirect procedure, q'_{mis} is the loss percentage due to miscellaneous heat rejection.

Considering both gas engine and compressor, the overall efficiency of integral engine compressor can be expressed as the ratio of the theoretical indicated power in compressor cylinders to the total thermal energy of fuel in gas engine, as presented in Equation (19).

$$\eta_{overall} = \frac{P_{th}}{\dot{Q}_{fuel}} \times 100\% \tag{19}$$

Separable compressor

The separable compressor is usually driven by electric motor and has a balanced-opposed design to minimize unbalanced forces and moments, which compressor unit and electric motor are separated by a coupling or gearbox, as shown in Figure 3. As can be seen in Figure 4, the energy balance of separable compressor reveals that the energy consists mainly of four parts: electrical energy, shaft power driving compressor unit, cooling power driving cooling unit and the other miscellaneous heat rejection, relationship of which can be expressed by Equation (20).

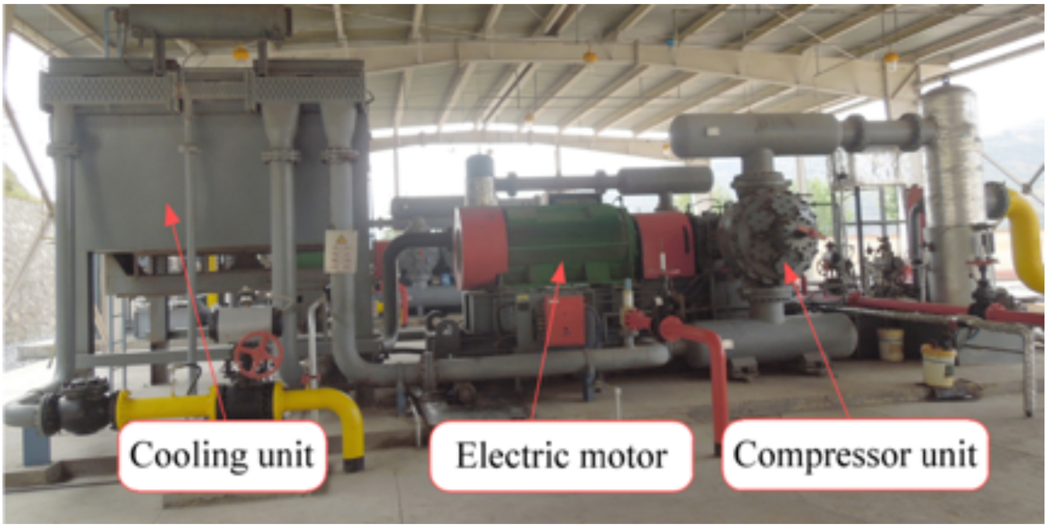

Fig. 3. Separable compressor driven by electric motor

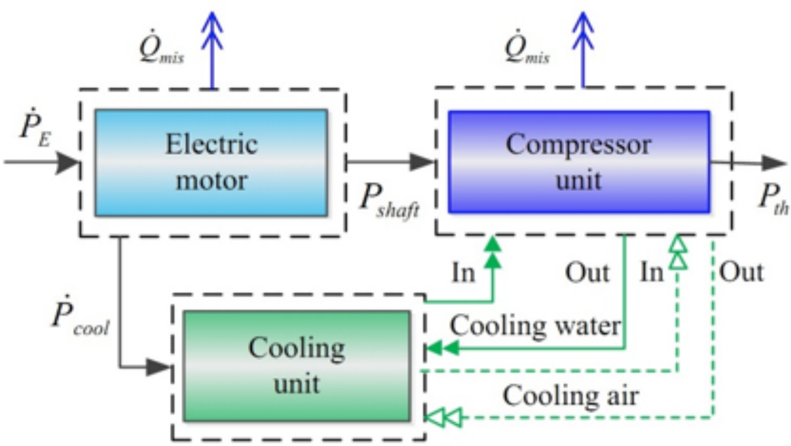

Fig. 4. Energy balance of separable compressor driven by electric motor

$$\dot{P}_E = \dot{P}_{cool} + P_{shaft} + \dot{Q}_{mis} \tag{20}$$

where $\dot{P}_E$ and $\dot{P}_{cool}$ measured by electric meter are the output electric energy of electric motor and cooling power respectively [kW], P_{shaft} and $\dot{Q}_{mis}$ are the same as those of integral engine compressor, as mentioned above.

The formulas calculating the electric motor efficiency ,η_{motor} the mechanical efficiency of compressor unit η_{me}, and the overall efficiency of separable compressor $\eta_{overall}$ are presented as follows.

$$\eta_{motor} = \frac{P_{shaft} + \dot{P}_{cool}}{\dot{P}_E} \times 100\% \tag{21}$$

$$\eta_{me} = \frac{P_{th}}{P_{shaft}} \times 100\% \tag{22}$$

$$\eta_{overall} = \frac{P_{th}}{\dot{P}_E} \times 100\% \tag{23}$$

EXPERIMENTAL TEST AND EFFICIENCY ANALYSIS

Integral engine compressor

The experimental setup of integral engine compressor is shown in Figure 5, which can be applied to measuring gas and water flow rate, components of natural gas and exhaust gas, inlet and outlet temperature, inlet and outlet pressure and so on. The required instruments and uncertainty of measured parameters are given in Table 1. The exhaust gas composition test is illustrated in Figure 6.

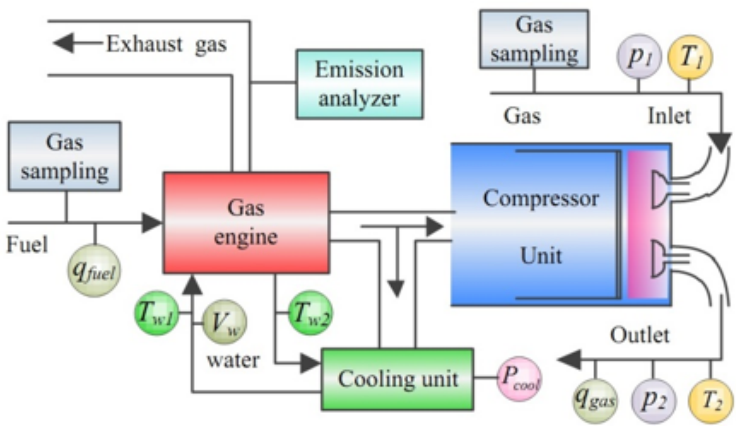

Fig. 5. Experimental setup of integral engine compressor

Table 1. Instruments and uncertainty of measured parameters

Instrument	Measurement	Error level
Gas chromatograph	Gas composition	0.01%
Ultrasonic flow meter	Volume flow rate	0.1m/s
Emission analyzer	Exhaust gas composition	5ppm
Torque meter	Torque	2.8 N.M
Speed meter	Rotate speed	1rpm
Thermometer	Temperature	0.1°C
Pressure meter	Pressure	0.1MPa
Power meter	Electric energy	0.5%

Fig. 6. Exhaust gas composition test on integral engine compressor

Seven experiments were conducted on an integral engine compressor (see Figure 1), under various operating conditions, to verify the correctness and feasibility of the efficiency calculation methods of integral engine compressor mentioned in previous sections. The first four experiments were performed under different inlet pressure and constant outlet pressure of compressor. Specifically, the inlet pressure varied from 0.9MPa to 1.2MPa at intervals of 0.1MPa, while the outlet pressure kept 7.5MPa. The last four experiments were tested under constant inlet pressure and different outlet pressure of compressor, which means the inlet pressure was always 1.2MPa, and the outlet pressure varied from 7.5MPa to 9.0MPa at intervals of 0.5MPa. According to Figure 5, each parameter needs to be collected three times and only the average value is selected to minimize the measurement errors when collecting data.

When the inlet pressure is 0.9MPa and outlet pressure is 7.5MPa, the natural gas and fuel composition for obtaining the lower heating value of fuel is listed in Table.2, the exhaust gas composition of gas engine for calculating the energy loss due to the exhaust gas is presented in Table 3, the test data of the integral engine compressor for calculating the theoretical indicated power of compressor unit and heat rejection carried away by the cooling water is listed in Table 4. Using these test data and the efficiency calculation methods of integral engine compressor mentioned above, the heat efficiency of gas engine and mechanical efficiency of compressor unit are determined by both the direct procedure and indirect procedure, and the various efficiencies and other parameters of the integral engine compressor are given in Table 5.

Table 2. The natural gas and fuel compositions

Component	Mole(%)	Component	Mole(%)
Methane (CH_4)	86.01	Carbon Dioxide (CO_2)	0.72
Ethane (C_2H_6)	2.55	Nitrogen (N_2)	1.20
Propane (C_3H_8)	0.52	Helium (H_e)	0.02
Isobutane (iC_4)	0.08	Hydrogen (H_2)	8.47
Normal Butane (nC_4)	0.06	Hydrogen Sulfide (H_2S)	0
Isopentane (iC_5)	0.03	Carbon Monoxide (CO)	0
Normal Pentane (nC_5)	0.02	Others	0.21
Hexane plus (C_6^+)	0.06		

Table 3. Exhaust gas compositions of the gas engine

Component	Value	Component	Value	Component	Value
O_2 (%)	16.45	NO (ppm)	52	SO_2 (ppm)	3
CO (ppm)	57	NO_2 (ppm)	9	H_2 (ppm)	7
CO_2 (%)	3.38	NO_x (ppm)	61	C_mH_n/(ppm)	17

Table 4. Test data of integral engine compressor

Parameter	Value	Parameter	Value	Parameter	Value
q_{fuel} (m³/h)	145.2	T_{21} (°C)	120	p_{22} (MPa)	7.57
q_{gas} (m³/h)	5504.3	T_{12} (°C)	35	P_{cool} (kW)	15.5
$\dot{V}_w$ (m³/h)	37.4	T_{22} (°C)	125	T_{w1} (°C)	29.3
t_{ex} (°C)	376.3	p_{11} (MPa)	0.89	T_{w2} (°C)	34.9
T_{11} (°C)	24.1	p_{21} (MPa)	2.69		

Table 5. Calculation results of integral engine compressor

Parameter	Value	Parameter	Value	Parameter	Value
$\dot{Q}_{fuel}$ (kW)	1303.57	$\dot{Q}_{cool}$ (kW)	174.58	η'_{heat} (%)	34.02
P_{th} (kW)	382.92	$\dot{Q}_{ex}$ (kW)	638.31	η'_{heat} (%)	35.14
P_{shaft} (kW)	428.01	$\dot{Q}_{mis}$ (kW)	47.17	η_{me} (%)	89.46
P_{cool} (kW)	15.5	$\eta_{overall}$ (%)	29.37	η'_{me} (%)	86.51

Similarly, rest of the six experiments were completed after setting the inlet or outlet pressure of compressor unit. Moreover, the various kinds of efficiencies of integral engine compressor are listed in Table 6.

Table 6. The various efficiencies of the integral engine compressor

Case	Pressure(MPa)		Gas engine efficiency (%)			Compressor unit efficiency (%)			Overall efficiency (%)
	Inlet	Outlet	Direct procedure	Indirect procedure	Relative error	Direct procedure	Indirect procedure	Relative error	
1	0.9	7.5	34.02	35.14	-3.29	89.47	86.52	3.30	29.37
2	1.0	7.5	33.03	34.01	-2.97	89.66	87.01	2.96	28.55
3	1.1	7.5	32.26	33.46	-3.72	89.92	86.58	3.71	27.94
4	1.2	7.5	31.88	32.54	-2.07	90.65	88.74	2.11	27.82
5	1.2	8.0	31.82	32.69	-2.73	92.07	89.54	2.75	28.21
6	1.2	8.5	32.47	32.84	-1.14	92.95	91.85	1.18	29.07
7	1.2	9.0	32.86	33.94	-3.29	92.86	91.78	1.16	29.15

It can be seen that the efficiency of gas engine calculated by direct procedure is slightly lower than that calculated by indirect procedure, while the efficiency of compressor unit acquired by direct procedure is slightly higher than that obtained by indirect procedure because of the difficulty in precisely measuring the loss percentage due to miscellaneous heat rejection. The relative error of the two procedures is small and within 5%, which meets the engineering allowance. The results show that either direct procedure or indirect procedure is feasible for calculating the efficiencies of integral engine compressor. With an increase in the compression ratio of compressor, the efficiency of compressor unit decreases; however, the efficiency of gas engine and overall efficiency of the integral engine compressor increases, because the loading percentage of gas engine and outlet temperature of compressor increase with higher compression ratio. So the increase of the overall efficiency is limited by the compression ratio.

Figure 7 illustrates the energy distribution of integral engine compressor, which shows the ratio of the useful power, heat rejection carried away by the cooling water, exhaust loss due to the exhaust gas, and other miscellaneous heat rejection to fuel energy in gas engine are 32.67%, 13.19%, 50.97% and 3.18% (on the average), respectively. Integral engine compressor suffers from a low efficiency because of a high heat rejection due to exhaust gas. Thus, reducing exhaust loss could improve the efficiency of integral engine compressor.

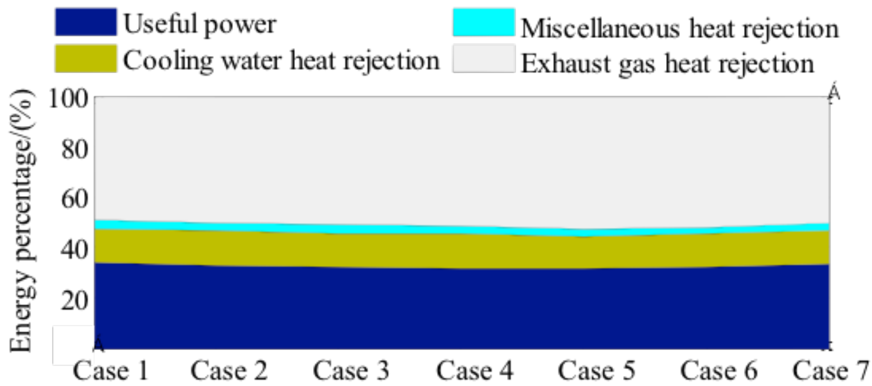

Fig. 7. Energy distribution of integral engine compressor

Separable compressor

The experimental setup of separable compressor is shown in Figure 8, which is applied to measuring electric power, gas flow rate, components of natural gas, inlet and outlet temperature and inlet and outlet pressure. The main parameters needed to be tested are natural gas compositions and operating parameters of separable compressor. Six separable compressors driven by electric motor were measured to determine their efficiencies.

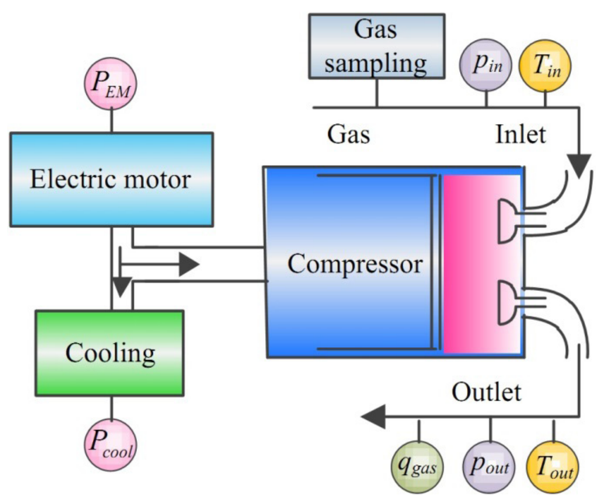

Fig. 8. Experimental setup of separable compressor

The natural gas compositions and operating parameters of one separable compressor (see Figure 3) are listed in Table 7 and Table 8, respectively. Hence, the various energy efficiencies of the separable compressor can be obtained, as shown in Table 9. Meanwhile, the various efficiencies of the rest five separable compressors were obtained in the same way, as presented in Figure 9. The results show that the mean overall separable compressor efficiency is 55.87%, the mean electric motor efficiency 66.63%, and the mean compressor unit efficiency 86.21%. The overall efficiency of the separable compressor driven by electric motor is high owing to a high efficiency of electric motor.

Table 7. Natural gas compositions of separable compressor

Component	Mole(%)	Component	Mole(%)
Methane (CH_4)	95.03	Carbon Dioxide (CO_2)	1.81
Ethane (C_2H_6)	2.23	Nitrogen(N_2)	0.28
Propane (C_3H_8)	0.26	Helium (H_e)	0.02
Isobutane (iC_4)	0.04	Hydrogen (H_2)	0.03
Normal Butane (nC_4)	0.03	Hydrogen Sulfide (H_2S)	0
Isopentane (iC_5)	0.01	Carbon Monoxide (CO)	0
Normal Pentane (nC_5)	0.01	Others	0.21
Hexane plus (C_6^+)	0.02		

Table 8. Test data of separable compressor

Parameter	Value	Parameter	Value	Parameter	Value
$\dot{Q}_E$ (kW)	4871	T_{21}(°C)	107.3	p_{11}(MPa)	0.91
q_{gas} (m³/h)	46501.2	T_{12}(°C)	37.1	p_{21}(MPa)	2.34
T_{11} (°C)	21.2	T_{22}(°C)	103.4	p_{22} (MPa)	4.46

Table 9. Calculation results of separable compressor

Parameter	Value	Parameter	Value	Parameter	Value
P_{th}(kW)	2705.19	$\dot{Q}_{mis}$ (kW)	1692.64	η_{me}(%)	85.11
P_{shaft} (kW)	3178.36	h_{motor} (%)	66.21	$\eta_{overall}$(%)	55.53

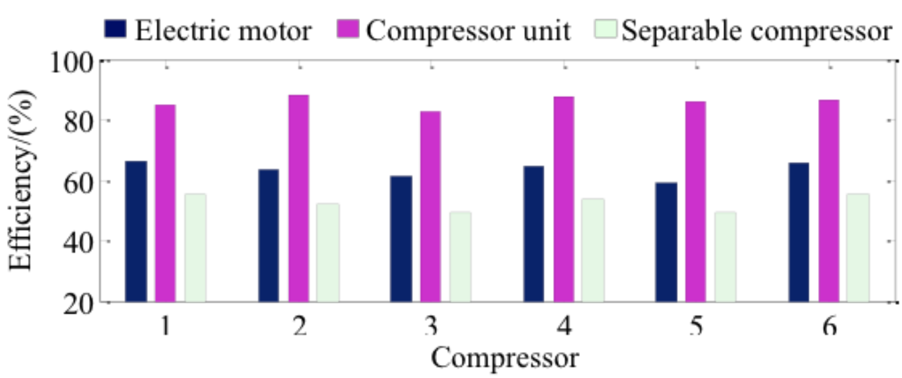

Fig. 9. Results of separable compressor efficiencies

FIELD TEST AND APPLICATION

By applying the various efficiencies calculation method and experimental setup of reciprocating compressor discussed above, the various kinds of efficiencies of thirty-one integral engine compressors and twenty separable compressors selected randomly were determined under their own steady-state operating conditions, as shown in Figure 10 and Figure 11, respectively. The results show that different reciprocating compressors have different efficiency, so the minimum allowable efficiencies of integral engine compressor and separable compressor are recommended via 4D rule to evaluate their performance in the paper. For integral engine compressor, the minimum allowable efficiency of compressor unit is 85%, gas engine 25%, and integral engine compressor 16%, as presented in Figure 10. For separable compressor, the minimum allowable efficiency of compressor unit is also 85%, electric motor 60%, and separable compressor 45%, as shown in Figure 11. As can be seen in Figure 10 and Figure 11, several integral engine compressors and separable compressors suffer from low efficiency, which indicates some energy-saving measures should be taken to improve the energy efficiency of compressor.

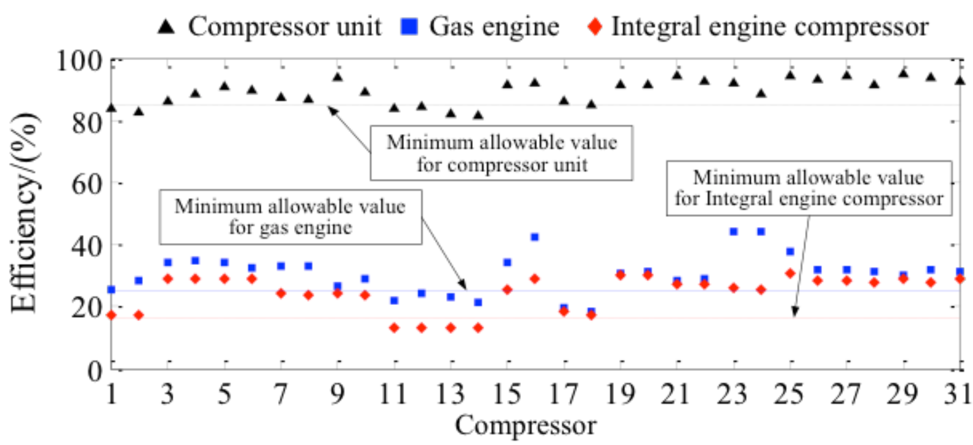

Fig. 10. Various kinds of efficiencies of integral engine compressors

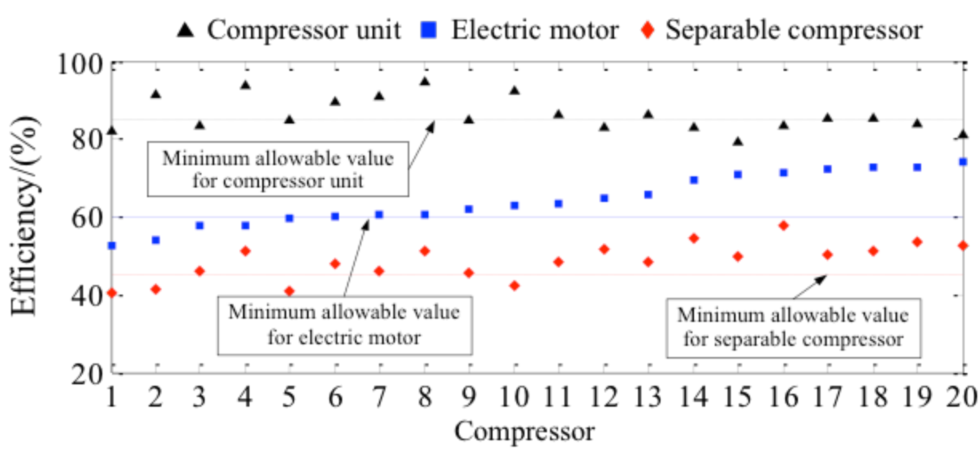

Fig. 11. Various kinds of efficiencies of separable compressors

CONCLUSIONS

A method was described to calculate the various kinds of energy efficiencies of natural gas reciprocating compressor. Analytical formulas of various energy efficiencies for integral engine compressor and separable compressor were proposed based on their energy balance equation, which were verified by several steady-state experimental tests on integral engine compressor and separable compressor.

Seven experiments on an integral engine compressor under various operating conditions by changing the inlet pressure and outlet pressure show that both the direct procedure and indirect procedure can be applied to determining its energy efficiencies as the relative error is less than 5%. The energy distribution shows a low overall efficiency of integral engine compressor mainly results from a large exhaust loss due to exhaust gas. Experiments on six separable compressors show the mean efficiencies of separable compressor, electric motor and compressor unit are 55.87%, 66.63% and 86.21%, respectively. Separable compressor driven by electric motor has high efficiency by reason of an efficient electric motor.

The minimum allowable efficiencies of integral engine compressor and separable compressor were given via 4D rule by testing thirty-one integral engine compressors and twenty separable compressors selected randomly. The minimum allowable efficiencies of compressor unit, gas engine, electric motor, integral engine compressor and separable compressor are 85%, 25%, 60%, 16% and 45%, respectively.

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REFERENCES

Abedin, M. J., Masjuki, H. H., Kalam, M. A., Sanjid, A., Rahman, S. A., & Masum, B. M. 2013. Energy balance of internal combustion engines using alternative fuels. Renewable and Sustainable Energy Reviews, 26: 20-33.

Ameri, M., Kiaahmadi, F., Khanaki, M., & Nazoktabar, M. 2010. Energy and exergy analyses of a spark-ignition engine. International Journal of Exergy, 7: 547-563.

Bin, T., Yuanyang, Z., Liansheng, L., Guangbin, L., Le, W., Qichao, Y., & Wenhui, M. 2013. Thermal performance analysis of reciprocating compressor with stepless capacity control system. Applied Thermal Engineering, 54(2): 380-386.

Bourhis, G., & Leduc, P. 2010. Energy and Exergy Balances for Modern Diesel and Gasoline Engines. Oil & Gas Science and Technology – Rev. IFP, 65:39-46.

Dutra, T., & Deschamps, C. J. 2015. A simulation approach for hermetic reciprocating compressors including electrical motor modeling. International Journal of Refrigeration, 59: 168-181.

Farzaneh Gord, M., Niazmand, A., & Deymi-DashteBayaz, M. 2013. Optimizing reciprocating air compressors design parameters based on first law analysis. UPB Scientific Bulletin, Series D: Mechanical Engineering, 75; 13-26.

Farzaneh-Gord, M., Niazmand, A., Deymi-Dashtebayaz, M., & Rahbari, H. R. 2015. Thermodynamic analysis of natural gas reciprocating compressors based on real and ideal gas models. International Journal of Refrigeration, 56:186-197.

Farzaneh-Gord, M., Niazmand, A., Deymi-Dashtebayaz, M., & Rahbari, H. R. 2015. Effects of natural gas compositions on CNG (compressed natural gas) reciprocating compressors performance. Energy, 90:1152-1162.

Fu, J., Liu, J., Feng, R., Yang, Y., Wang, L., & Wang, Y. 2013. Energy and exergy analysis on gasoline engine based on mapping characteristics experiment. Applied Energy, 102: 622-630.

Giampaolo, T. 2010. Compressor Handbook: Principles and Practice. The Fairmont Press.

Ibrahim, T. K., & Rahman, M. M. 2012. Effect of compression ratio on performance of combined cycle gas turbine. International Journal of Energy Engineering, 2: 9-14.

Kakaee, A. H., Rahnama, P., & Paykani, A. 2015. Influence of fuel composition on combustion and emissions characteristics of natural gas/diesel RCCI engine. Journal of Natural Gas Science and Engineering, 25: 58-65.

Mutlu, M., & Kilic, M. 2014. Effects of piston speed, compression ratio and cylinder geometry on system performance of a liquid piston. Thermal Science, 00: 146-146.

Navarro, E., Granryd, E., Urchueguia, J. F., & Corberan, J. M. 2007. A phenomenological model for analyzing reciprocating compressors. International Journal of Refrigeration, 30: 1254-1265.

Negrao, C. O., Erthal, R. H., Andrade, D. E., & Da Silva, L. W. 2011. A semi-empirical model for the unsteady-state simulation of reciprocating compressors for household refrigeration applications. Applied Thermal Engineering, 31:1114–1124.

Taymaz, I. 2006. An experimental study of energy balance in low heat rejection diesel engine. Energy, 31: 364-371.

Tian, J., Liang, Z., & Yang, L., 2013. A counter-balance method for energy efficiency calculation of the integral natural gas engine-compressor. Acta Petrolei Sinica, 34: 787-791.

Tuhovcak, J., Hejcik, J., & Jicha, M. 2016. Comparison of heat transfer models for reciprocating compressor. Applied Thermal Engineering, 103: 607-615.

Willich, C., Markides, C. N., & White, A. J. 2017. An investigation of heat transfer losses in reciprocating devices. Applied Thermal Engineering, 111: 903-913.

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