Comparative Analysis of Air Compressor Energy Efficiency Standards of China, EU and USA

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Abstract.

China has established a comprehensive standardization framework for air compressors, encompassing both product specification and energy efficiency standards. This paper presents the latest iteration of “GB 19153-2019 Minimum allowable values of energy efficiency and energy efficiency grades for displacement air compressor”[1] (GB19153), elucidating its scope, energy efficiency metrics, classification criteria, and testing parameters.

Moreover, this paper delineates China's recent endeavors in enhancing the efficiency standardization of compressed air systems, as articulated in the industry standard" T/CGMA 033001-2018 Guide to Energy Efficiency Classification for Compressed Air Stations." [2] (T/CGMA033001) . This standard proffers a classification scheme for the energy efficiency of compressed air stations within China, exhibiting a discernible 10% variance in efficiency between adjacent grades and a notable 45% discrepancy between Grade 1 and Grade 5. Grade 5's energy efficiency level typifies the average performance of extant compressed air stations in China.

Furthermore, a comparative analysis of air compressor minimum energy performance standard (MEPS) across GB19153, the EU Lot31 proposal "Possible requirements for compressors for standard air applications DRAFT ECODESIGN REGULATION"[3] (Lot31) , and the US standard "Energy Conservation Program: Energy Conservation Standards for Air Compressors[4]"(ECSAC) is conducted, encompassing facets such as product scope, energy efficiency metrics, tolerance thresholds, testing conditions, and MEPS stipulations.

It is recommended that the potential for energy savings in compressed air systems far exceeds that of individual components. As efforts in energy conservation deepen, emphasis will inevitably shift towards enhancing system-wide energy efficiency, particularly concerning the energy conservation of compressed air stations. International organizations and societies ought to pay greater attention to promoting the efficiency of compressed air systems.

1 Introduction of air compressor energy efficiency standardization of China

In accordance with the "Energy Conservation Law of the People's Republic of China", minimum energy performance standard GB 19153 have been developed for air compressors. The mandatory energy efficiency standards set the minimum energy efficiency requirements for products on sale based on corresponding energy efficiency metrics, and they have strong legal effect.

The first version of the MEPS for air compressors in China, GB 19153-2003, was published on May 23, 2003, and implemented on November 1, 2003. The second version of the MEPS, GB 19153-2009, was implemented on December 1, 2009. Currently, the third version, GB 19153-2019, is being implemented, which was released on December 31, 2019, and implemented on July 1, 2020.

China has also established MEPS, GB 28381-2012, titled "Minimum allowable values of energy efficiency and evaluating values of energy conservation for centrifugal blower" for blowers. Based on ISO pressure classifications, blowers are categorized as low-pressure compressors too. Within the Chinese standard context, the compressors with discharge pressures greater than 0.2 MPa are referred to as air compressors, while those with pressures lower than 0.2 MPa are called blowers. The air compressors referred to in this paper are displacement compressors with discharge pressures greater than 0.2 MPa.

The Chinese air compressor standard system consists of product specification standards and energy efficiency standards. The product specification standards mainly define the parameters, technologies (such as safety, environmental protection, and operating requirements), testing, and packaging and storage requirements for the products. There are more than 20 product standards for air compressors, including those for standard pressure air, high-pressure air, process air, hydrogen, oxygen, and carbon dioxide applications, as well as compressors with piston, screw, single screw, and sliding vane structures.

2 Analysis of China air compressor MEPS

GB 19153 stipulates the energy efficiency classification, minimum efficiency requirements, and testing and efficiency calculation methods for displacement air compressors.

2.1 Product scope

The MEPS in China must be based on product standards, which determine the product scope. Air compressor product types: fixed-speed rotary air compressors, variable-speed rotary air compressors, oil-lubricated reciprocating piston air compressors, and oil-free reciprocating piston air compressors.

The power range of air compressors is significant, as the power of driving motors have been used as the reference for air compressor power classification and categorizing.

The pressure and power ranges for each type of product are as follows [1] :

- **Oil-injected rotary air compressors**: the motor power ranges from 1.5 kW to 630 kW, and the discharge pressure ranges from 0.25 MPa to 1.4 MPa.
- **Variable-speed oil-injected rotary air compressors**: the motor power ranges from 2.2 kW to 315 kW, and the discharge pressure ranges from 0.25 MPa to 1.4 MPa.
- **Reciprocating piston air compressors**: the motor power ranges from 0.75 kW to 75 kW, and the discharge pressure ranges from 0.25 MPa to 1.4 MPa. Related air compressor product standards include GB/T 13928 and GB/T 13928.
- **Oil-free reciprocating piston air compressors**: the motor power ranges from 0.55 kW to 22 kW, and the discharge pressure ranges from 0.4 MPa to 1.4 MPa.

2.2 Energy efficiency metric

GB19153 employs the specific energy requirements (SER) as the energy efficiency metric for air compressors. This choice is based on several key considerations as following:

1. Continuity with previous versions: The 2003 and 2009 editions of GB 19153 already utilized SER approach, which is familiar to a wide range of users and energy management departments.
2. Historical usage and alignment with other compressor standards in China: SER has been employed in Chinese standards for a long time. Over 20 compressor standards, have utilized this metric. As early as the 1980s, SER was adopted as the energy efficiency metric in Chinese air compressor standards, and subsequently, various standards, including screw, piston, sliding vane, and diaphragm compressors, as well as compressors for other gases such as compressed oxygen, hydrogen, and carbon dioxide, have utilized this metric.

2.3 Energy efficiency classification

GB 19153 are classified into 3 energy efficiency grades. The energy efficiency levels 1, 2, and 3 are divided into three performance categories: entry level, energy-saving level, and advanced level. The entry level is the minimum energy efficiency threshold for relevant product equipment to access the market, and its value is consistent with the current mandatory energy efficiency standard limit values.

2.4 Test conditions

2.4.1 Standard inlet conditions

The standard conditions from GB 19153 for air compressors adopts the methods of the ISO 1217:2009 MOD for the inlet conditions of air compressors, which is consistent with Lot31 and ECSAC. The reference standard inlet conditions for compressors are specified as follows:

- Inlet air pressure: 100 kPa [1 bar] (a);
- Inlet air temperature: 20°C;
- Relative water vapor pressure: 0
- Cooling water temperature: 20°C

As SER is greatly influenced by the outlet pressure, GB 19153 specifies several rated outlet pressure points. These points assess SER tested at one of the rated pressure points within the operating pressure range of the air compressor. The rated pressures for rotary compressors are: 0.3, 0.5, 0.7, 0.8, 1.0, 1.25 MPa , and for piston compressors: 0.25, 0.4, 0.5, 0.7, 0.8, 1.0, 1.25 MPa.

2.4.2 Temperature

GB 19153 adopts the national test standard GB/T 3853 "Displacement Compressor - Acceptance Test"[6]. This compressor test standard is derived from ISO 1217. But GB19153 adds a correction for SER when the intake temperature of the air compressor deviates from the standard conditions during the test.

The test environment has a certain impact on the energy performance of the air compressor. GB19153 require the energy efficiency of air compressors to be indicated under standard inlet conditions. However, due to the high power of many air compressors, it may not be feasible to maintain the intake condition of the air compressor at a stable temperature of 20°C and a pressure of 1 bar during testing. The actual temperature and pressure can deviate significantly from 20°C and 1 bar(a). While ISO 1217 provides a method to correct the SER value for deviations in the intake pressure, it does not provide a correction for deviations in intake temperature. We have noticed that the approach taken by ECSAC is to specify a narrower range for the intake temperature of the air compressor to ensure that the measured SER deviates minimally from the SER under standard inlet conditions "DOE seeks comment regarding its proposal to maintain the current ambient temperature range requirement of 68-90 °F for testing air compressors." [4] (20 - 32.2°C)

Due to the large scale of China's territory and significant temperature differences between regions and seasons, there is also a considerable variation in the test environment temperature. GB 19153 specifies an environmental temperature range of 5°C to 40°C for testing and provides a SER correction formula for temperature deviation:

$$e_{VC} = K_{14} \cdot \frac{P_{corr}}{q_{V,corr}} \quad \text{..............} \ (1)$$

$$K_{14} = \sqrt{\frac{T_x}{293.2}} \quad \text{..............} \ (2)$$

e_{VC} – rated SER of the compressor

K_{14} - dimensionless correction factor for SER with respect to suction temperature. This value is obtained through statistical data analysis.

Pcorr - power of the compressor measured and corrected according to GB/T 3853;

$q_{(V,corr)}$ - volume flow rate of the compressor measured and corrected according to GB/T 3853.

K_{14} is an empirical correction factor. The graph below illustrates the pre- and post-correction deviations, demonstrating the significant effect of the correction formula.

Fig. 1. SER deviation of tested and corrected value at different temperatures

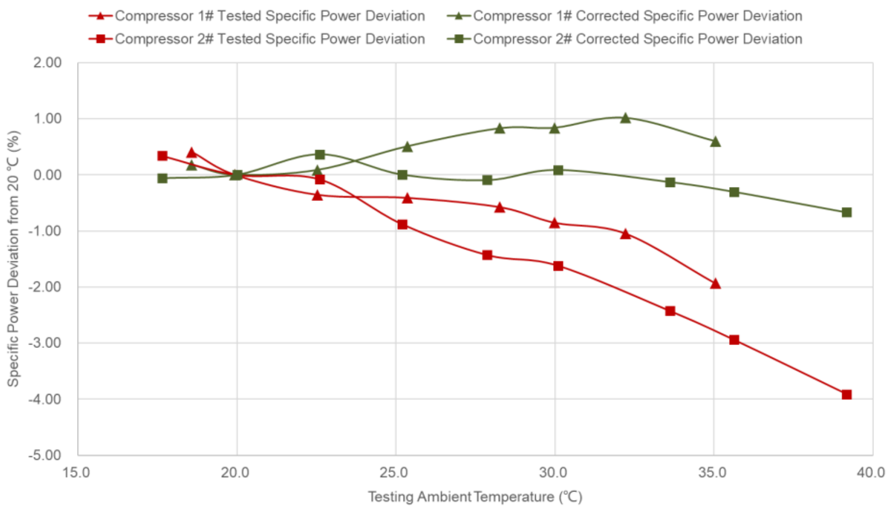


Figure 1 illustrates the deviation of measured and corrected SER values of two air compressors at different temperatures from SER tested at the standard testing environment temperature of 20℃. Centered around the standard testing temperature of 20℃, the measured SER values of the two prototypes gradually decrease as the measured environmental temperature rises. The higher the temperature, the greater the disparity in SER values. However, after applying Formula 1 to correct the measured SER, although there are variances between the corrected SER values and those tested at the standard temperature of 20℃, the range of differences is effectively controlled (within ±1%).

3 China compressed air station energy efficiency classification standard

Nowadays, most factories construct compressed air stations to produce compressed air for production processes and equipment.

The main equipment of the compressed air station includes air compressors, compressed air purification and drying equipment and accessories.

The system design, equipment configuration, and operating parameters of the compressed air station have a significant impact on the energy consumption of compressed air production. In practical operations, different compressed air stations with the same purpose can have a significant difference in energy efficiency. The energy-saving potential of the compressed air station is much higher than that of air compressor.

In 2018, the China Compressor Association issued the industry standard T/CGMA 033001. This is not a mandatory standard. It specifies the energy efficiency metric and grades, energy efficiency calculation, energy efficiency measurement methods, and comprehensive evaluation for industrial compressed air stations.

T/CGMA 033001 classified the energy efficiency of compressed air stations into five grades, with approximately a 10% difference in energy efficiency between adjacent grades and a 45% difference between Grade 1 and Grade 5. Grade 1 has the highest energy efficiency, while Grade 5 has the lowest. The energy efficiency level of Grade 5 represents the average performance of existing compressed air stations in China. However, in reality, many compressed air stations in factories fail to meet the grade 5 energy efficiency requirements.

Based on different supply pressure dew point ranges, T/CGMA 033001 sets energy efficiency grade requirements in tabular form for five pressure dew point ranges. Each classification table establishes energy efficiency requirements based on the scale of the compressed air station (air volume), and oil content. T/CGMA 033001 uses output work efficiency as the energy efficiency metric for compressed air stations. The output work efficiency is minimally affected by the compressed air station's output air pressure. Therefore, when setting the energy efficiency grading table, the influence of supply pressure can be ignored.

Table 1. Energy efficiency grades for compressed air station with pressure dew point ≥3℃[2]

Energy efficiency grade	Air volume flow rate Q_Z / (m^3/m9n)							
	4≤Q<20		20≤ Q<80		80≤Q<300		Q≥300	
	Output work efficiency (%)							
	Oil	Oil-free	Oil	Oil-free	Oil	Oil-free	Oil	Oil-free
Grade 1	55	51.5	58	54.5	61	57.5	64	60
Grade 2	50	47	53	50	55.5	52.5	58	55
Grade 3	45.5	43	48	45	50.5	47.5	53	50
Grade 4	41.5	39	44	41.5	46	43.5	48.5	45.5
Grade 5	38	35.5	40	37.5	42	39.5	44	41.5

4 Comparison analysis of GB19153, Lot31 and ECSAC

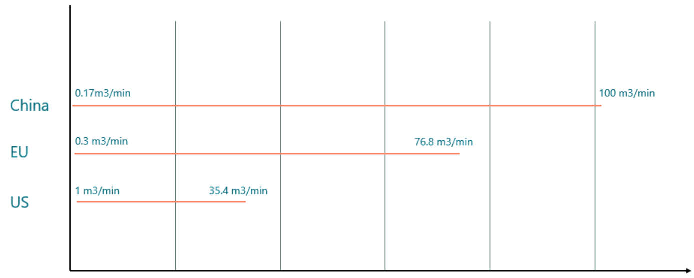
4.1 Product scope

GB19153 and Lot31 and ECSAC have certain differences in their product scope, primarily including:

- **Variations in product types**: GB19153 encompasses both oil-injected rotary air compressors and piston air compressors, with the further distinguished by lubricated and oil-free for piston type. Lot 31 includes both oil-injected rotary air compressors and piston air compressors. ECSAC only covers oil-injected rotary air compressors.
- **Differences in pressure range**: GB19153 has a pressure range of 0.25–1.4 MPa, while Lot 31's range is 7-14 bar (0.7 — 1.4 MPa), and ECSAC has a pressure range of 75 — 200 psi (0.517 — 1.38 MPa).
- **Disparities in product specifications**: GB19153 specifies a range of 1.5—630 kW for rotary air compressors (equivalent to volumetric flow rate of 0.17 - 100 m^3/min) and 0.75—75 kW for piston air compressors (0.06 - 15 m^3/min). Lot 31 specifies a range of 5 — 1280 l/s (0.3—76.8 m^3/min) for rotary air compressors and 2 — 64 l/s (0.12—3.8 m^3/min) for piston air compressors. ECSAC specifies a range of 35 — 1250 cfm (0.99 — 35.375 m^3/min) for rotary air compressors and a power range of 10 — 200 hp (7.35 kW — 147 kW).

A comparison of the volumetric flow rates for GB19153, Lot 31, and ECSAC is illustrated in Figure 2.

Fig. 2. Volumetric flow rate ranges of GB9153, Lot31 and ECSAC



4.2 Energy efficiency metric

GB 19153 employs the SER as energy efficiency metric, while Lot31 and ECSAC employ the isentropic efficiency.

SER is an energy performance indicator used in ISO 1217. The amendment to ISO 1217:2009/Amd.1:2016 (E) expanded it as a parameter for assessing the energy efficiency of air compressors. Lot31 and ECSAC adopt the isentropic efficiency primarily due to the belief that isentropic efficiency remains unaffected by pressure within a certain range. ECSAC states: "concludes that package isentropic is relatively independent of full-load operating pressure at full-load operating pressures between 75 and 200 psig." However, the independence of isentropic efficiency from pressure is only an approximation; within the pressure range of 75 to 200 psig, the variation in isentropic efficiency of air compressors is minimal, allowing the influence of pressure on isentropic efficiency to be disregarded.

However, in the low-pressure range of air compressors, the isentropic efficiency is significantly affected by pressure. The pressure range specified in GB19153 is 0.25 MPa to 1.4 MPa (36 psig to 203 psig), with many regions falling below 75 psig, where the influence of pressure on isentropic efficiency cannot be overlooked.

In comparison to isentropic efficiency, the SER offers the advantages of directly reflecting the relationship between compressed air output and electrical energy consumption, making it easier for users to intuitively understand. The SER has been in application for many years, initially within ISO and adopted by various countries and regions, thus widely recognized. Its drawback lies in the necessity of setting SER values at rated pressure, which lacks continuity and cannot be easily summarized and presented in a simple formula, often requiring the presentation of complex efficiency tables. The advantage of output working efficiency is that it essentially represents the energy conversion efficiency of air compressors and serves as an energy efficiency indicator for other equipment within compressed air systems, such as air dryers, filters, and pipelines.

For variable speed rotary air compressors, GB19135, like Lot31 and ECSAC, calculates the SER for variable speed rotary air compressors based on the weighted average of three volumetric flow conditions as outlined in ISO 1217:2009 D3.3.2.

Table 2. Weighing factors for variable speed rotary standard air compressors

Volume flow rate (V1,i, expressed as % of full load volume flow Vi)	Weighing factor (fi)
100%	25%
70%	50%
40%	25%

4.3 Tolerance

Table 3 shows the testing tolerance of ISO 1217.

Table 3. Maximum deviations permissible at test of ISO 1217

Volume flow rate at specified conditions (m^3/s) $\times$ 10^{-3}	Volume flow rate %	Specific energy requirement %	Power requirement (at zero volume flow rate or at pressure ratio of 1) [a] %
$0 < q_V \leqslant 8{,}3$	± 7	± 8	± 10
$8{,}3 < q_V \leqslant 25$	± 6	± 7	± 10
$25 < q_V \leqslant 250$	± 5	± 6	± 10
$q_V > 250$	± 4	± 5	± 10
NOTE The tolerance values in this table cover and include manufacturing tolerances of the compressor and tolerances relating to the measurements taken during the test.			
[a] Where specified, the manufacturer shall state the method used.			

Table 4 shows the testing tolerance of Lot 31.

Table 4. Lot 31 verification testing tolerances

Volume flow rate (l/s)	**Maximum deviation from declared values**			
	Volume flow rate	Isentropic efficiency	Input power at zero volume flow	Outlet pressure
$0 < V_1 \leq 8.3$	± 7%	± 8%	± 10%	± 2%
$8.3 < V_1 \leq 25$	± 6%	± 7%	± 10%	± 2%
$25 < V_1 \leq 250$	± 5%	± 6%	± 10%	± 2%
$V_1 > 250$	± 4%	± 5%	± 10%	± 2%

GB 19153 does not specify tolerance values for the technical parameters of air compressors. When establishing the energy efficiency level requirements for air compressors, GB 19153 has directly considered the impact of tolerance on energy efficiency values. For example, in terms of the SER for air compressors, GB19153 proposes to set its limit value at 8 kW/(m^3/min), while also providing an tolerance margin of 5% for the test method. According to this tolerance setting, the minimum required SER value for air compressors must not exceed 8.4 kW/(m^3/min).

GB 19153 clearly sets the limit value for SER as 8.4 kW/(m^3/min) but does not establish a tolerance value for SER. The standard mandates that the measured SER value of air compressors must not be higher than the declared value, meaning that the actual measured SER value of air compressors must not exceed 8.4 kW/(m^3/min).

Regarding the Level 3 energy efficiency requirement in GB 19153, it is calculated based on the isentropic efficiency of ECSAC energy levels (d=-15), taking into account a 5% tolerance. Therefore, this Level 3 SER value is actually 95% of ECSAC isentropic efficiency value.

In conclusion, although GB19153 energy efficiency limit requirement is not high, when combined with the requirements of tolerance, the actual energy efficiency requirements are in fact higher than this specified value.

4.4 Test condition

As previously mentioned, the intake temperature has a certain impact on the efficiency of air compressors. Considering the difficulty of maintaining a stable ambient temperature during testing of high-power air compressors, GB 19153 specifies the intake temperature range for air compressor testing as 5℃-40℃, and provides a correction formula for SER value when the test intake temperature deviates from 20℃. This correction formula has gained recognition from mainstream domestic and international air compressor manufacturers in the Chinese market.

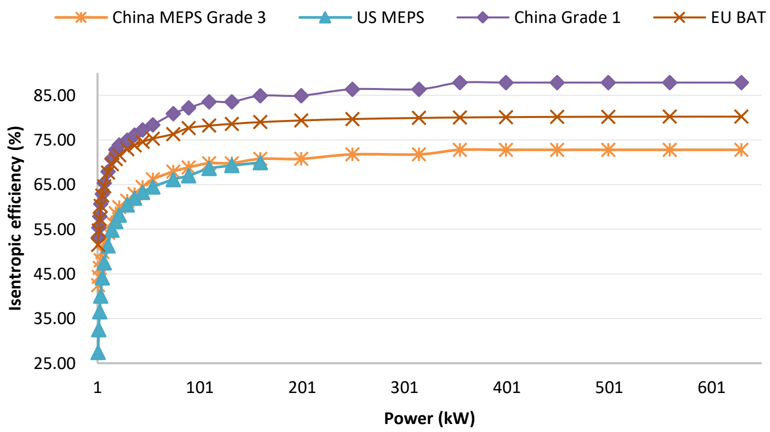
Lot 31 does not currently mention the issues regarding intake temperature during testing.

ECSAC states that: "As a result, DOE is not able to evaluate the magnitude of the effect of inlet temperature on measured compressor performance and weigh the potential challenges of narrowing the permitted temperature range against the corresponding improvement in test procedure repeatability. Consequently, DOE is not proposing to amend the current ambient temperature range requirement of 68 to 90 °F for testing air compressors in this NOPR." [4] [5]

4.5 MEPS requirements

Due to the different energy efficiency metrics chosen for GB19153, Lot31, and ECSAC, it is challenging to conduct a comprehensive comparison of minimum energy efficiency requirements for all product types. Fig. 3 presents a comparative analysis of an air-cooled, fixed-speed compressor at a pressure of 0.8 MPa, converted into isentropic efficiency. In this scenario, the grade 3 energy efficiency requirements set by GB 19153 corresponds to the minimum requirements of ECSAC and the d=-15 level of Lot 31. The Level 1 isentropic efficiency value in GB 19153 surpasses the d=25 level.

Fig. 3. Isentropic efficiency analysis of GB9153, Lot31 and ECSAC



5 Conclusions and recommendations

China has been implementing the air compressor MEPS GB 19153 for more than 20 years. China's product MEPS is revised approximately every 5 to 10 years, with each revision increasing the minimum energy efficiency requirement. Although there are differences between GB19153 and those in Lot31 and ECSAC, the current version of MEPS GB 19153 published 2019 takes references to the energy efficiency settings of Lot31 and ECSAC. The minimum energy efficiency requirement for mainstream rotary air compressors has significantly increased by approximately 8%, while the energy efficiency requirement for grade 1 products has improved by 3.2%.

The energy-saving potential of compressed air systems is far greater than that of individual equipment. With the deepening of energy-saving work, there will inevitably be a focus on system energy efficiency, specifically the energy saving of compressed air stations. The T/CGMA 033001 standard vigorously promotes users' attention to system energy efficiency and encourages manufacturers to prioritize providing systematic high-efficiency solutions. It is currently being elevated to become a Chinese national standard for evaluating the energy efficiency of compressed air stations, with completion expected in 2025. It is hoped that the application of the energy efficiency standard for compressed air stations will provide valuable experience for ISO TC118 and related international organizations and society in promoting compressed air system efficiency.

The T/CGMA 033001 applies a new energy efficiency metric, called output working efficiency. Output working efficiency can be seen as the efficiency of a compressed air station converting electrical energy into compressed air power under specific conditions. It can also be seen as the efficiency of an air compressor converting electrical energy into compressed air power. It can further be used to evaluate the energy efficiency of compressed air dryers, filters, and pipelines. It is hoped that the application of this metric will receive international attention and be extensively studied for its application value in air compressors and compressed air systems.

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