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Combustion Stability of Offshore Gas Motor Compressors Operating on Associated Petroleum Gas

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Abstract

Reliable combustion is essential for the efficient and reliable operation of aging offshore gas motor compressors fueled by associated petroleum gas (APG). This study investigated the combined influence of fuel composition, scavenging-air pressure, and compressor loading on combustion stability under real industrial conditions. Operational data were obtained from four low-speed 10GKNAM gas motor compressors operating on APG with elevated heavy-hydrocarbon content. Fuel composition was determined by gas chromatography, while combustion stability was evaluated using exhaust-gas temperatures measured in all engine cylinders together with scavenging-air pressure and compressor loading. Two dimensionless diagnostic indicators, the Combustion Stability Index (*CSI*) and the Temperature Dispersion Coefficient (*TDC*), were developed using routinely monitored operating parameters, providing a practical combustion-diagnostic approach without additional instrumentation. Although the investigated fuel exhibited increased combustion reactivity, fuel composition did not account for the observed differences in combustion stability because all compressors operated on essentially identical APG. Instead, scavenging-air pressure was identified as the dominant operational factor, whereas higher compressor loading provided an additional stabilizing effect. Increased scavenging-air pressure reduced exhaust-gas temperature dispersion and improved combustion uniformity, whereas the influence of compressor loading became more pronounced under adequate scavenging conditions. The proposed methodology provides a practical basis for quantitative combustion assessment using existing industrial monitoring systems and may support condition-based maintenance, operational optimization, and future development of predictive combustion-diagnostic approaches for aging offshore gas motor compressors.

Keywords: associated petroleum gas; combustion stability; gas motor compressors; scavenging-air pressure; combustion diagnostics; combustion monitoring; exhaust-gas temperature



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1. Introduction

The decarbonization of the oil and gas industry has intensified efforts to reduce routine flaring of associated petroleum gas (APG), which remains one of the major sources of avoidable greenhouse-gas emissions worldwide. Consequently, the efficient utilization of APG in industrial energy-conversion systems has become an important technological and environmental objective. In parallel with environmental considerations, the reliable

utilization of APG has become increasingly important to improve the energy efficiency and economic performance of mature oil and gas production facilities.

Associated petroleum gas is one of the most valuable secondary energy resources generated during crude oil production. Historically, large volumes of APG have been flared, owing to limited utilization opportunities, insufficient gas-processing infrastructure, and economic constraints. However, increasingly stringent environmental regulations and the growing demand for sustainable energy technologies have significantly accelerated the utilization of APG as a fuel for industrial power generation and gas-compression facilities. The effective use of APG not only reduces routine flaring and associated carbon emissions but also improves the overall energy efficiency and economic performance of oil-production operations, making it an important component of sustainable hydrocarbon development [1–4].

Low-speed gas motor compressors remain essential components of offshore oil and gas infrastructure, where they are extensively employed for gas gathering, transportation, gas-lift operations, and process gas compression. Owing to their robust construction, relatively simple mechanical design, and high operational reliability under harsh offshore conditions, these units continue to play a key role at many mature oil and gas production facilities.

Nevertheless, a considerable proportion of the existing compressor fleet has been in continuous operation for several decades, resulting in progressive deterioration of engine components, reduced scavenging efficiency, and increasing challenges related to combustion stability, energy efficiency, and operational reliability. Among the various factors affecting long-term compressor performance, combustion stability is of particular importance because it directly influences thermal loading, fuel efficiency, equipment reliability, maintenance requirements, and service life [5–11].

Combustion stability governs the quality of heat release and the thermal behavior of gas engines. Stable combustion promotes balanced thermal loading of engine cylinders, efficient fuel utilization, and reliable operation under variable industrial conditions. Conversely, combustion instability may lead to elevated exhaust-gas temperatures, increased thermal stresses, reduced thermal efficiency, accelerated wear of critical engine components, and abnormal combustion phenomena such as knock or misfire. These effects become particularly significant in aging gas motor compressors, where the degradation of scavenging systems and other engine components further aggravates combustion non-uniformity. Therefore, understanding the mechanisms governing combustion stability is essential for improving the operational reliability, energy efficiency, and condition-based maintenance of long-service compressor fleets [12–18].

One of the distinguishing features of offshore gas motor compressors is the widespread use of associated petroleum gas as fuel. Unlike conventional pipeline natural gas, APG exhibits considerable variation in chemical composition and often contains elevated concentrations of heavier hydrocarbons, including propane, butanes, and pentanes. These components increase the calorific value and chemical reactivity of the fuel, modify flame-propagation characteristics, and reduce the methane number. Consequently, variations in APG composition may significantly affect combustion behavior, thermal loading, combustion stability, and resistance to abnormal combustion [19–25].

Previous studies have demonstrated that increasing concentrations of heavy hydrocarbons accelerate combustion kinetics, shorten ignition-delay periods, and increase combustion intensity. At the same time, fuels enriched with C_3^+ hydrocarbons generally exhibit lower methane numbers and reduced resistance to knock. For large-bore low-speed gas engines, which are characterized by relatively long combustion duration and extended end-

gas residence time, these changes in fuel properties may substantially influence combustion stability and thermal loading [19–25].

However, fuel composition alone cannot fully explain the combustion behavior observed in industrial gas motor compressors. Practical operating experience demonstrates that compressors supplied with essentially identical fuel gas frequently exhibit markedly different thermal conditions and combustion stability. This observation indicates that operational factors also play a decisive role in determining combustion quality. Among these factors, scavenging-air pressure is particularly important because it governs cylinder charging, air–fuel mixture formation, and the removal of residual combustion products.

Long-term operation often results in blower degradation, contamination of air passages, and reduced charging efficiency, leading to insufficient air supply and uneven air distribution among cylinders. Such conditions contribute to thermal imbalance, increased exhaust-gas temperature dispersion, and deterioration of combustion stability. Compressor loading represents another important operational parameter. Industrial gas motor compressors rarely operate continuously at rated capacity, and prolonged operation under partial-load conditions changes cylinder pressure, combustion temperature, turbulence intensity, and heat-release characteristics, thereby influencing combustion stability and overall engine performance [21,26–30].

Recent investigations have further demonstrated that advanced combustion diagnostics, optical measurement techniques, and numerical simulations substantially improve the understanding of flame development and combustion instability in gaseous-fuel engines. However, these studies have been performed predominantly under laboratory or controlled experimental conditions and are not directly applicable to aging industrial gas motor compressors operating on associated petroleum gas under offshore field conditions [31,32].

Although fuel composition, scavenging characteristics, engine loading, and combustion diagnostics have each been extensively investigated, these factors have generally been considered separately and predominantly under laboratory or controlled test-bench conditions. Consequently, the combined influence of fuel properties and actual industrial operating conditions on combustion stability remains insufficiently understood. In particular, there is limited information on how scavenging-air pressure degradation and compressor loading interact with APG properties to influence combustion stability in aging offshore gas motor compressors operating under long-term industrial service conditions.

To the best of the authors' knowledge, no previous study has quantitatively evaluated these combined effects using industrial measurements obtained from operating offshore gas motor compressors. Furthermore, practical diagnostic indicators suitable for continuous combustion assessment using only routinely monitored industrial parameters have not yet been developed.

To address these research gaps, the present study combines the thermochemical characterization of associated petroleum gas with industrial measurements obtained from four operating offshore gas motor compressors. The combined influence of fuel composition, scavenging-air pressure, and compressor loading on combustion stability is systematically investigated. In addition, two novel dimensionless diagnostic indicators—the Combustion Stability Index (CSI) and the Temperature Dispersion Coefficient (TDC)—are proposed for practical industrial combustion assessment using existing monitoring systems without additional instrumentation.

The proposed methodology establishes a practical framework for quantitative combustion stability assessment in aging offshore gas motor compressors operating on associated petroleum gas. The developed methodology may support condition-based maintenance, operational optimization, and the future development of predictive diagnostic approaches based on routinely monitored industrial operating parameters.

2. Literature Review

2.1. Combustion Characteristics of Associated Petroleum Gas

Associated petroleum gas (APG) differs from conventional pipeline natural gas because of its variable composition and elevated concentrations of heavier hydrocarbons, including ethane, propane, butanes, pentanes, and heavier fractions [19–25]. These compositional differences significantly influence fuel heating value, methane number, flame speed, ignition characteristics, and knock resistance, thereby affecting combustion behavior and engine performance [12–25].

Compared with methane-rich natural gas, APG generally exhibits higher chemical reactivity, resulting in faster flame propagation, shorter ignition-delay periods, and increased heat-release rates [19–25]. Although these characteristics may improve combustion efficiency, they are accompanied by a lower methane number and reduced knock resistance, particularly under elevated cylinder pressures and temperatures [20–25]. Consequently, engines operating on APG may experience higher thermal loading, increased exhaust-gas temperatures, and greater susceptibility to abnormal combustion [22–26].

Recent studies on combustion processes have demonstrated that combustion behavior is governed not only by fuel composition but also by the interactions between combustion kinetics, mixture preparation, flame dynamics, and operating conditions. Advanced experimental and numerical investigations have emphasized the importance of integrated analyses for improving the understanding of combustion stability and thermal behavior under practical operating conditions [31,32].

Previous studies have investigated the influence of APG composition on combustion characteristics, emissions, and engine performance [19–25]. However, most investigations have been performed using laboratory combustion systems or controlled engine-test facilities. Comparatively little attention has been devoted to low-speed offshore gas motor compressors operating under long-term industrial conditions, where fuel composition interacts with equipment aging, scavenging-air performance, and compressor loading. Moreover, only limited attention has been paid to practical combustion-diagnostic methodologies based exclusively on routinely monitored industrial operating parameters. These combined effects remain insufficiently understood and constitute an important research gap [20–32].

2.2. Effect of Heavy Hydrocarbon Content on Combustion Stability

The concentration of heavy hydrocarbons is a key factor governing combustion behavior in gas engines operating on associated petroleum gas. Compared with methane, propane, butanes, and pentanes exhibit lower autoignition temperatures, higher laminar flame speeds, and greater chemical reactivity, thereby accelerating flame development, shortening ignition-delay periods, and increasing heat-release rates [8,19–25]. These characteristics generally improve combustion completeness but simultaneously increase thermal loading and reduce knock resistance, particularly under elevated cylinder pressures and temperatures [22–26].

The influence of heavy hydrocarbons on combustion stability is commonly characterized by the methane number, which is widely accepted as the principal indicator of knock resistance for gaseous fuels [19–23]. Increasing concentrations of C_3^+ hydrocarbons reduce the methane number, resulting in higher combustion reactivity, elevated exhaust-gas temperatures, and greater susceptibility to abnormal combustion [22–26]. These effects become particularly important in large-bore, low-speed gas engines, where long combustion duration and extended end-gas residence time increase sensitivity to fuel reactivity [8,19–23].

Recent investigations have confirmed that the influence of heavy hydrocarbons on combustion cannot be evaluated solely by methane number or fuel composition. Combustion

performance also depends on flame propagation, local mixture distribution, combustion dynamics, and engine operating conditions. Consequently, practical combustion stability results from the combined interaction of fuel properties and engine operating parameters rather than from fuel composition alone [31,32].

Nevertheless, both industrial experience and recent combustion studies indicate that fuel composition alone cannot fully explain combustion instability in gas motor compressors. Compressors supplied with essentially identical associated petroleum gas frequently exhibit markedly different combustion behaviors and thermal conditions, suggesting that operational parameters, particularly scavenging-air pressure and compressor loading, play equally important roles in determining combustion stability under industrial operating conditions [20–32].

Figure 1 illustrates the inverse relationship between C_3^+ hydrocarbon concentration and methane number, together with the corresponding increase in fuel reactivity and knock tendency. The present study extends this conventional fuel property relationship by considering its interaction with scavenging-air pressure and compressor loading under real industrial operating conditions, thereby providing the conceptual basis for the proposed combustion-diagnostic methodology [19–32].

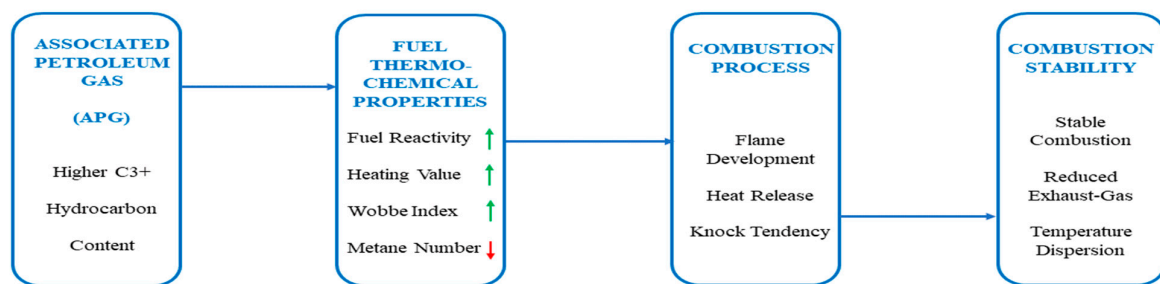


Figure 1. Conceptual relationship between associated petroleum gas composition, fuel thermochemical properties, combustion process, and combustion stability. Green arrows indicate the primary process flow; blue arrows indicate operational influencing factors; red arrows indicate the resulting effects on combustion stability.

2.3. Combined Influence of Scavenging-Air Pressure and Compressor Loading on Combustion Stability

Efficient cylinder charging is essential for stable combustion in low-speed gas motor compressors. The scavenging-air system supplies fresh air for combustion, removes residual gases, and improves mixture formation, thereby directly affecting volumetric efficiency, combustion completeness, and thermal-load distribution among engine cylinders [17,20–30]. Insufficient scavenging-air pressure reduces cylinder-filling efficiency, increases the residual-gas fraction, and deteriorates air–fuel mixing, resulting in incomplete combustion, elevated exhaust-gas temperatures, and greater combustion variability [17,20–22,27–30]. In aging gas motor compressors, these effects are often aggravated by blower wear, fouling of intercoolers, contamination of air passages, and increasing aerodynamic resistance, all of which progressively reduce scavenging efficiency [17,20,22,27–30].

Compressor loading is another important operational parameter affecting combustion stability. Variations in loading influence cylinder pressure, turbulence intensity, heat-release characteristics, and combustion efficiency [20–24,28–30]. Under prolonged partial-load operation, reduced turbulence weakens flame propagation and increases sensitivity to local variations in the air–fuel ratio, promoting non-uniform thermal loading among cylinders [20–24,28–30].

Several studies have shown that the adverse effects of partial-load operation become considerably more pronounced when combined with insufficient scavenging-air supply [17,20–24,28–30]. Under these conditions, poor cylinder charging and reduced turbulence act simultaneously, leading to incomplete combustion, increased exhaust-gas temperature dispersion, and deteriorated combustion stability. The combined influence of these factors therefore exceeds the individual effects of either parameter alone. Despite the recognized importance of scavenging-air characteristics and engine loading, most published investigations have examined these factors separately and primarily under laboratory or controlled engine-test conditions [17,20–30]. Quantitative assessments of their combined influence and possible interaction under long-term industrial operating conditions remain limited, particularly for aging offshore gas motor compressors operating on associated petroleum gas. This lack of integrated industrial investigations constitutes one of the principal research gaps addressed in the present study.

Figure 2 summarizes the interaction between fuel composition, scavenging-air pressure, and compressor loading. Fuel composition determines combustion reactivity and knock resistance, and scavenging-air pressure governs cylinder charging and mixture formation, while compressor loading influences in-cylinder pressure, turbulence, and heat-release characteristics. Their combined interaction determines combustion stability, exhaust-gas temperature distribution, and overall engine performance. Figure 2 emphasizes that combustion stability should be considered the result of interacting fuel and operational factors rather than the isolated influence of any single parameter, thus providing the theoretical basis for the integrated diagnostic methodology proposed in this study.

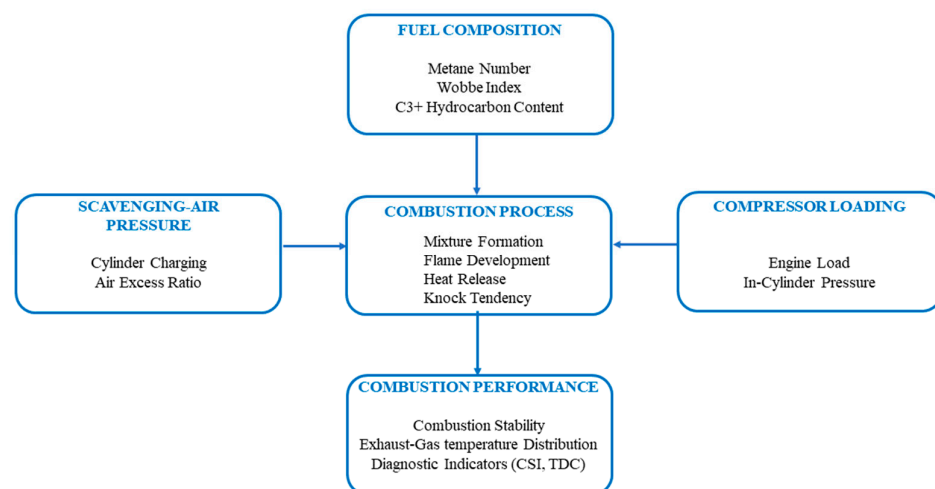


Figure 2. Conceptual framework illustrating the interaction between fuel composition, scavenging-air pressure, and compressor loading in determining combustion performance.

This conceptual framework also provides the basis for interpreting the proposed combustion-diagnostic indicators, since the *CSI* and *TDC* are intended to characterize the cumulative effect of interacting operational factors rather than any individual combustion parameter.

2.4. Exhaust-Gas-Temperature-Based Combustion Diagnostics

Exhaust-gas temperature is one of the most informative indicators of combustion quality in industrial gas engines and gas motor compressors. Unlike in-cylinder pressure measurements, exhaust-gas temperature is routinely monitored by standard compressor-station control systems and therefore provides a practical basis for continuous combustion diagnostics and condition monitoring without additional instrumentation [20–25,29,30].

Although exhaust-gas temperature cannot replace direct measurements of in-cylinder pressure or detailed combustion diagnostics, it represents the cumulative thermal response of the combustion process and therefore reflects the combined influence of fuel properties, mixture formation, combustion completeness, cylinder charging, and engine operating conditions. For this reason, exhaust-gas temperature has long been recognized as one of the most practical indicators for industrial combustion monitoring in large stationary gas engines and compressor units [20–25,29–32].

Under stable operating conditions, cylinders supplied with nearly identical air–fuel mixtures exhibit relatively uniform exhaust-gas temperatures. Significant temperature deviations indicate combustion imbalance, non-uniform air distribution, injector malfunction, cylinder deterioration, or developing mechanical faults. Consequently, the statistical dispersion of exhaust-gas temperatures is widely recognized as a reliable indicator of combustion deterioration, thermal imbalance, and reduced combustion efficiency [20–25,29,30].

Although modern combustion diagnostics increasingly employ in-cylinder pressure measurements, ion-current sensing, vibration analysis, machine learning techniques, and virtual sensing, the implementation of these approaches in aging offshore compressor stations is often constrained by hardware complexity, installation requirements, and economic considerations [19–25]. As a result, practical quantitative diagnostic criteria based solely on routinely monitored operational parameters remain limited, particularly for long-service industrial gas motor compressors [19,20,23–25,27–30]. Unlike diagnostic methods based on individual combustion variables, exhaust-gas-temperature-based indicators provide an integrated assessment of combustion quality, as they reflect the cumulative influence of multiple interacting physical processes. Consequently, such indicators are intended to evaluate the overall combustion condition rather than establish a direct correlation with any single parameter such as peak cylinder pressure, knock intensity, or emission concentration.

Previous investigations have examined individual factors affecting combustion stability, including fuel composition, heavy-hydrocarbon content, scavenging-air characteristics, engine loading, and exhaust-gas temperature. However, these factors have generally been studied independently, while their combined influence under long-term industrial operating conditions has received comparatively little attention. To summarize the current state of knowledge and identify the research gap addressed in this study, a comparative assessment of representative published investigations is presented in Table 1.

Table 1. Comparative assessment of previous studies on combustion stability in natural-gas-powered engines and the research contribution of the present study.

Ref.	Study	1	2	3	4	5	6	7	8
Karim (1987) [1]	Fundamentals of combustion in gas engines	✓	○	–	✓	–	✓	–	–
Heywood (2018) [11]	Internal combustion engine fundamentals	✓	–	✓	✓	✓	✓	–	–
Kubesh et al. (1992) [22]	Methane number and fuel composition	✓	✓	–	–	–	✓	–	–
Ladd et al. (2017) [26]	Large-bore two-stroke pipeline gas engines	✓	✓	✓	✓	✓	✓	–	✓
Yang et al. (2021) [27]	Influence of scavenging on natural-gas engine performance	–	–	✓	✓	–	✓	–	–
Liu et al. (2021) [28]	Exhaust-gas temperature prediction using machine learning	–	–	–	✓	✓	✓	ML-based	✓
Algayyim et al. (2024) [2]	Fuel properties and combustion characteristics (review)	✓	✓	–	✓	✓	✓	–	–
Lott et al. (2024) [30]	Lean-burn natural-gas engines and exhaust after-treatment	✓	–	–	✓	✓	✓	–	✓

Table 1. *Cont.*

Ref.	Study	1	2	3	4	5	6	7	8
Present study	Integrated assessment of combustion stability in offshore gas motor compressors operating on associated petroleum gas	✓	✓	✓	✓	✓	✓	CSI + TDC	✓✓

Notation: 1—fuel composition; 2—heavy hydrocarbons (C_3^+); 3—scavenging-air pressure; 4—engine/compressor load; 5—exhaust-gas temperature; 6—combustion stability; 7—integrated combustion-diagnostic methodology; 8—industrial validation. ✓—factor investigated; ○—partially investigated; —not investigated; ✓✓—comprehensively investigated and industrially validated in the present study.

As shown in Table 1, previous studies have primarily focused on individual factors affecting combustion stability and have largely been conducted using laboratory combustion systems, research engines, or controlled engine-test facilities [16–30]. Integrated diagnostic methodologies specifically developed for long-term monitoring of offshore gas motor compressors operating on associated petroleum gas remain unavailable.

To address this research gap, the present study develops and industrially validates two integrated combustion-diagnostic indicators: the Combustion Stability Index (CSI) and the Temperature Dispersion Coefficient (TDC). Unlike conventional diagnostic parameters that characterize individual combustion phenomena, the proposed indicators quantify the overall thermal uniformity of the combustion process by integrating the cumulative effects of fuel composition, scavenging-air performance, compressor loading, and engine condition. Because they are derived exclusively from routinely monitored operating parameters, the proposed indicators can be directly implemented in existing compressor-station monitoring systems for continuous combustion assessment, condition-based maintenance, operational optimization, and early identification of combustion deterioration without additional instrumentation.

3. Materials and Methods

3.1. Industrial Facilities, Fuel Characterization and Data Acquisition

The experimental investigation was carried out at two offshore compressor stations located in the Caspian Sea oil-production region, where associated petroleum gas (APG) is continuously compressed and transported using low-speed gas motor compressors. Four industrial compressor units representing the 10GKNAM2/5-55 and 10GKNAM3/5-100 series were selected for detailed investigation. These compressors were manufactured by JSC “RUMO” (Nizhny Novgorod, Russia) and are employed for gas gathering, process-gas compression, and associated petroleum gas transportation under long-term industrial operating conditions.

All investigated compressor units had accumulated more than twenty years of continuous industrial operation without major replacement of their primary engine systems. Consequently, they represent a typical aging compressor fleet currently encountered at mature offshore oil-production facilities, where the gradual deterioration of engine components and auxiliary systems may significantly affect combustion stability and overall operational performance. Such long-term operation is characteristic of many industrial gas-compression systems and creates favorable conditions for the application of condition-based maintenance and operational diagnostics [20–25,27,29,30]. The investigated compressors were driven by ten-cylinder low-speed spark-ignition gas engines operating according to a two-stroke cycle with forced scavenging. Each engine had a rated power of 1103 kW and a crankshaft rotational speed of 300 rpm. Owing to their large cylinder dimensions, low rotational speed, and extended combustion duration, these engines are particularly sensitive to variations in fuel composition, scavenging-air pressure, cylinder charging efficiency, and thermal-load distribution [1–7,17,20,22,28–30].

Consequently, they provide an appropriate industrial platform for investigating combustion stability under real operating conditions.

The principal technical characteristics of the investigated compressor units are summarized in Table 2.

Table 2. Main technical characteristics of the investigated gas motor compressors.

Parameter	10GKNAM2/5–55	10GKNAM3/5–100
Number of cylinders	10	10
Rated power, kW	1103	1103
Rated rotational speed, rpm	300	300
Cylinder bore, mm	355	355
Stroke, mm	356	356
Fuel type	APG	APG
Ignition system	Spark ignition	Spark ignition
Scavenging system	Mechanical blower	Mechanical blower

The investigated compressors represent some of the most widely used low-speed gas motor compressor designs employed at offshore oil-production facilities in the Caspian Sea region. Therefore, the obtained experimental results are representative of a large population of aging industrial compressor units operating under comparable field conditions.

Associated petroleum gas used as engine fuel was sampled directly from the compressor-station fuel-supply system during normal operation. The gas composition was determined by gas chromatography in accordance with accepted industrial analytical procedures. The chromatographic analysis included methane, ethane, propane, iso-butane, n-butane, iso-pentane, n-pentane, hexane, carbon dioxide, nitrogen, oxygen, hydrogen sulfide (H_2S), and mercaptan sulfur.

Based on the measured gas composition, the principal thermochemical properties governing combustion behavior were calculated, including the lower heating value (LHV), Wobbe Index, relative gas density, and methane number. Particular attention was devoted to the concentration of C_3^+ hydrocarbons because these components strongly influence fuel reactivity, flame-propagation characteristics, combustion intensity, and knock resistance [19–25].

The component composition of the investigated fuel gas, together with the manufacturer's recommended fuel specifications, is presented in Table 3.

Table 3. Component composition of the investigated associated petroleum gas and manufacturers' requirements.

Component	Investigated Qaz, mol.%	Manufacturer Requirement, vol.%	Complies with the Standard
methane CH_4	91.88	≥ 80.00	Within the acceptable limit
ethane C_2H_6	3.89	≤ 5.00	Within the acceptable limit
propane C_3H_8	1.75	≤ 1.00	1.75 times higher than the allowable limit
n-butane $\text{n-C}_4\text{H}_{10}$	0.65	≤ 0.50	2.58 times higher than the allowable limit
i-butane $\text{i-C}_4\text{H}_{10}$	0.64		
n-pentane $\text{n-C}_5\text{H}_{12}$	0.18	≤ 0.10	4.8 times higher than the allowable limit
i-pentane $\text{i-C}_5\text{H}_{12}$	0.22		
hexane C_6H_{14}	0.08	Not regulated	-
nitrogen N_2	0.17		
carbon dioxide CO_2	0.52	Not regulated	-
oxygen O_2	0.02	≤ 0.50	Within the acceptable limit

As shown in Table 3, methane remained the dominant fuel component, accounting for approximately 92 mol.% of the gas mixture. Nevertheless, the cumulative concentration of heavy hydrocarbons exceeded the manufacturer's recommended limits. In particular, the propane concentration was approximately 1.75 times higher than the allowable value, whereas the total concentration of butanes and pentanes considerably exceeded the specified limits. Such enrichment indicates a fuel with elevated chemical reactivity and an increased knock tendency compared with conventional transmission-grade natural gas [19–25].

The thermophysical properties of the investigated fuel gas are summarized in Table 4.

Table 4. Thermophysical properties of the investigated associated petroleum gas.

Parameter	Value	Parameter	Value
Lower heating value	8696 kcal/m ³	CO ₂ mole fraction	0.52%
Higher Wobbe index	51.15 MJ/m ³	O ₂ mole fraction	0.02%
Density in standard conditions	0.7526 kg/m ³	Water dew point	−2.8 °C
H ₂ S content	0.0084 g/m ³	Hydrocarbon dew point	1.8 °C
Mercaptan sulfur	0.001 g/m ³		

The analyzed gas satisfied the general fuel gas quality requirements specified in GOST 5542-2022 [33]. However, its measured lower heating value reached 8696 kcal/m³, exceeding the manufacturer's recommended upper limit of 8500 kcal/m³ by approximately 2.3%. In addition, the relatively high Wobbe Index indicates increased volumetric energy input into the engine cylinders. The combined effect of the elevated heating value and increased concentrations of C₃⁺ hydrocarbons is expected to intensify combustion heat release, increase thermal loading, and reduce knock resistance under severe operating conditions, in agreement with previous investigations of APG-fueled gas engines [19–25]. Operational data were obtained directly from the compressor-station monitoring system and verified through on-site field inspections. The collected dataset included scavenging-air pressure, compressor throughput, compressor loading, crankshaft rotational speed, and exhaust-gas temperatures measured individually for all ten engine cylinders.

Exhaust-gas temperatures were measured using permanently installed industrial K-type thermocouples integrated into the standard monitoring systems of the compressor stations. The measurement system complied with the manufacturer's specified accuracy of ±2–3 °C over the operating temperature range, which is sufficient for comparative statistical analysis of combustion-temperature distribution. All measuring channels were periodically calibrated according to the maintenance procedures adopted at the compressor stations. Scavenging-air pressure was measured downstream of the mechanical blower, whereas compressor throughput, rotational speed, and engine loading were acquired from the station supervisory control system.

All operational parameters were continuously acquired by the Supervisory Control and Data Acquisition (SCADA) systems of the investigated compressor stations at 3 min intervals. The monitoring systems automatically archived the data and allowed for their aggregation into hourly and three-hour observation periods for operational analysis. The present investigation used only validated steady-state operating records extracted from this continuously monitored industrial database. The combustion analysis was based on 320 individual exhaust-gas temperature measurements obtained from the ten cylinders of four compressor units during repeated steady-state operating inspections. Simultaneously, scavenging-air pressure, compressor throughput, crankshaft speed, and compressor loading were recorded for each measurement series.

Steady-state operation was defined as operation at a constant crankshaft speed of 300 rpm without load transitions and without significant fluctuations of scavenging-air

pressure or compressor throughput during the observation interval. Data affected by obvious sensor malfunctions, maintenance activities, start-up, shutdown, or other transient operating events were excluded prior to statistical analysis.

Because all investigated compressor units were installed at the same offshore production facilities and operated simultaneously under essentially identical environmental conditions, the influences of ambient temperature, atmospheric pressure, and humidity on the comparative combustion analysis were considered negligible.

Since all investigated compressor units were supplied from the same gas-production system and operated on essentially identical associated petroleum gas, the observed differences in combustion behavior could primarily be attributed to variations in scavenging-air conditions, compressor loading, and engine operating characteristics, rather than to differences in fuel composition.

This experimental design allowed the individual influences of operational parameters on combustion stability to be isolated under real industrial conditions [17,20–24,27–30].

The overall experimental methodology consisted of five sequential stages: sampling and chromatographic analysis of the associated petroleum gas; determination of the principal thermochemical fuel properties; acquisition and verification of industrial operating parameters; statistical processing and analysis of operational data; and calculation and validation of the proposed combustion-diagnostic indicators, namely the Combustion Stability Index (CSI) and the Temperature Dispersion Coefficient (TDC). The overall experimental procedure and data-processing workflow adopted in the present study are illustrated in Figure 3.

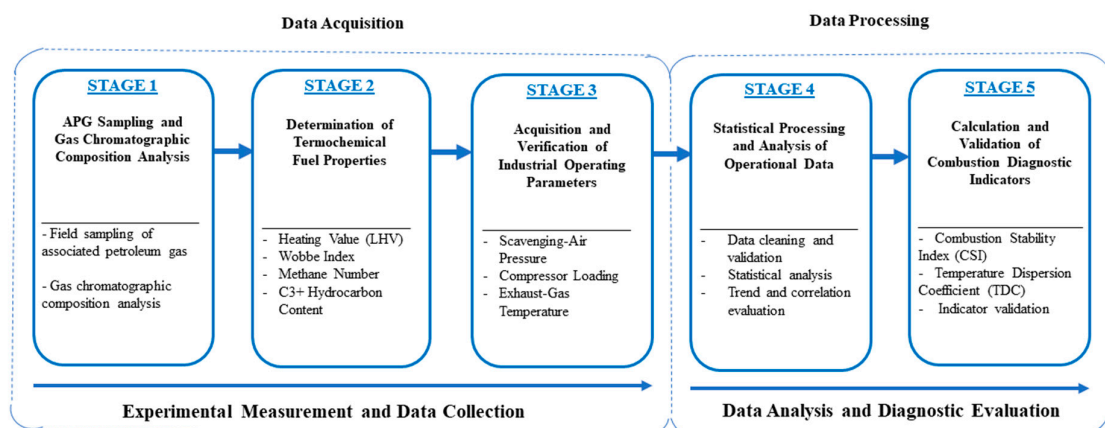


Figure 3. Experimental workflow adopted in the present study.

3.2. Evaluation of Compressor Loading and Combustion Conditions

Compressor loading was evaluated as the ratio of the actual compressor throughput to the rated compressor capacity, according to

$$L = \frac{Q_{act}}{Q_{rated}} \times 100 \quad (1)$$

where

- Q_{act} is the actual compressor throughput;
- Q_{rated} is the rated compressor throughput.

The throughput-based loading ratio was selected because compressor throughput is continuously measured and archived by the compressor-station SCADA system, whereas indicated mean effective pressure (IMEP) requires direct in-cylinder pressure measurements that are not available under routine industrial operating conditions. Since all investigated

compressors operate on essentially identical associated petroleum gas under comparable operating conditions, the adopted loading parameter provides a consistent and practically applicable basis for comparative industrial analysis.

The investigated compressor units operated at loading levels ranging from approximately 33% to 51% of their rated capacity. These operating conditions are representative of offshore oil-production facilities, where compressor loading continuously varies in response to changes in gas-production rates and process requirements. Consequently, prolonged operation under partial-load conditions represents the normal operating mode for the investigated compressor fleet rather than an exceptional condition.

Scavenging-air pressure was selected as the principal indicator of cylinder-charging efficiency because it directly determines the quantity of fresh air supplied to the cylinders and consequently influences mixture formation, combustion completeness, heat-release characteristics, and thermal loading [17,20,22,28–30].

The investigated compressors exhibited substantial differences in scavenging-air performance, with measured pressures ranging from 19–21 kPa under the least favorable operating conditions to 47–54 kPa under the most favorable conditions. This relatively wide operating range made it possible to quantitatively evaluate the influence of air-supply degradation on combustion stability while minimizing the effect of fuel variability, since all investigated compressor units were supplied with essentially identical associated petroleum gas.

The observed reduction in scavenging-air pressure is characteristic of long-service compressor units and may result from blower wear, fouling of intercoolers, contamination of air passages, clogging of air filters, or increased aerodynamic resistance of the scavenging system. Consequently, scavenging-air pressure also serves as an indirect indicator of the technical condition of the air-supply system.

Exhaust-gas temperature was adopted as the primary indicator of combustion quality because it reflects the combined effects of air–fuel ratio, combustion completeness, combustion intensity, heat-release characteristics, and thermal loading. In industrial gas motor compressors, exhaust-gas temperature is continuously monitored using permanently installed thermocouples incorporated into the standard monitoring system. The thermocouple signals were continuously recorded by the compressor-station SCADA system and automatically archived for subsequent operational analysis. Consequently, it represents one of the most informative and readily available operational parameters for continuous combustion diagnostics [20–25,29,30].

Under stable operating conditions, cylinders supplied with nearly identical air–fuel mixtures are expected to exhibit relatively uniform exhaust-gas temperatures. Significant temperature deviations among cylinders generally indicate non-uniform air distribution, incomplete combustion, local mixture enrichment, ignition irregularities, or progressive deterioration of engine components. Therefore, the statistical distribution of exhaust-gas temperatures provides valuable information regarding combustion stability and the thermal condition of multicylinder gas engines [20–25,29,30].

Unlike individual combustion parameters, exhaust-gas temperature reflects the cumulative influence of cylinder charging, air–fuel mixture formation, combustion completeness, heat-release characteristics, and thermal loading. It therefore provides an integrated measure of combustion quality rather than representing any single combustion phenomenon.

Unlike laboratory engine investigations, routine industrial monitoring of offshore gas motor compressors does not include direct in-cylinder pressure measurements, knock sensors, ion-current sensing, or continuous emission monitoring. Consequently, combustion stability was evaluated using only parameters that are continuously available from existing industrial monitoring systems.

The proposed Combustion Stability Index (*CSI*) and Temperature Dispersion Coefficient (*TDC*) were therefore developed as integrated diagnostic indicators that characterize the combined influence of scavenging efficiency, combustion completeness, thermal loading, and compressor operating conditions. Rather than replacing direct measurements of individual combustion parameters, these indicators provide a practical industrial tool for continuous condition monitoring using routinely available operational data.

3.3. Development of Combustion Stability Indicators

Routine monitoring of exhaust-gas temperatures is widely employed in industrial gas motor compressors as a practical means of assessing the engine operating condition. However, in most industrial applications, these measurements are interpreted qualitatively by comparing individual cylinder temperatures with recommended operating limits.

Although such an approach allows the identification of obvious thermal abnormalities, it does not provide an objective, quantitative assessment of combustion stability, nor does it facilitate reliable comparison among compressor units operating under different thermal and loading conditions [20–25,29,30].

Unlike conventional monitoring based on individual cylinder temperatures or fixed alarm thresholds, the methodology proposed in the present study was designed to evaluate combustion stability as an integrated characteristic of the entire multicylinder engine. The objective was not to replace advanced combustion-diagnostic techniques, such as in-cylinder pressure analysis, knock detection, or emission measurements, but to provide a quantitative diagnostic tool that can be implemented using routinely available industrial operating data.

To overcome these limitations, two complementary combustion-diagnostic indicators were developed in the present study: the Temperature Dispersion Coefficient (*TDC*) and the Combustion Stability Index (*CSI*). Both indicators are calculated exclusively from routinely measured exhaust-gas temperatures and, therefore, can be readily implemented within existing compressor-station monitoring systems without requiring additional measuring equipment or modifications to the engine instrumentation.

The Temperature Dispersion Coefficient (*TDC*) was introduced to characterize the maximum thermal non-uniformity among engine cylinders and is defined as follows:

$$TDC = \frac{T_{max} - T_{min}}{T_{avg}} \quad (2)$$

where

- T_{max} is the maximum cylinder exhaust-gas temperature;
- T_{min} is the minimum cylinder exhaust-gas temperature;
- T_{avg} is the average exhaust-gas temperature of all cylinders.

The proposed coefficient represents the normalized exhaust-gas temperature range and therefore reflects the degree of thermal imbalance within the engine. Low *TDC* values indicate nearly uniform heat release and balanced combustion among cylinders, whereas increasing *TDC* values correspond to progressively greater thermal non-uniformity and the deterioration of combustion stability.

Although the *TDC* effectively characterizes the largest temperature deviation, it does not describe the overall distribution of temperatures among all engine cylinders. Therefore, a second indicator, referred to as the Combustion Stability Index (*CSI*), was developed to quantify the overall uniformity of the combustion process:

$$CSI = 1 - \frac{\sigma_T}{T_{avg}} \quad (3)$$

where

- σ_T is the standard deviation of cylinder exhaust-gas temperatures;
- T_{avg} is the average exhaust-gas temperature.

Unlike the *TDC*, which depends only on the extreme temperature values, the *CSI* incorporates information from the complete temperature distribution and therefore provides an integral measure of combustion uniformity throughout the engine. Under ideal combustion conditions, when exhaust-gas temperatures are nearly identical in all cylinders, the standard deviation approaches zero and the *CSI* approaches unity. As thermal imbalance increases, the standard deviation increases and the *CSI* decreases accordingly.

The proposed indicators should therefore be regarded as integrated combustion-performance metrics rather than direct substitutes for individual combustion variables such as maximum cylinder pressure, knock intensity, or exhaust-emission concentrations. In practical industrial operation, these variables reflect different manifestations of the combustion process, whereas the *CSI* and *TDC* characterize their combined influence through the resulting thermal distribution among all engine cylinders.

Normalization by the average exhaust-gas temperature represents an essential feature of both indicators because it minimizes the influence of the absolute thermal operating level and enables meaningful comparisons among compressors operating under different loading conditions and thermal regimes.

Normalization also reduces sensitivity to variations in absolute operating temperature associated with compressor loading and normal operating fluctuations, thereby allowing direct comparisons of combustion stability among different compressor units.

Consequently, both indicators characterize the relative uniformity of combustion rather than the absolute exhaust-gas temperature itself. The simultaneous application of the *TDC* and *CSI* provides complementary diagnostic information. The *TDC* identifies the magnitude of the largest thermal deviation within the engine, whereas the *CSI* evaluates the overall combustion uniformity across all cylinders. Together, these indicators provide a substantially more comprehensive quantitative assessment of combustion stability than the conventional interpretation of individual exhaust-gas temperatures alone.

The combined application of both indicators was intentionally adopted because they describe different aspects of combustion behavior. The *TDC* is primarily sensitive to localized cylinder-to-cylinder thermal deviations, whereas the *CSI* reflects the statistical uniformity of the combustion process as a whole. Their simultaneous interpretation therefore provides a more robust assessment of combustion stability than either parameter used independently.

Unlike previously reported combustion-monitoring approaches, which frequently require in-cylinder pressure transducers, knock sensors, ion-current probes, vibration monitoring systems, emission analyzers, or machine learning algorithms [20–25,29,30], the proposed methodology relies exclusively on operational parameters routinely available from standard industrial compressor-station monitoring systems. Consequently, the developed indicators are particularly suitable for continuous combustion monitoring, early fault detection, condition-based maintenance, and long-term operation of aging offshore gas motor compressors fueled with associated petroleum gas. This practical applicability represents one of the principal contributions of the present study.

3.4. Selection of Preliminary Diagnostic Thresholds

To facilitate the practical industrial application of the proposed diagnostic methodology, preliminary threshold values were established for both combustion stability indicators. The threshold values were derived from the operational database obtained from the four investigated compressor units operating under steady-state industrial conditions.

For each operating condition, the values of *TDC* and *CSI* were calculated and subsequently compared with the corresponding combustion characteristics, exhaust-gas temperature distribution, scavenging-air pressure, compressor loading, and technical condition of the investigated compressor units. Particular attention was given to operating conditions exhibiting pronounced thermal non-uniformity and reduced scavenging-air pressure, which were confirmed during routine maintenance inspections.

Based on this engineering analysis, *TDC* values below approximately 0.15 were associated with stable and well-balanced combustion, whereas values approaching or exceeding 0.25 consistently corresponded to significant thermal non-uniformity and deteriorating combustion conditions. Similarly, *CSI* values above approximately 0.96 indicated highly uniform combustion, while values below approximately 0.94 were repeatedly associated with noticeably increased combustion variability.

Accordingly, the values of *TDC* = 0.25 and *CSI* = 0.94 are proposed in the present study as preliminary engineering diagnostic thresholds intended for industrial condition monitoring, rather than as universal combustion criteria. Their principal purpose is to provide practical guidance for maintenance personnel by identifying compressor units requiring additional technical inspection.

The proposed threshold values should therefore be regarded as preliminary engineering recommendations derived from the investigated industrial compressor fleet. Their wider applicability to other gas engine designs and operating conditions requires further validation using larger industrial datasets and additional statistical analysis.

3.5. Statistical Analysis and Diagnostic Methodology

Descriptive statistical analysis was performed for all monitored operating parameters. For each measurement series, the average, minimum, maximum, range, and standard deviation of exhaust-gas temperatures for the ten engine cylinders were calculated. These statistical characteristics formed the basis for evaluating combustion-temperature distribution and for calculating the proposed combustion stability indicators.

The Temperature Dispersion Coefficient (*TDC*) and the Combustion Stability Index (*CSI*) were calculated independently for each operating condition and each investigated compressor unit. Their values were subsequently compared to scavenging-air pressure, compressor loading, and exhaust-gas temperature characteristics in order to evaluate their diagnostic sensitivity under practical industrial operating conditions.

Because all investigated compressors operated on essentially identical associated petroleum gas supplied from the same fuel system, the fuel composition was treated as a controlled parameter. Consequently, the observed differences in combustion stability could be attributed primarily to variations in scavenging-air performance and compressor loading rather than to variations in fuel properties. This experimental design enabled the combined influence of operational factors on combustion stability to be isolated under real industrial conditions.

Rather than correlating the proposed indicators with individual combustion variables such as in-cylinder pressure, knock intensity, or emission concentrations, the present methodology evaluates combustion quality through the integrated thermal response of the engine. The exhaust-gas temperature distribution reflects the cumulative influence of the air–fuel ratio, combustion completeness, cylinder charging, heat-release characteristics, and thermal loading. Therefore, the proposed indicators represent integrated diagnostic measures of overall combustion stability rather than surrogate indicators of any single combustion parameter.

To assess the practical applicability of the proposed methodology, comparative analyses were performed for compressor units operating over a wide range of scavenging-air

pressures and compressor-loading conditions. Changes in the *CSI* and *TDC* were interpreted alongside the corresponding operating parameters to identify the principal factors governing combustion stability and to establish preliminary diagnostic thresholds suitable for industrial monitoring.

The overall methodology therefore combines fuel characterization, industrial operational monitoring, statistical evaluation of exhaust-gas temperatures, and integrated combustion diagnostics into a unified engineering framework suitable for continuous monitoring, predictive diagnostics, condition-based maintenance, and operational optimization of aging offshore gas motor compressors.

4. Results and Discussion

4.1. Fuel Gas Composition and Thermochemical Characteristics

The chromatographic analysis of the associated petroleum gas (APG) demonstrated that methane remained the dominant fuel component, accounting for approximately 91.9 mol.% of the total gas composition (Table 3). However, unlike conventional transmission-grade natural gas, the investigated fuel contained appreciable concentrations of heavier hydrocarbons, including propane, butanes, pentanes, and traces of hexane. The cumulative concentration of C_3^+ hydrocarbons exceeded 3.5 mol.%, indicating a considerably richer fuel composition than that typically encountered in commercial pipeline natural gas [19–25].

The increased concentration of heavy hydrocarbons significantly affected the thermochemical characteristics of the fuel. As summarized in Table 4, the calculated lower heating value reached 8696 kcal/m³, exceeding the manufacturer's recommended upper limit of 8500 kcal/m³ by approximately 2.3%. Simultaneously, the higher Wobbe Index exceeded 51 MJ/m³, indicating increased volumetric energy input into the engine cylinders. Fuels with an elevated heating value and Wobbe Index generally exhibit higher combustion intensity and increased thermal loading of combustion-chamber components, particularly in large-bore gas engines operating under high cylinder pressures [19–25].

It should be emphasized that all four investigated compressor units operated on essentially the same associated petroleum gas supplied from a common offshore fuel-distribution system. Consequently, the thermochemical properties presented in Tables 3 and 4 characterize the common fuel supplied to all investigated compressors, rather than the variables responsible for the observed differences in combustion stability. This experimental condition made it possible to distinguish the influence of fuel properties from the influence of operational factors during the subsequent analysis.

The methane number of the investigated fuel was estimated to lie within the range of 74–78, which is noticeably lower than that of conventional transmission-grade natural gas. Since the methane number is widely accepted as one of the principal indicators of knock resistance for gaseous fuels, the observed reduction indicates increased fuel reactivity together with a narrower operating margin before the onset of abnormal combustion phenomena [20–23]. Consequently, although the investigated APG provides favorable conditions for ignition and rapid flame propagation, it also increases the susceptibility of the combustion process to thermal instability when unfavorable operating conditions are present. The influence of increasing heavy-hydrocarbon concentration on methane number and knock tendency is illustrated schematically in Figure 4.

Figure 4 summarizes the generally accepted relationship between increasing C_3^+ hydrocarbon concentration, decreasing methane number, and increasing knock tendency reported in previous combustion studies [19–25]. In the present investigation, however, this relationship serves only as thermochemical background because all investigated compressors operated on essentially identical associated petroleum gas. Therefore, the differences

in combustion stability observed in the following sections cannot be attributed to variations in fuel composition.

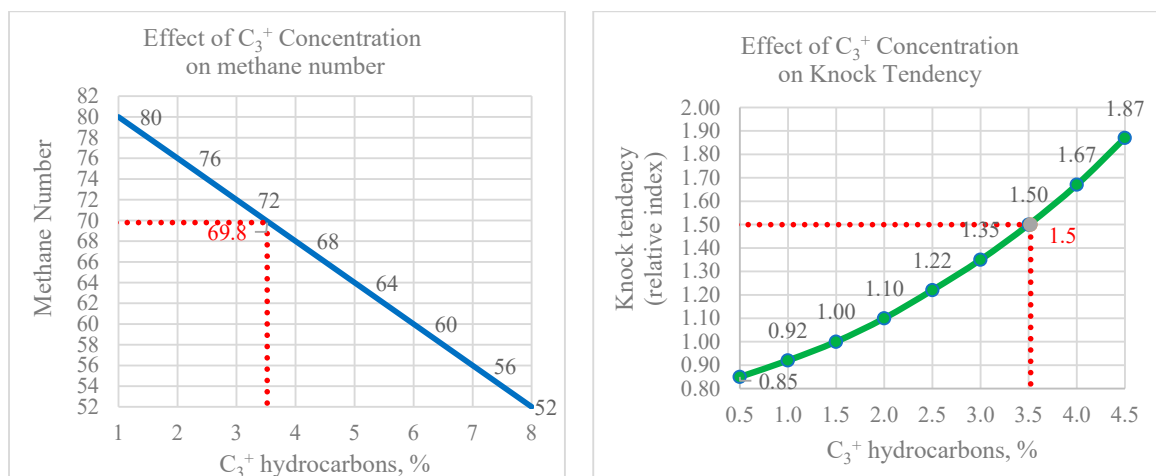


Figure 4. Effect of C₃⁺ hydrocarbon concentration on methane number and knock tendency.

The influence of heavy-hydrocarbon concentration on combustion reactivity is presented schematically in Figure 5.

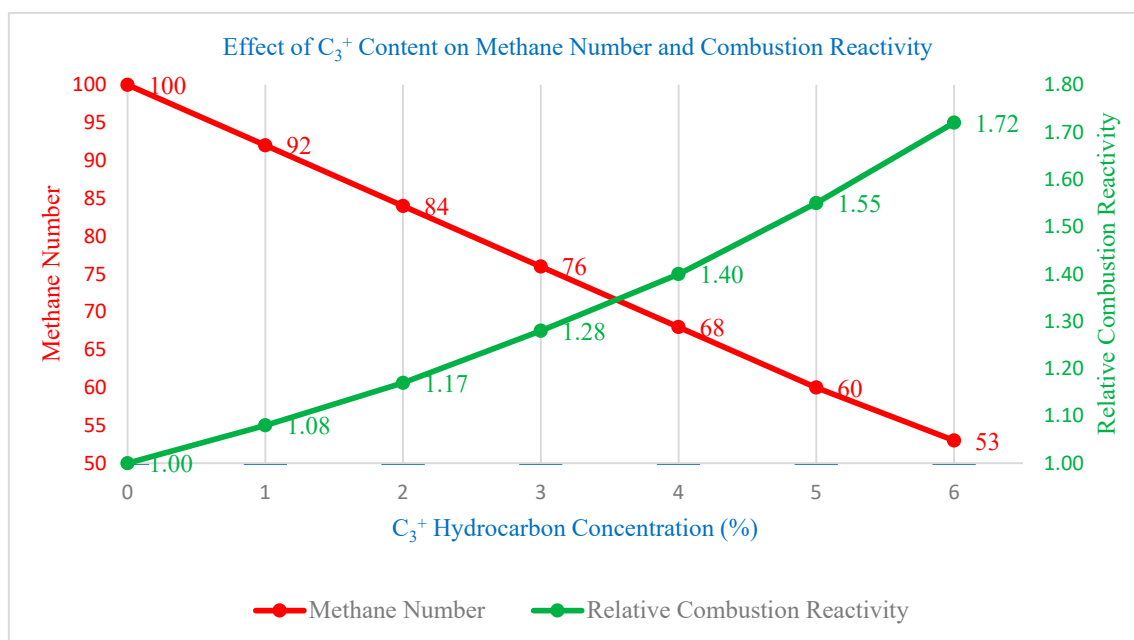


Figure 5. Influence of C₃⁺ hydrocarbon concentration on methane number and combustion reactivity.

Figure 5 illustrates that increasing concentrations of heavier hydrocarbons enhance fuel chemical reactivity and promote more rapid flame development. Such behavior generally improves combustion completeness and can contribute to higher thermal efficiency. However, under conditions of insufficient scavenging-air supply or elevated thermal loading, increased combustion intensity may also promote non-uniform heat release, higher cylinder-to-cylinder thermal imbalance, and increased exhaust-gas temperature dispersion [12,17,20–22].

The present industrial measurements indicate that the increased combustion reactivity associated with APG was common to all investigated compressor units. Consequently, although fuel composition established the thermochemical conditions for combustion, it did

not explain the observed differences in exhaust-gas temperature distribution, Combustion Stability Index (CSI), or Temperature Dispersion Coefficient (TDC). These differences were instead governed predominantly by scavenging-air performance and compressor operating conditions, as demonstrated in the following sections.

Overall, the obtained results indicate that the investigated associated petroleum gas provides a common thermochemical basis for combustion in all compressor units by determining fuel energy density, combustion reactivity, and knock resistance. However, because fuel composition remained essentially constant throughout the investigation, it could not account for the substantial differences in combustion stability observed among individual compressors. This finding represents one of the principal outcomes of the present study and demonstrates that scavenging-air pressure and compressor loading constitute the dominant operational factors controlling combustion stability under long-term industrial operating conditions. Their influence is analyzed quantitatively in the following sections.

4.2. Effect of Scavenging-Air Pressure on Combustion Stability of Gas Motor Compressors

The influence of scavenging-air pressure on combustion stability was evaluated by comparing compressor units operating under nearly identical fuel compositions and compressor-loading conditions but exhibiting substantially different scavenging-air performance. This approach made it possible to isolate the effect of cylinder charging on combustion behavior while minimizing the influence of other operational variables.

The most illustrative comparison was obtained at Compressor Station No. 3, where Compressors No. 3 and No. 5 operated at approximately 33% of their rated capacity while being supplied with fuel from the same associated petroleum gas (APG) distribution system. Under these nearly identical operating conditions, the scavenging-air pressure differed markedly. Compressor No. 3 operated with only 19–21 kPa, whereas Compressor No. 5 maintained significantly higher values of 47–54 kPa.

The reduced scavenging-air pressure observed in Compressor No. 3 resulted in pronounced cylinder-to-cylinder thermal non-uniformity. Exhaust-gas temperatures varied from 240 °C to 368 °C, producing a maximum temperature difference of 128 °C. The average exhaust-gas temperature was 305.5 °C, while the corresponding standard deviation reached 28.6 °C, indicating considerable combustion instability and non-uniform heat release among the cylinders. By contrast, Compressor No. 5 exhibited substantially more uniform combustion behavior. Although the average exhaust-gas temperature remained comparable, the temperature distribution became considerably narrower. The exhaust-gas temperature range decreased to 72 °C, while the standard deviation was reduced to 16.6 °C. Since both compressors operated under essentially identical fuel compositions and loading conditions, the observed improvement can primarily be attributed to enhanced scavenging-air performance rather than differences in fuel properties.

The comparison was intentionally performed for compressors operating at nearly identical loading conditions and supplied with the same APG source, thereby minimizing the influence of fuel composition and engine load. Consequently, scavenging-air pressure represented the principal independent variable governing the observed differences in combustion behavior.

The temporal variations in the operating parameters for Compressor No. 3 are summarized in Table 5.

As shown in Table 5, Compressor No. 3 exhibited persistent thermal non-uniformity throughout the observation period. The maximum cylinder exhaust-gas temperature consistently exceeded 360 °C, whereas the minimum temperature remained close to 250 °C, resulting in a temperature spread exceeding 120 °C. Throughout the monitoring period, the

scavenging-air pressure remained almost constant at 19–21 kPa, indicating chronically insufficient cylinder charging. Such operating conditions promote incomplete air–fuel mixing, increased residual-gas concentration, uneven flame propagation, and, consequently, significant thermal imbalance among the cylinders [1,4,6,17,22]. The corresponding operating parameters for Compressor No. 5 are presented in Table 6.

Table 5. Variations in the operating parameters of Compressor No. 3 at Compressor Station No. 3.

Parameters	Time (3 h Intervals)					
	01.00	04.00	07.00	10.00	13.00	16.00
Exhaust-gas temperature, Cylinder 1, °C	252	264	240	271	263	254
Exhaust-gas temperature, Cylinder 2, °C	309	312	314	311	301	303
Exhaust-gas temperature, Cylinder 3, °C	280	284	289	303	303	297
Exhaust-gas temperature, Cylinder 4, °C	319	293	313	317	333	331
Exhaust-gas temperature, Cylinder 5, °C	327	336	330	321	311	313
Exhaust-gas temperature, Cylinder 6, °C	318	322	320	313	300	302
Exhaust-gas temperature, Cylinder 7, °C	306	311	305	308	303	296
Exhaust-gas temperature, Cylinder 8, °C	310	314	313	305	288	290
Exhaust-gas temperature, Cylinder 9, °C	269	284	277	275	274	259
Exhaust-gas temperature, Cylinder 10, °C	364	356	367	368	360	359
Crankshaft rotational speed, n , rpm	214	212	213	219	224	222
Scavenging-air pressure, kPa	20	19	19	21	21	20

Table 6. Variations in the operating parameters of Compressor No. 5 at Compressor Station No. 3.

Parameters	Time (3 h Intervals)					
	01.00	04.00	07.00	10.00	13.00	16.00
Exhaust-gas temperature, Cylinder 1, °C	340	347	343	346	324	325
Exhaust-gas temperature, Cylinder 2, °C	300	327	322	312	307	293
Exhaust-gas temperature, Cylinder 3, °C	324	326	316	321	308	309
Exhaust-gas temperature, Cylinder 4, °C	317	307	315	320	314	309
Exhaust-gas temperature, Cylinder 5, °C	335	338	332	338	318	313
Exhaust-gas temperature, Cylinder 6, °C	328	337	340	340	325	325
Exhaust-gas temperature, Cylinder 7, °C	318	323	317	324	304	301
Exhaust-gas temperature, Cylinder 8, °C	331	322	355	352	343	338
Exhaust-gas temperature, Cylinder 9, °C	345	348	345	340	328	328
Exhaust-gas temperature, Cylinder 10, °C	359	355	365	362	348	343
Crankshaft rotational speed, n , rpm	234	228	233	237	224	225
Scavenging-air pressure, kPa	53	52	53	54	47	48

Unlike Compressor No. 3, the data presented in Table 6 demonstrate substantially more stable combustion conditions. Although the average exhaust-gas temperatures were similar, the thermal distribution among cylinders became considerably more uniform. Throughout the monitoring period, scavenging-air pressure remained within 47–54 kPa, providing improved cylinder charging, more efficient scavenging of residual gases, enhanced mixture formation, and consequently more homogeneous combustion throughout the engine [1,4,6,17].

The temporal evolution of scavenging-air pressure, crankshaft rotational speed, and cylinder exhaust-gas temperatures for Compressors No. 3 and No. 5 is illustrated in Figure 6.

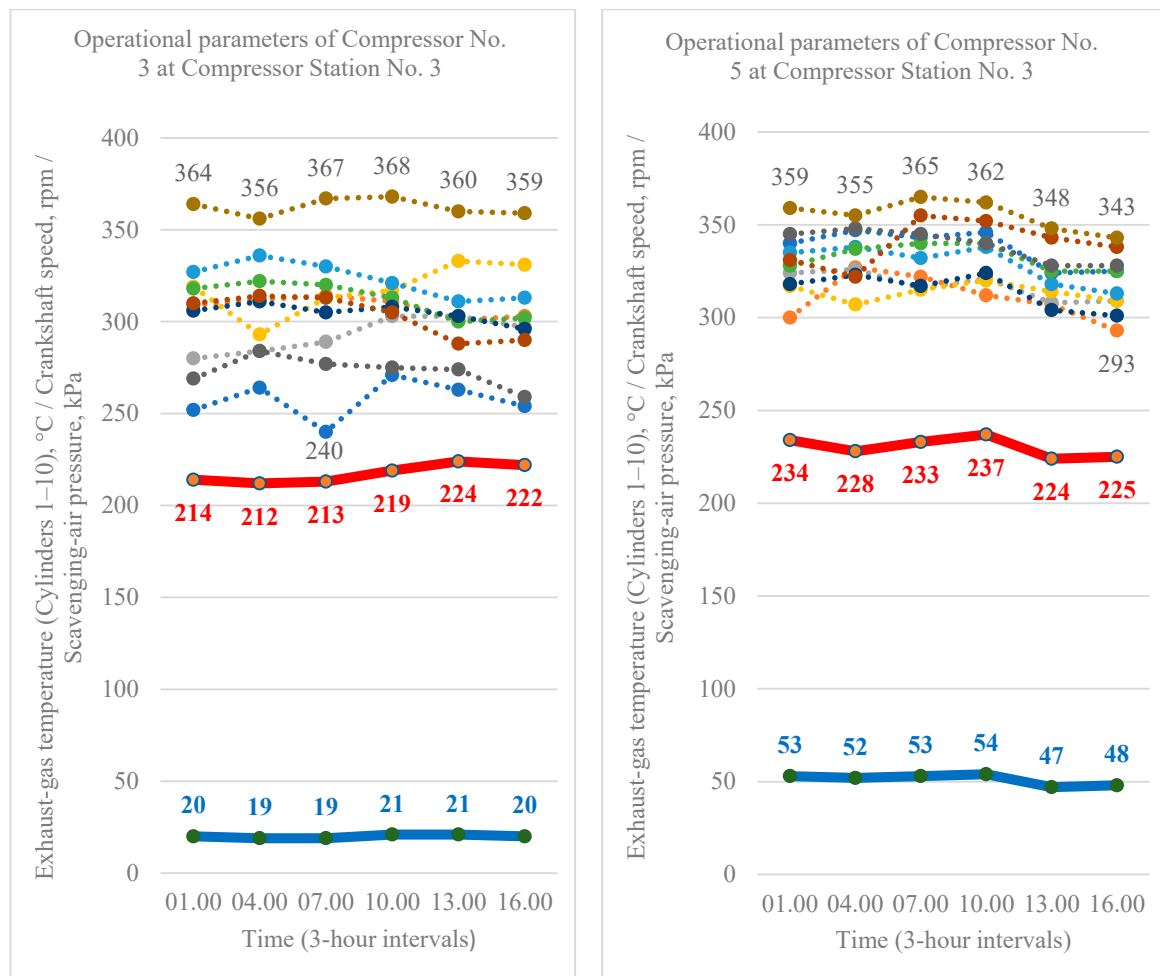


Figure 6. Temporal variations in exhaust-gas temperatures, crankshaft rotational speed, and scavenging-air pressure for Compressors No. 3 and No. 5 at Compressor Station No. 3.

The obtained results clearly demonstrate that scavenging-air pressure represents one of the dominant operational parameters governing combustion stability in low-speed gas motor compressors. Increasing scavenging-air pressure from 19–21 kPa to 47–54 kPa reduces the exhaust-gas temperature range from 128 °C to 72 °C, corresponding to a reduction of approximately 44%. Simultaneously, the standard deviation of cylinder exhaust-gas temperatures decreased from 28.6 °C to 16.6 °C, confirming a substantial improvement in combustion uniformity.

The improvement was observed consistently throughout the monitoring period, rather than during isolated operating intervals, indicating that the relationship between scavenging-air pressure and combustion stability is systematic and reproducible under routine industrial operating conditions.

This behavior is fully consistent with the combustion mechanisms discussed in Section 2. Higher scavenging-air pressure improves cylinder filling, increases the excess-air ratio, enhances air–fuel mixture formation, and promotes more uniform flame propagation throughout the combustion chamber. Conversely, degradation of the scavenging system results in insufficient air supply, increased residual-gas fraction, locally fuel-rich combustion zones, incomplete combustion, elevated exhaust-gas temperatures, and greater thermal imbalance among the cylinders [1,4,6,17,22].

These observations are also consistent with previous investigations emphasizing the importance of efficient scavenging for combustion development in large-bore gas engines [17,22,27–30]. However, unlike previous laboratory and engine-test studies, the

present work quantifies this relationship using operational data obtained from long-service offshore gas motor compressors under continuous industrial operating conditions.

The experimental observations further indicate that scavenging-air performance exerts a considerably stronger influence on combustion stability than the relatively small variations in fuel composition observed during the present investigation. Because both compressors were supplied with essentially identical associated petroleum gas and operated under comparable loading conditions, the substantial improvement in combustion stability can be attributed primarily to enhanced scavenging-air pressure rather than to differences in fuel thermochemical properties.

From an engineering perspective, these results indicate that restoration of scavenging-air performance may represent one of the most effective operational measures for improving combustion stability in aging offshore gas motor compressors without major modifications to the engine design.

The obtained results also provide practical validation of the proposed combustion-diagnostic methodology based on exhaust-gas temperature analysis. The observed reduction in thermal dispersion with increasing scavenging-air pressure establishes a quantitative foundation for the integrated combustion stability indicators developed in the present study, namely the Temperature Dispersion Coefficient (*TDC*) and the Combustion Stability Index (*CSI*), which are evaluated in the following section.

Accordingly, the field observations presented in this section provide the experimental basis for validating the proposed *CSI* and *TDC* indicators as practical tools for continuous combustion monitoring, predictive diagnostics, and condition-based maintenance of offshore gas motor compressors.

4.3. Effect of Compressor Loading on Combustion Stability

The influence of compressor loading on combustion stability was evaluated by comparing gas motor compressors operating at approximately 33% and 51% of their rated capacity. Since all investigated units were supplied with essentially identical associated petroleum gas, the observed differences in combustion behavior can primarily be attributed to operating conditions rather than to variations in fuel composition.

The compressors operating at Compressor Station No. 4, under a loading level of approximately 51%, exhibited considerably more stable combustion than those operating at Compressor Station No. 3, where the loading level was approximately 33%. In particular, Compressor No. 5 at Compressor Station No. 4 demonstrated the most uniform cylinder temperature distribution among all investigated units, with exhaust-gas temperatures varying only between 333 °C and 370 °C. This relatively narrow temperature interval indicates highly uniform heat release and balanced thermal loading of the engine cylinders.

The observed improvement in combustion stability at higher loading levels is consistent with the established combustion behavior of large-bore spark-ignition gas engines. Increased compressor loading raises the effective cylinder pressure and promotes stronger in-cylinder turbulence, resulting in improved air–fuel mixing, more stable flame propagation, and more complete combustion.

Operation at higher compressor loading promotes increased cylinder pressure, stronger in-cylinder turbulence, and more stable flame propagation. These factors improve combustion repeatability, increase combustion completeness, and reduce cycle-to-cycle variations in heat release. Consequently, higher loading generally contributes to improved combustion stability and lower thermal imbalance, which is consistent with previous investigations on large-bore natural-gas engines [22,26–28].

Conversely, prolonged operation under partial-load conditions reduces turbulence intensity and combustion temperature, making the combustion process more sensitive to local variations in the air–fuel ratio and scavenging efficiency.

Industrial measurements indicate that these adverse effects become particularly pronounced when reduced compressor loading is combined with insufficient scavenging-air pressure.

The calculated values of the Combustion Stability Index (*CSI*), Temperature Dispersion Coefficient (*TDC*), and compressor loading factor are summarized in Table 7.

Table 7. Calculated values of the Combustion Stability Index (*CSI*), Temperature Dispersion Coefficient (*TDC*), and compressor loading factor.

Compressor	T_{avg} (°C)	σ_T	<i>TDC</i>	<i>CSI</i>	<i>L.</i> %
No. 3 at CS No. 3	305.5	28.6	0.419	0.906	33
No. 5 at CS No. 3	328.9	16.6	0.219	0.949	33
No. 5 at CS No. 4	360.1	9.8	0.103	0.973	51
No. 10 at CS No. 4	344.9	17.2	0.206	0.950	51

As shown in Table 7, the highest combustion stability was observed for Compressor No. 5 at Compressor Station No. 4, which operated at approximately 51% loading and exhibited the highest *CSI* (0.973), together with the lowest *TDC* (0.103).

In contrast, Compressor No. 3 at Compressor Station No. 3, operating at approximately 33% loading, demonstrated the lowest combustion stability, with *CSI* = 0.906 and *TDC* = 0.419, indicating substantially greater thermal non-uniformity. The relationship between compressor loading and the proposed combustion stability indicators is illustrated in Figure 7.

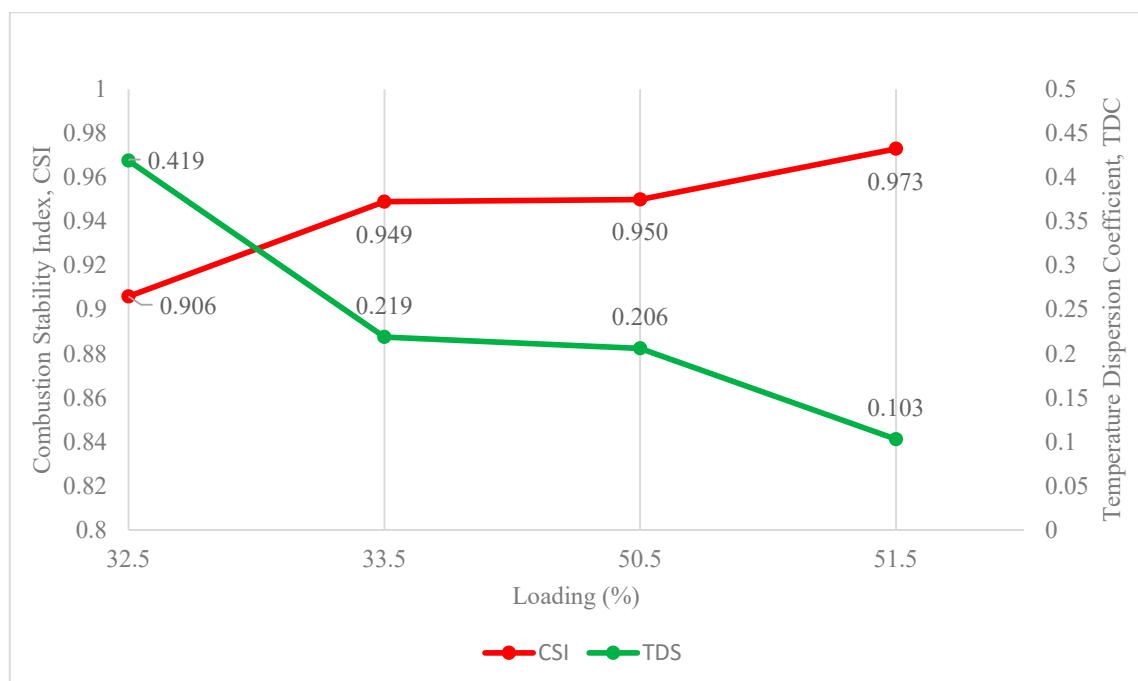


Figure 7. Relationship of compressor loading with the Combustion Stability Index (*CSI*) and Temperature Dispersion Coefficient (*TDC*).

As shown in Figure 7, compressors operating under lower loading conditions consistently exhibited higher *TDC* values and lower *CSI* values than compressors operating at higher loading.

Although only four industrial compressor units were investigated, the observed trends were consistent for all examined operating conditions and therefore provide practical evidence of the relationship between compressor loading and combustion stability in long-service offshore gas motor compressors.

The results also indicate that compressor loading alone cannot fully explain the observed combustion behavior. A comparison with the results presented in Section 4.2 shows that compressors operating with adequate scavenging-air pressure consistently exhibited better combustion stability than those with degraded scavenging performance, even when operating under similar loading conditions.

These findings suggest that compressor loading and scavenging-air pressure act synergistically in determining combustion stability. Increased loading improves combustion only when sufficient cylinder charging is maintained, whereas deterioration of the scavenging system substantially reduces the beneficial effects of higher loading.

The proposed *CSI* and *TDC* indicators successfully reflected these changes, demonstrating their capabilities to distinguish different combustion regimes under practical industrial operating conditions.

These results indicate that compressor loading is an important operational parameter influencing combustion stability in low-speed gas motor compressors; however, its effect is secondary to that of scavenging-air pressure.

Overall, the industrial results demonstrate that scavenging-air pressure represents the primary controlling factor, whereas compressor loading acts as a secondary parameter that either enhances or suppresses combustion stability, depending on the effectiveness of cylinder charging.

This conclusion agrees well with previous studies on large stationary natural-gas engines [17,22,26–28] while extending their findings through quantitative industrial validation using the proposed *CSI* and *TDC* indicators.

4.4. Combined Influence of Fuel Composition, Scavenging-Air Pressure, and Compressor Loading

One of the principal objectives of the present investigation was to quantify the relative contributions of fuel composition, scavenging-air pressure, and compressor loading to combustion stability in offshore gas motor compressors operating on associated petroleum gas (APG). The thermochemical analysis demonstrated that the investigated APG contained elevated concentrations of C_3^+ hydrocarbons, resulting in an increased lower heating value, a higher Wobbe Index, and a reduced methane number compared with conventional transmission-grade natural gas. These fuel characteristics increase chemical reactivity, accelerate flame propagation, and promote faster heat release, while simultaneously reducing knock resistance and narrowing the stable operating range of the engine [10–18].

However, because all the investigated compressor units were supplied from the same APG distribution system, variations in fuel composition among the compressors were negligible throughout the monitoring period.

Consequently, the substantial differences in combustion stability observed during industrial operation cannot be explained solely by differences in fuel properties.

This finding demonstrates that, under the investigated industrial conditions, fuel composition established the thermochemical boundary conditions for combustion, whereas operational parameters governed the actual combustion behavior.

The comparative analysis identified scavenging-air pressure as the dominant operational parameter controlling combustion stability. Compressors operating with scavenging-air pressures of 47–54 kPa consistently exhibited lower exhaust-gas temperature dispersion, higher Combustion Stability Index (*CSI*) values, and more uniform thermal loading than compressors operating with scavenging-air pressures of only 19–21 kPa. Improved cylinder

charging enhanced air–fuel mixture formation, promoted more complete combustion, and produced more uniform heat release throughout the engine [17,23–27].

Compressor loading also influenced combustion stability, although its effect was less pronounced than that of scavenging-air pressure. Compressors operating at approximately 51% of rated capacity demonstrated higher *CSI* values and lower Temperature Dispersion Coefficient (*TDC*) values than compressors operating at approximately 33% loading. Increased loading enhanced in-cylinder turbulence and combustion intensity, thereby improving flame propagation and reducing combustion variability. Nevertheless, the present results indicate that favorable loading conditions alone cannot compensate for inadequate scavenging-air supply [17,22–25].

The combined analysis therefore indicates that combustion stability should be regarded as the result of the interaction between fuel properties and operating conditions rather than the consequence of any single controlling factor.

The combined analysis therefore demonstrates that fuel composition determines the thermochemical potential of the combustion process, whereas scavenging-air pressure and compressor loading determine how effectively this potential is realized under industrial operating conditions. Among the investigated parameters, scavenging-air pressure exerted the strongest influence on combustion stability, compressor loading provided an additional stabilizing effect, and fuel composition established the overall combustion characteristics but did not account for the observed differences in combustion performance because all compressors operated on essentially identical APG.

These observations are consistent with previous investigations reporting the importance of fuel reactivity, cylinder charging, and engine operating conditions for combustion performance. However, earlier studies generally evaluated these factors separately or under laboratory conditions, making direct extrapolation to aging industrial compressor fleets difficult [12–18,23–27].

These findings are consistent with previous studies highlighting the importance of gaseous-fuel properties, cylinder charging, and engine operating conditions for combustion behavior [12–18,23–27]. However, unlike earlier investigations, which generally considered these factors independently and predominantly under laboratory or engine-test conditions, the present study quantitatively evaluates their combined influence using long-term operational data obtained from industrial offshore gas motor compressors.

An important contribution of the present work is the industrial validation of the proposed combustion-diagnostic methodology using routinely monitored operational parameters collected under real production conditions.

Furthermore, the proposed Combustion Stability Index (*CSI*) and Temperature Dispersion Coefficient (*TDC*) provide a practical, quantitative framework for assessing combustion stability using only routinely monitored operational parameters, making the methodology directly applicable to industrial compressor stations without additional instrumentation.

Unlike diagnostic approaches requiring in-cylinder pressure measurements, knock sensors, or advanced combustion instrumentation, the proposed methodology can be readily incorporated into existing SCADA-based monitoring systems without hardware modification, thereby facilitating continuous combustion assessment in long-service compressor stations.

From an engineering perspective, the results indicate that maintaining adequate scavenging-air pressure represents the most effective operational strategy for improving combustion stability in aging offshore gas motor compressors. Compressor loading should be optimized within technological constraints, whereas fuel-quality monitoring should primarily be used to anticipate changes in combustion behavior associated with variations in APG composition. The proposed diagnostic methodology therefore provides a practical

basis for continuous combustion monitoring, predictive diagnostics, and condition-based maintenance, contributing to improved operational reliability, higher energy efficiency, and safer long-term operation of offshore compressor stations utilizing associated petroleum gas [20,25–30].

Overall, the present results demonstrate that reliable combustion diagnostics in aging offshore gas motor compressors require simultaneous consideration of fuel thermochemical properties, scavenging-air performance, and compressor loading. The proposed *CSI* and *TDC* indicators provide a simple industrial tool for integrating these factors into a unified framework for combustion assessment and operational decision-making.

4.5. Validation of the Proposed Combustion Stability Indicators

The practical applicability of the proposed Combustion Stability Index (*CSI*) and Temperature Dispersion Coefficient (*TDC*) was validated using operational data collected from all four investigated gas motor compressors operating under real industrial conditions. The objective of the validation was to assess the ability of the proposed indicators to distinguish different combustion regimes and to quantify the influence of operating conditions on combustion stability. Validation was performed by comparing the calculated *CSI* and *TDC* values with independently measured operational parameters, including scavenging-air pressure, compressor loading, and cylinder exhaust-gas temperature distributions. The consistency between these independent datasets was used to evaluate the diagnostic capability of the proposed indicators under actual industrial operating conditions.

The lowest combustion stability was observed for Compressor No. 3 at Compressor Station No. 3, which exhibited the lowest *CSI* (0.906) and the highest *TDC* (0.419).

These values indicate pronounced thermal imbalance, significant cylinder-to-cylinder temperature variation, and substantial non-uniformity of the combustion process. This compressor also operated at the lowest scavenging-air pressure recorded during the investigation (19–21 kPa), confirming the strong relationship between inadequate cylinder charging and combustion deterioration [17,23–27].

A considerable improvement was observed for Compressor No. 5 operating at the same compressor station. Despite operating under essentially identical fuel composition and compressor loading, the higher scavenging-air pressure (47–54 kPa) increased the *CSI* from 0.906 to 0.949, while reducing the *TDC* from 0.419 to 0.219. The observed improvement confirms that both indicators are sufficiently sensitive to detect relatively small changes in combustion conditions caused by operational rather than fuel-related factors.

The highest combustion stability was achieved by Compressor No. 5 at Compressor Station No. 4, where the *CSI* reached 0.973 and the *TDC* decreased to 0.103. These values correspond to highly uniform combustion, balanced thermal loading of all cylinders, and excellent overall combustion performance. The second compressor, operating at the same station, also demonstrated favorable diagnostic characteristics (*CSI* = 0.950, *TDC* = 0.206), further confirming the consistency and repeatability of the proposed methodology under industrial operating conditions. The relationship between the two diagnostic indicators is illustrated in Figure 8, which was constructed using the calculated values summarized in Table 7.

As illustrated in Figure 8, a pronounced inverse correlation exists between the two indicators. Increasing *CSI* values consistently correspond to decreasing *TDC* values, indicating progressively improved combustion uniformity and reduced thermal imbalance among cylinders. The observed inverse relationship demonstrates that both indicators respond consistently to changes in combustion conditions while characterizing different aspects of combustion stability.

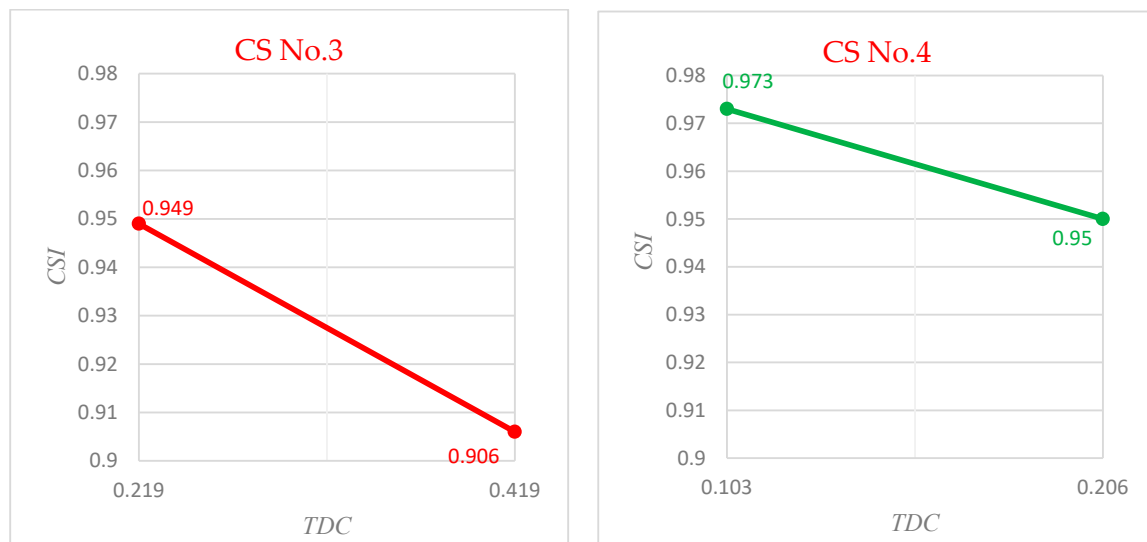


Figure 8. Relationship between the Combustion Stability Index (CSI) and Temperature Dispersion Coefficient (TDC) at different loads for the investigated gas motor compressors.

This behavior confirms that the two indicators provide complementary diagnostic information.

While the *TDC* quantifies the maximum thermal non-uniformity within the engine, the *CSI* evaluates the overall consistency of combustion across all cylinders. Their simultaneous application therefore provides a more comprehensive assessment of combustion quality than either parameter used independently.

Because the present investigation included four industrial compressor units operating under representative offshore conditions, the proposed diagnostic thresholds should be regarded as preliminary engineering guidelines rather than universal limit values. Their applicability to other compressor types and operating conditions should be verified in future industrial studies involving larger datasets.

Based on the industrial dataset analyzed in this study, preliminary diagnostic thresholds can be proposed for practical application. Compressors operating with *CSI* values above approximately 0.96 and *TDC* values below approximately 0.15 can be classified as operating under excellent combustion conditions. Conversely, *CSI* values below approximately 0.94 or *TDC* values exceeding approximately 0.25 indicate progressive deterioration of combustion stability and should trigger inspection of the scavenging-air system, ignition equipment, fuel-distribution system, and cylinder condition. A major advantage of the proposed methodology is that both diagnostic indicators are calculated exclusively from routinely monitored exhaust-gas temperatures. Unlike conventional combustion-diagnostic techniques based on in-cylinder pressure measurements, ion-current sensors, knock sensors, or advanced combustion-monitoring systems, the proposed approach requires no additional instrumentation and can therefore be implemented directly within existing industrial compressor-station monitoring systems [20,24–30]. Since exhaust-gas temperature measurements are continuously acquired by standard SCADA systems at compressor stations, the proposed methodology can be implemented entirely through software without modification of existing measurement hardware. This considerably simplifies practical implementation and reduces monitoring costs.

The industrial validation confirms that the proposed *CSI* and *TDC* indicators are sufficiently sensitive to distinguish different combustion regimes, identify progressive deterioration of combustion quality, and quantify the combined influence of scavenging-air pressure and compressor loading on combustion stability. Consequently, they provide a

practical engineering tool for continuous combustion monitoring, predictive diagnostics, condition-based maintenance, and operational optimization of aging offshore gas motor compressors operating on associated petroleum gas [20,24–30].

Overall, the validation results demonstrate that the proposed *CSI* and *TDC* indicators provide a robust and practically applicable framework for quantitative combustion assessment using only routinely available industrial operating data, thereby facilitating reliable long-term monitoring of offshore gas motor compressors.

5. Limitations and Future Research

Although the proposed methodology was successfully validated using operational data obtained from four offshore gas motor compressors operating on associated petroleum gas under real industrial conditions, several limitations should be acknowledged when interpreting the results.

First, the investigation was conducted exclusively on low-speed 10GKNAM-series gas motor compressors installed at offshore compressor stations supplied from a common associated petroleum gas production system. While this configuration ensured nearly identical fuel composition and allowed the effects of scavenging-air pressure and compressor loading to be isolated with high confidence, further validation involving other compressor designs, engine configurations, and gaseous-fuel compositions would enhance the general applicability of the proposed methodology.

In particular, future validation involving larger industrial datasets collected from multiple compressor stations and different geographical regions would improve the statistical robustness of the proposed diagnostic thresholds.

Second, the present study focused primarily on three major factors affecting combustion stability, namely fuel composition, scavenging-air pressure, and compressor loading. Although these parameters were identified as the dominant operational variables under the investigated conditions, other factors—including ignition-system performance, cylinder-to-cylinder air–fuel distribution, lubrication conditions, ambient environmental parameters, and progressive mechanical wear—may also influence combustion behavior during long-term industrial operation. Their combined effects warrant further investigation.

Furthermore, the present investigation was performed under steady-state operating conditions. Future studies should examine the applicability of the proposed indicators during transient operating regimes, including compressor start-up, shutdown, rapid load variations, and fuel composition fluctuations.

Third, the proposed Combustion Stability Index (*CSI*) and Temperature Dispersion Coefficient (*TDC*) were developed exclusively from routinely monitored exhaust-gas temperatures. This represents an important practical advantage because it enables implementation without additional instrumentation. Nevertheless, future studies could combine the proposed indicators with complementary diagnostic techniques, including in-cylinder pressure measurements, vibration monitoring, ion-current sensing, and data-driven diagnostic algorithms, in order to further improve diagnostic sensitivity and fault-identification capability [20,24–30]. In addition, future research should investigate the long-term predictive capability of the proposed indicators for identifying the progressive deterioration of combustion quality before the occurrence of measurable operational failures. Such studies would further support their application in predictive maintenance and reliability-oriented asset management. Future research should also evaluate the applicability of the proposed methodology to other categories of large-bore reciprocating gas engines operating on variable-composition gaseous fuels, including liquefied natural gas boil-off gas, refinery fuel gas, hydrogen-enriched natural gas, biomethane, and other renewable gaseous fuels. In addition, the integration of the proposed diagnostic indicators into digital-twin envi-

ronments, predictive-maintenance platforms, and real-time condition-monitoring systems represents a promising direction for further industrial development [20,25,30]. Such integration would facilitate automated combustion-quality assessment, early fault detection, and optimized operational control of aging gas motor compressor fleets operating under variable fuel and process conditions.

6. Conclusions

The present study investigated the combined influence of associated petroleum gas composition, scavenging-air pressure, and compressor loading on the combustion stability of low-speed offshore gas motor compressors operating under real industrial conditions. Based on the obtained results, the following conclusions can be drawn.

1. Combustion stability is governed by the combined interaction of fuel properties and operating conditions. Although the investigated associated petroleum gas contained elevated concentrations of C_3^+ hydrocarbons and exhibited increased chemical reactivity, the observed differences in combustion stability among the investigated compressors were controlled primarily by operational parameters rather than by fuel composition alone [10–18,22–27].
2. Scavenging-air pressure was identified as the dominant operational factor affecting combustion stability. Increasing scavenging-air pressure from 19–21 kPa to 47–54 kPa reduced the cylinder exhaust-gas temperature range from 128 °C to 72 °C and decreased the standard deviation of cylinder temperatures from 28.6 °C to 16.6 °C, demonstrating a substantial improvement in combustion uniformity [17,23–27].
3. Compressor loading also influenced combustion behavior. Compressors operating at approximately 51% of rated capacity exhibited lower thermal imbalance and more stable combustion than compressors operating at approximately 33% loading. Nevertheless, the beneficial effect of increased loading became significant only when adequate scavenging-air pressure was maintained [22–28].
4. Two novel combustion-diagnostic indicators were developed and industrially validated: the Combustion Stability Index (*CSI*) and the Temperature Dispersion Coefficient (*TDC*). Unlike conventional combustion-diagnostic approaches, both indicators are calculated exclusively from routinely monitored exhaust-gas temperatures, allowing for practical implementation without additional measuring equipment or modifications to existing monitoring systems [20,24–30].
5. Industrial validation demonstrated that the proposed indicators provide reliable quantitative discrimination between different combustion regimes. The *CSI* and *TDC* values consistently reflected changes in combustion quality caused by variations in scavenging-air pressure and compressor loading, confirming their suitability for practical combustion diagnostics under long-term industrial operating conditions.
6. Based on the analyzed industrial dataset, preliminary diagnostic thresholds were established for practical application. *CSI* values above approximately 0.96, together with *TDC* values below approximately 0.15, indicate stable combustion, whereas *CSI* values below approximately 0.94 or *TDC* values above approximately 0.25 may serve as early warning indicators requiring inspection of the scavenging-air, ignition, fuel-distribution, and cylinder systems.
7. The proposed methodology represents an integrated engineering approach that combines fuel characterization, operational monitoring, statistical analysis, and quantitative combustion diagnostics within a unified framework. Unlike previously reported approaches that often rely on specialized combustion instrumentation, the proposed methodology can be implemented using only routinely monitored industrial operating parameters available from existing compressor-station monitoring systems.

8. The obtained results demonstrate that practical combustion diagnostics based on routinely monitored operational data can substantially improve the reliability of aging offshore gas motor compressors operating on associated petroleum gas. The proposed methodology provides a scientific and engineering foundation for predictive diagnostics, condition-based maintenance, digital monitoring systems, and future intelligent management of industrial gas-compression facilities.

Practical Implications

The proposed combustion-diagnostic methodology can be readily integrated into existing compressor-station monitoring systems because both the Combustion Stability Index (*CSI*) and the Temperature Dispersion Coefficient (*TDC*) are calculated exclusively from routinely monitored exhaust-gas temperatures. Consequently, implementation requires neither additional instrumentation nor major modifications to existing industrial monitoring infrastructure, making the approach particularly suitable for aging offshore compressor stations.

Because all required input parameters are already available in conventional industrial SCADA systems, the proposed methodology can be implemented through software-based calculations of the diagnostic indicators without interrupting normal compressor operation.

Continuous evaluation of the proposed indicators enables early detection of progressive combustion deterioration and provides maintenance personnel with quantitative information on the development of thermal imbalance before significant reductions in efficiency and abnormal combustion or component failures occur. The preliminary diagnostic thresholds identified in this study ($CSI \approx 0.94$ and $TDC \approx 0.25$) may therefore serve as practical decision-support criteria for combustion monitoring, maintenance scheduling, and operational control.

The industrial results further demonstrate that restoring and maintaining adequate scavenging-air pressure provides substantially greater improvements in combustion stability than moderate improvements in fuel quality under the investigated operating conditions. From an operational perspective, this finding indicates that maintenance activities should primarily focus on preserving scavenging-system efficiency, including blower performance, intercooler cleanliness, and air distribution uniformity [17,23–27].

The proposed diagnostic indicators may also be incorporated into automated alarm and decision-support systems, allowing maintenance personnel to identify progressive combustion deterioration before conventional alarm limits based on individual cylinder temperatures are exceeded.

The proposed methodology also supports the transition from traditional corrective maintenance toward predictive and condition-based maintenance strategies. The integration of the *CSI* and *TDC* indicators into industrial monitoring systems enables continuous assessment of combustion quality, early fault detection, optimized maintenance planning, and improved operational decision-making. These capabilities can contribute to increased fuel-utilization efficiency, more uniform thermal loading of engine components, enhanced operational reliability, extended equipment service life, and reduced greenhouse-gas emissions associated with offshore gas-compression operations [20,24–30].

Beyond offshore compressor stations, the proposed methodology can be adapted to other large-bore reciprocating gas engines operating on variable-composition gaseous fuels, provided that continuous exhaust-gas temperature monitoring is available.

From a broader industrial perspective, the proposed diagnostic framework provides operators with a simple, low-cost, and scalable tool for improving the operational efficiency of existing gas motor compressor fleets without requiring expensive modernization or the installation of dedicated combustion-monitoring equipment. Consequently, the methodol-

ogy has strong potential for practical application at mature offshore oil and gas production facilities utilizing associated petroleum gas as the primary engine fuel [20,25,30].

Overall, the proposed approach demonstrates how routinely monitored industrial operating parameters can be transformed into quantitative engineering indicators that support real-time combustion assessment, predictive diagnostics, and intelligent operation of industrial gas-compression facilities.

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