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IMPACT OF COMBUSTION CHAMBER SIZE OF EMISSIONS IN SPARK IGNITION ENGINE: A REVIEW

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Abstract. *One of the most critical aspects of the internal combustion engines (ICE) which can affect the performance and emissions is the combustion chamber design. Given comparable chamber size changes, the combustion rate and natural mixing (i.e., fuel-air mixing) change significantly (nearly a half of the energy of the fuel supplied to the engine goes to the combustion chamber), flame speed, and thermal efficiency (roughly half of the energy of the fuel liberated at the combustion zone). The emissions criteria based on chamber sizes on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2) will be discussed in this review article. The combustion efficiency shows significant improvement with decreasing chamber volume, but CO and HC emissions reduced but simultaneously, due to increased peak temperatures NOx tends to increase from experimental and theoretical studies [3]. Smaller chamber size decreases NOx but also increases CO and HC emissions because of incomplete combustion. Abstract:It is a concise literate review, trade-offs between emissions and technology interventions to balance the performance with emissions.*

Keywords: *Chamber size; Combustion chamber; Engine emissions; Engine performance; Internal combustion engine (ICE).*

1. INTRODUCTION

While electric vehicles develop rapidly, demand for internal combustion engines has not gone down in industrial and transportation jobs. Still, the harm ICE emissions cause to the environment led experts to examine how to make engines greener without losing their efficiency [1]. The size of the combustion chamber plays a big role in determining emissions because it influences the highest combustion temperatures, speed of the flame and how well air and fuel mix. Adjusting the chamber in an emissions management system plays a direct role in producing NOx, CO, HC and CO_2 [2, 3].

The way turbulence, heat transport and combustion efficiency respond to chamber size results in different combustion processes. Because of these factors, less space for flames to develop in a small chamber usually causes complete or almost total, fuel burning. Still, doing this regularly increases the temperature at the cylinder peak, leading to more NOx emissions. At the same time, without enough disturbed air and colder combustion, large chambers may produce more unburned carbon and hydrocarbon gases. Emission reduction and increased performance must both be considered when designing combustion chambers.

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Emissions are affected by changes in the combustion chamber and this has been the target of various investigations. Doppalapudi et al. (2024) recently found that changes in chamber design lowered NOx and CO_2 generation. Authorities discovered that, while improved chamber design raised efficiency, it also resulted in more NOx and lower burning quality when not fully loaded [4].

Key design elements that influence emissions are (a) the piston bowl shape, (b) throat radius, and (c) squish area [5]. According to Wang et al. (2022) and it turn out that by varying the radius of the chamber neck, it has a significant effect on the pressure and heat generated by the combustion chamber, in turn, have different emission levels at different engine speeds. It was evident from their studies that the chamber dimensions cannot be over-sized to achieve environmental targets while maintaining efficiencies [6].

With the arrival of new international emission standards the absolute number of emissions from ICE's can be minimized by optimizing the combustion chamber [7,8]. When engineers and researchers understand the relationship between emissions and the size of the engine's chambers, they are able to create greener, more efficient engines. To gain some insights on design factors that are associated with cleaner combustion, this author intends to explore the effect of changing combustion chamber volume on IC engine emission. Our study aims to explore the connection between combustion chamber dimensions and the emissionsprofile, to lead to better engine designs and consequently a cleaner environment.

2. BACKGROUND ON INTERNAL COMBUSTION ENGINES

Internal combustion engines convert chemical energy from fuel into mechanical work by combusting fuel within a confined chamber, see Fig. 1.

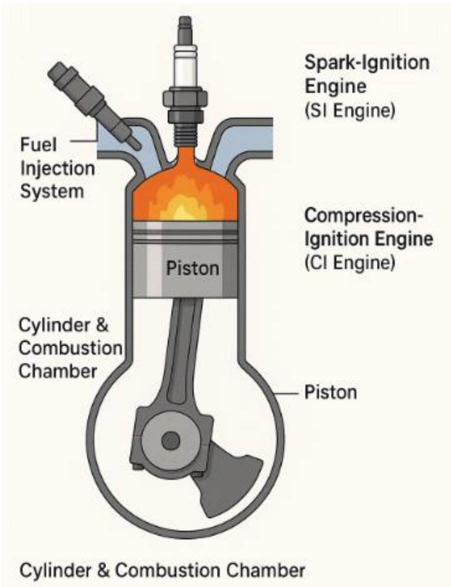

Fig. 1. Internal combustion engines.

Most internal combustion engines work on a four-stroke cycle that includes intake, compression, power, and exhaust strokes. The piston moves down during the intake stroke, which pulls a mixture of air and fuel into the cylinder. The next step is the compression stroke, in which the piston rises up and compresses the mixture to raise the pressure and temperature before it ignites. The spark plug starts the combustion at the end of this stroke, which leads to the power stroke, which changes chemical energy into mechanical work. The exhaust stroke finally pushes the burnt gasses out of the cylinder [12].

2.1 TYPES OF ICES

- Spark-Ignition (SI) Engines: Use spark plugs to ignite air-fuel mixtures.
- Compression-Ignition (CI) Engines: Rely on high compression for fuel ignition, typical in diesel engines [9].

2.2 KEY COMPONENTS

- Cylinder & Combustion Chamber: Where the fuel-air mixture burns.
- Piston: Moves up and down to convert combustion energy into mechanical work.
- Crankshaft: Converts the piston's reciprocating motion into rotational motion.
- Valves: Control the intake of air-fuel mixture and exhaust gas release.
- Fuel Injection System: Delivers fuel into the combustion chamber [10].

2.3 HISTORICAL PERSPECTIVE ON COMBUSTION CHAMBER DESIGN

The combustion chamber shape and size are so important in defining how combustion takes place. The use of smaller chambers allows for the mixing of fuel and air to be improved, as does the speed of the flame development, making the engine relatively more thermally efficient while increasing peak temperature and, by extension, NOx. However, larger chambers tend to slow flame propagation and reduce efficiency, although they do help lower NOx levels. Thus, it is necessary in this respect to optimize the size [14] as large chambers will be less efficient while small chambers will have higher emissions.

ICE (Internal Combustion Engine) upgrades We still are asking ICEs to deliver more power while using less fuel and emitting less pollution, so the ICE design is constantly being refined over the decades. The smelting chambers of the first ICE prototypes were quite primitive in design in the late 1800s. These primitive designs meant the engines consumed far less fuel, but spewed out quite a bit more pollution. A renewed interest in concert hall design emerged among music societies in search of better performance [11–13].

The introduction of the L-head engine accelerated industry development. By positioning the valves alongside the cylinder, the arrangement produced a more compact chamber. Even so, there were a couple of issues with the L-head engine. Due to the inventory of fuel that one can burn effectively (in the form of volume as well as speed of burning), it faced some limitations in the performance and efficiency arena [17].

A milestone in engine development was the design of the first I-head, or overhead valve (OHV) engine. By moving the valves over to the cylinder head on OHV, designers were able to fit larger, higherflowing valves into the cylinder head, which greatly increased airflow into the engine. This increase in volumetric efficiency, in turn, resulted in higher power output. Moreover, to some extent, the OHV architecture promotes small and efficient combustion chambers, ensuring a turbulent mixture of charge and fuel[18–20]..

Chrysler began using its Hemi engine During the middle of the 20th century, which achieved new heights for effective combustion and power output compared to its rivals. A dome-shaped the combustion chamber in the Hemi, placing the spark plug inside; the valves were planned to assure swirling in the chamber during each stroke. With this design, combustion was carried out as efficiently as possible for high power results. Still, because the Hemi had complex internal structures, making and moving the valves was difficult for factories [21].

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Its simple construction and proven ability to improve turbulence in the cylinder led to the wedge-shaped combustion chamber being used everywhere. The usual practice was to pair overhead valves with this configuration since it allowed for both better performance, reduced emissions and practical manufacturing. Because it was straightforward and efficient, it was widely used in engines [22, 23].

Modern high-performance gasoline engines often have pentroof combustion chambers which are recognized by their tilted roof and valves arranged in a V shape [24]. As a result of these types of designs, faster mixing and stronger turbulence of the fuel support better combustion efficiency and less pollution.

Recent advancements in this area incorporate toroidal and re-entrant combustion chambers [25] which suggest enhanced mixing and uniform combustion in diesel engines.

For this reason, the development of combustion chambers is currently mainly done using Computational Fluid Dynamics (CFD) [3]. CFD simulations allow the engineers to visualize and analyze the flow and combustion within the cylinder to improve the design and reduce the harmful emissions. The development of the combustion chamber has been a result of optimising various factors influencing the combustion process, which includes fuel economy, power output, emissions and manufacturability. The different design iterations were based on previous designs, overcoming some of the limitations found in older designs and pushing the envelope of engine performance further and further [18].

3. METHODOLOGY

A systematic review of existing literature evaluating the effect of combustion chamber size on internal combustion engine emissions A systematic methodology was adopted to enhance rigor, transparency and reproducibility of the review..

3.1 LITERATURE SEARCH STRATEGY

The electronic databases searched were Scopus, Web of Science, Google Scholar and IEEE Xplore.

Searches were conducted on combustion chamber size, ICE emissions, internal combustion engine emissions, combustion chamber design, NOx emissions, CO emissions, HC emissions, CO2 emissions, engine efficiency and combinations of the above.

AND/OR/NOT operators were used to narrow the search and obtain pertinent articles. An example of such command could be: (combustion chamber size OR combustion chamber design) AND (internal combustion engine emission OR emission of ICE) AND (CO, CO2, HC OR NOx) [26–28].

Search results were limited only to English writings published between January 2000 and May 2025.

3.2 INCLUSION AND EXCLUSION CRITERIA

- The following inclusion criteria were applied:
  1. Studies that investigated the impact of combustion chamber size or geometry on emissions in internal combustion engines.
  2. Studies that presented original experimental data, numerical simulation results, or comprehensive reviews of the literature.
  3. Studies that were published in peer-reviewed journals or conference proceedings.
- The following exclusion criteria were applied:
  1. Studies that focused on external combustion engines or gas turbines.
  2. Studies that did not provide quantitative data on emissions or engine performance.
  3. Studies that were not available in English.

4. Studies that were deemed to be of low quality or lacking in methodological rigor.

3.3 DATA EXTRACTION PROCESS

- Data was extracted from the included studies using a standardized data extraction form.
- The following data elements were extracted:
  1. Study characteristics (authors, year of publication, journal/conference, study design).
  2. Engine characteristics (engine type, fuel type, combustion chamber size/geometry, compression ratio).
  3. Operating conditions (engine speed, load, air-fuel ratio).
  4. Emissions data (CO, HC, NOx, CO_2, PM).
  5. Engine performance data (power, torque, fuel consumption).
  6. Emission control technologies used (EGR, SCR, VVT, Turbocharging).
- The extracted data was synthesized and analyzed to identify trends, inconsistencies, and key findings related to the impact of combustion chamber size on emissions.

3.4 EMISSIONS AND IMPACT

ICEs emit CO, HC, NOx, and CO_2, contributing to smog, respiratory issues, and climate change [29].

3.5 TECHNOLOGICAL TRENDS

End of 2023 approaches in the energy efficiency and environmental friendly are the so called Reactivity Controlled Compression Ignition (RCCI), Homogeneous Charge Compression Ignition (HCCI), hybridization and alternative fuels as hydrogen and bioethanol [30].

Efficiency, fuel consumption and emission are controllable factors from the architecture of combustion chamber itself, because architecture of combustion chamber is highly sensitive. By altering the volume and geometry of the chamber, the tumbling of the fuel-air mixture, the burning propagation, and the conduction of heat away to the cylinder walls from the combustion chamber all affected. These things work in ways that need to be understood if you are to optimise combustion and reduce harmful emissions. During this review, a clamour is firstly made for how important a combustion chamber design is. Covers after discussion of effects of total volume of the chamber on combustion and later emissions compromises.

4. CHAMBER GEOMETRY AND EMISSION TRADE-OFFS

The geometry of the combustion chamber is a significant factor influencing turbulence intensity, air–fuel mixing, flame propagation, and local temperature gradients; therefore, it can be used to characterize much of the key thermodynamic characteristics of the ICE [31]. Which in turn influences combustion efficiency, leading to emissions of different exhaust pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), carbon dioxide (CO_2) and particulate matters (PM) [32].

Here you can see that trade-off shifts over the combustion chamber with thermal efficiency and pollutants generation trend lines. Lean combustion tends to lead to increased efficiency due to higher Temperatures in the combustion chamber and faster flame propagation, but higher NOx emissions follows. Conversely, designs limited by peak temperature would reduce nox but are likely to leave unburnt hydrocarbon and have a lower efficiency As a result, An optimal mixture of performance and emissions control chamber geometry needs optimization [15].

. This section presents a broad literature review [33–35] on the impact of chamber shape, compression ratio, and various methods for technical improvement on emissions performance.

Emission Trade-off With Different Combustion Chamber Geometries Are Summarized in Table 1 They are affected, due to turbulence generation, flame advancement and detention time, each configuration amounting an autonomous parameter with reference to pollutants production. This information is required to select a chamber design that can produce emissions that meet regulatory and/or efficiency requirements..

Table 1. Emission trade-offs associated with various combustion chamber geometries (Summarized from previous studies [31, 32, and 35]).

Chamber Type	CO	HC	NOx	PM	Efficiency	Remarks
Hemispherical	↓	↓	↑	–	High	Excellent airflow, high temp
Flat-Head	↑	↑	↓	↑	Low	Simple but inefficient mixing
Pentroof	↓	↓	Moderate	–	High	Common in modern SI engines
Toroidal	↓	↓	↓	↓	Very High	Expensive, advanced design
Re-Entrant	↓	↓	↓	↓	High	Optimal for diesel engines
Wedge	↓	↓	↑	–	Moderate	Used in both SI & CI engines

4.1 CHAMBER SHAPE AND EMISSIONS

Multiple studies have demonstrated the influence of combustion on the shape of the chamber:

According to Doppalapudi et al. 2024) -- Flame motion and turbulence increases in engine deeper grooves and shallow chambers Such a design leads to rapid combustion and more complete combustion which leads to reduced CO and HC pollution. But this means the higher temperature in the cylinder raised the NOx as represented by [36].

Li et al. However, when operating the low load of the engine, it said the large valve diameter produces a result of both turbid air-fuel mixing inside the engine (2022). Consequently the engine emits excessive CO and HC emissions and also it forms unburnt fuel rich regions [37-39].

Wang et al. It should be noted that the throat radius can change how in-cylinder pressures react (Vandesande, 2022). Throat radius change tends to vary pressure-rise rate and heat release profiles, which affects NOx and particulate emissions [40e42].

Emissions production in internal combustion engines is complex and is determined by an interplay of thermodynamic, chemical, and operational factors. Each particular pollutant, such as CO, HC, NOx, CO_2 and PM is created from a different pathway based on specific mechanisms that vary with fuel composition, air-fuel stoichiometry, combustion temperature profiles, and combustion chamber architecture [43–45].

A brief summary of the main formation mechanisms of major emissions emissions in diesel engines is provided in Table 2 along with the governing factors for their formation and the associated engine operating conditions. This high level background is drawn from the background to the upcoming more detailed discussions on emission control measures specific to each pollutant [46, 47].

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Table 2. Primary formation mechanisms of key emissions in internal combustion engines.

Emission	Formation Mechanism	Key Influencing Factors	Typical Engine Conditions
CO	Incomplete combustion	Rich air-fuel ratio, low O_2	Cold starts, high loads
HC	Unburned fuel	Poor mixing, low temp	Cold start, lean zones
NOx	High temp reaction of $N_2 + O_2$	High temp, high pressure	High load, small chambers
CO_2	Complete combustion	Fuel consumption rate	All normal conditions
PM	Incomplete combustion, soot	Fuel type, injection, swirl	Diesel, high-load

4.2 COMPRESSION RATIO AND EMISSIONS

The CR is one of the most crucial design parameters that influences thermal efficiency and emission behavior:

As per Jha & Patel (2017), an increase in CR raises the thermal efficiency by increasing the thermodynamic work obtained from combustion. However, this lowers combustion temperatures, since air–fuel ratio contributes to increase in combustion temperatures, ultimately resulting in higher NOx production [48–50].

CR optimization is one of the procedures within a single combustion chamber design process (Prakash and Arora, 2021). A balanced CR can deliver adequate power output and fuel economy but at the same time minimize the adverse effects on NOx and particulate emissions [51-53].

Consequently, it is essential to select an appropriate compression ratio to achieve simultaneously both the objectives of environmental legitimacy and engine efficiency [1]..

Theoretical Note (for Compression Ratio Section)

According to Jha and Patel in 2017 [16], the relationship between compression ratio and thermal efficiency in spark-ignition engines follows the Otto cycle law:

$$\eta = 1 - 1 / r^{(\gamma - 1)}$$

where η represents the thermal efficiency, r is the compression ratio, and γ is the specific heat ratio (approximately 1.4 for air). For instance, increasing the CR from 8 to 10 theoretically raises the efficiency from about 56% to 60%.

Zeldovich Mechanism for NOx Formation

The thermal Zeldovich process is the major way that NOx originates in spark-ignition engines at high temperatures (>1800 K). This occurs when nitrogen combines with oxygen radicals.

$$O + N_2 \rightleftharpoons NO + N$$
$$N + O_2 \rightleftharpoons NO + O$$

NOx goes up when the temperature goes up, while EGR brings it down by lowering the peak combustion temperature [12].

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4.3 CHAMBER MODIFICATIONS WITH TECHNOLOGY

In order to address the underlying emission trade-offs that exist with fixed chamber geometries, multiple more advanced technologies have been incorporated into modern engine design:

The camshaft angles and the timing of the valves. The order of the intake and exhaust valves operates in turn in a four-stroke cycle, as shown in Figure 2. Intake valve opens 10–20° BTDC, and closes 40–60° ABDC. The exhaust valve commonly opens at around 40–60° BBDC and closes 10–20° ATDC. These things can impact the combustion stability and the fuel utilization of an engine. Changing valve phasing has been found to improve breathing [54, 55] and reduce pumping losses within recent research [54, 55].

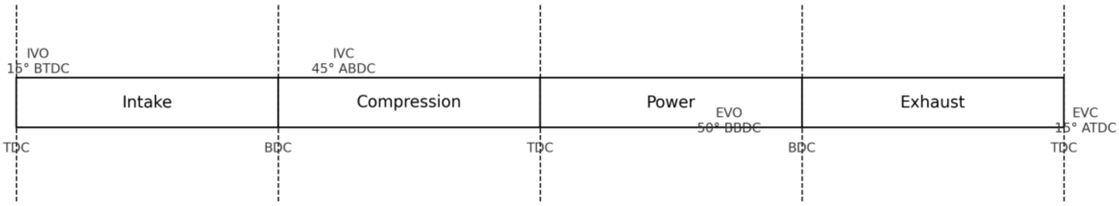

Fig. 2. Valve timing diagram for a four-stroke spark-ignition engine.

· VVT (Variable Valve Timing) enables more specific and accurate timings of valve closure and opening. Such flexibility would streamline intake and exhaust processes leading to higher volumetric efficiency while decreasing residual gas formation [51, 52].

Exhaust gas recirculation (EGR) inserts a finite amount of exhaust gases into the inlet manifold which reduces peak combustion temperatures and thus limits NOx emissions [53, 56].

· Turbocharger pumps more air mass in the combustion chamber. It encourages a leaner air-fuel mixture, helps to achieve complete combustion, and allows the use of small, highly efficient chambers with little power lost [57].

Combustion chamber design development should go hand-in-hand with these supporting technologies, but the two must be balanced for ICEs to be protected against future emission regulations. We compare the said technologies in This is Table 3..

Table 3. Comparative effectiveness of technologies used for emission control in ICEs.

Technology	CO	HC	NOx	PM	Cost	Complexity	Common Use
EGR	–	–	↓↓↓	–	Medium	Moderate	SI & CI Engines
VVT	↓	↓	↓	–	High	High	Modern engines
Turbocharging	↓	↓	↓	↓	High	High	Performance engines
Catalytic Converter	↓↓↓	↓↓↓	↓	↓	Medium	Low	Standard in SI engines
DPF	–	–	–	↓↓↓	High	Moderate	Diesel engines

4.4 PARTICULATE MATTER (PM) IN INTERNAL COMBUSTION ENGINES

In ICEs especially within diesel engines, particulate matter (PM) emissions are a main concern. Particulate matter (PM) include solid and liquid particles in the air, ranging in size from soot to aerosol200[J1]200, suspended in the exhaust plume [58, 59]. Such particles are usually classified by size, as PM_{10} (≤ 10 µm) and $PM_{2,5}$ (≤ 2.5 µm), which is particularly dangerous as it can reach deep into the human respiratory system [60].

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· Incompletion: PM forms during the combustion process in general, and especially by incomplete combustion, under fuel-rich conditions, during cold starts, and in the high-load area. Thus, higher levels of PM in diesel engines would be expected because of increased compression ratios and lack of throttle (play on words, direct injection can result in localized fuel-rich zones).

Well, human health has been known to be severely affected by PM exposure, eventually leading to serious health repercussions such as asthma, bronchitis, cardiovascular diseases and even cancer. On the one hand, PM causes haze in the atmosphere, decreases visibility [61, 62], and shortens the time of acid rain [61, 62].

Control Technologies: Diesel Particulate Filters (DPFs) are very efficient in PM capturing. Various techniques such as oxidation catalysts, advanced combustion control (i.e., injection timing and pressure), and cleaner burning fuels. Particulate filters and tuned injection strategies help Gasoline Direct Injection (GDI) engines, too.

Thought process behind PM mitigation cannot be limited to combustion chamber shape, fuel strategy or after-treatment systems–it needs to be part of holistic design.

5. TYPES OF COMBUSTION CHAMBERS

The combustion chamber architecture has advanced over the years with different designs allowing for better combustion, thermal management and emissions control. Here, six major ICE chamber types are reviewed and discussed. Fig. 2 shows these types.

5.1 HEMISPHERICAL (HEMI) CHAMBER

Characterized by a dome-shaped ceiling, the hemispherical chamber offers superior airflow dynamics, uniform flame propagation, and high power density. Its central spark plug placement promotes symmetrical combustion, making it ideal for high-performance and racing applications [22].

5.2 FLAT-HEAD CHAMBER

This chamber features a planar ceiling and side-valve configuration. While it simplifies manufacturing and reduces engine height, its poor turbulence characteristics limit combustion efficiency, restricting its use to economical, low-power engines [23].

5.3 PENTROOF CHAMBER

Common in modern multi-valve engines, the pentroof design incorporates a sloped ceiling and V-shaped valve layout. This configuration enhances tumble flow and air-fuel mixing, leading to efficient combustion, lower emissions, and improved fuel economy [24].

5.4 TOROIDAL CHAMBER

The toroidal (donut-shaped) chamber ensures consistent flame propagation and minimal quenching zones. Though difficult to manufacture, it promotes high efficiency and is used in specialized diesel and gasoline engine designs focused on emission minimization [25].

5.5 RE-ENTRANT CHAMBER

This chamber includes a re-entrant bowl within the piston, intensifying squish and swirl. It ensures homogeneous charge mixing, especially in diesel engines, supporting higher compression ratios and lowering soot and NOx formation [63].

5.6 WEDGE CHAMBER

Featuring an inclined roof and piston-crown shaping, the wedge chamber improves squish and flame travel as shows in Figure 3. It strikes a balance between manufacturability, performance, and emissions, making it versatile across both spark and compression ignition engines [64].

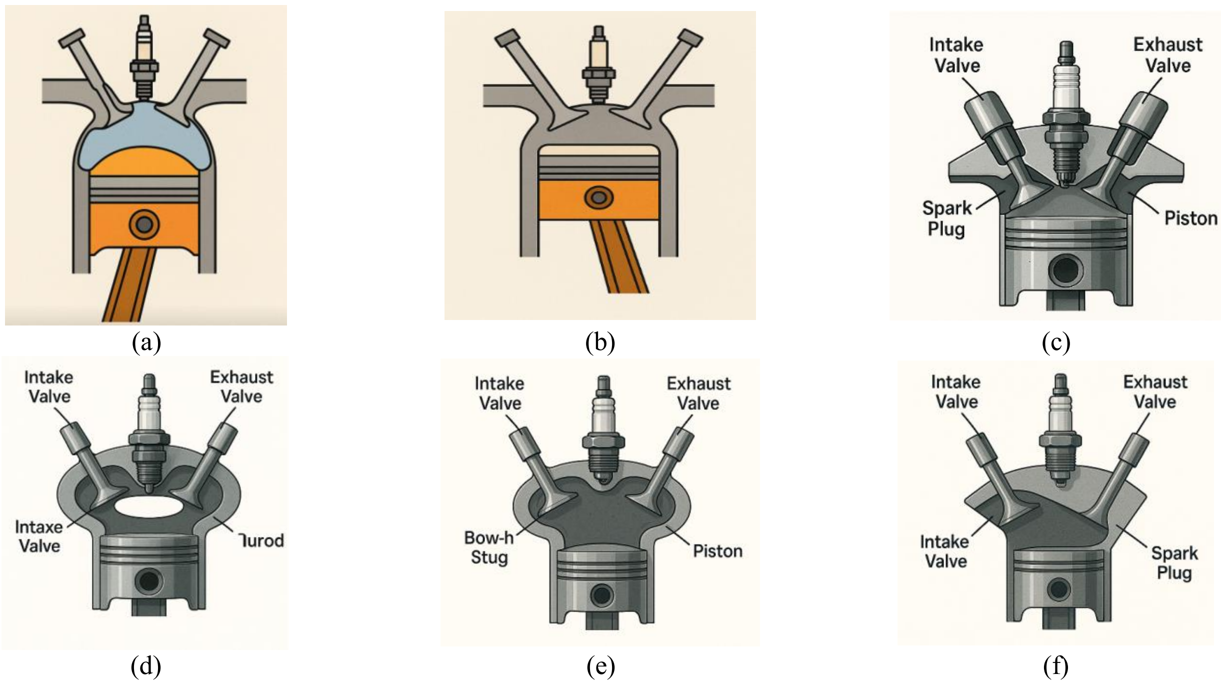

Fig. 3. Combustion chamber types (a) hemispherical combustion chamber (hemi) (b) flat-head combustion chamber (c) pentroof combustion chamber (d) toroidal combustion chamber (e) re-entrant combustion chamber (f) wedge combustion chamber.

The combustion chamber configuration significantly impacts in-cylinder turbulence, flame propagation, and volumetric efficiency. Table 4 provides a comparative summary of commonly employed chamber types, outlining their performance advantages and typical application domains in ICEs.

Table 4. Summary of combustion chamber types.

Type	Advantages	Applications
Hemispherical	High efficiency, reduced knocking	Performance/racing engines
Flat-head	Simple, compact design	Small, economical engines
Pentroof	Enhanced turbulence and fuel mixing	Modern high-performance engines

Toroidal	Uniform combustion, efficient airflow	Advanced gasoline/diesel engines
Re-entrant	Improved air-fuel mixing, lower emissions	High-efficiency diesel engines
Wedge	Good flame propagation, reduced heat loss	SI and CI engine applications

6. CRITICAL EVALUATION AND RESEARCH GAPS

6.1 CONSENSUS AND CONTRADICTIONS IN LITERATURE

First, the literature review related to the influence of combustion chamber volume on internal combustion engine emissions showed many similarities but also many conflicts. It is generally accepted that the size of the combustion chamber has a significant impact on emissions due to the fact that it affects combustion efficiency, peak temperature and the promote the formation of pollutants. Also, as a popular trade off smaller combustion chambers enhances the combustion, reduces the CO and HC during the combustion process but it increases the NOx as a result of higher flame temperature [65]. In contrast, bigger chambers decrease the NOx while at the same time the CO and HC emissions are increased, meaning that combustion is not completed [26, 28, 64]. In other words, the chamber type may not matter if air-fuel mixing is effective -- but then again, that means effective chamber design -- and the same is arguably true of the VVT, EGR and turbocharging variants that must offset the ills of chamber-size decisions. However, the ideal chamber sizes for certain fuels contradict the showings of improved performance with optimal chamber size for gasoline or diesel engines; smaller chambers tended to perform better in gasoline engines [26, 27] while larger chambers performed better in diesel engines [67, 68]. Variable effect of chamber geometry on PM emissions is also seen, possibly due to the complex formation mechanism of PM. Studies also differ in the effectiveness of emission control technologies, and measure trade-offs across pollutants with either zero or low sensitivity (Appendix 1). These seemingly contradictory observations are largely attributable to differences in experimental conditions, the complexities in the combustion phenomena, the limitations in the CFD models, and in some cases, the publication bias.To remedy the discrepancies, future work should standardize experimental protocol, utilize in depth CFD modeling, meta-analyze existing studies of this relationship, and employ more real-world driving conditions; all of which are required to develop a consistent understanding of the appropriate impact of combustion chamber size on engine emissions..

6.2 DIFFERENCES IN RESEARCH METHODOLOGIES

In investigating the impact of combustion chamber size on emissions for internal combustion engines, a series of test methodologies have been used that need to be defined in order to facilitate comparison between studies. As displayed in Table 5, these methodologies fall into an experimental, computational, or review/meta-analysis framework..

Table 5. Conceptual summary of key contradictions and consensus.

Topic	Consensus	Contradictions
Chamber Size vs NOx	Smaller size â†' higher NOx	NOx varies with cooling/EGR
Fuel Type Response	Gasoline: better in small chambers	Diesel shows mixed trends
Cold Start Behavior	Shallow chambers heat faster	Inconsistent effects reported
PM Emission Predictability	PM linked to chamber + fuel	Sparse validation data

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- Experimentally: Engine dynamometer test is a widely used method where the engine is put on a dynamometer, and its emissions are measured by using various analyzers within a controlled environment where speed, load and temperature are all controlled parameters. Differences are in engine type (gasoline, diesel, single-cylinder, multi-cylinder), fuel type (gasoline, diesel, biofuels, alternative fuels), instrumentation (precision and kind of emission analyzers used), and operating conditions (fixed engine speeds and loads, or driving cycles). Laser & optical diagnostics: These techniques employ lasers and other optical methods to visualize and measure processes in the chamber as combustion happens. For instance, Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF). There are variations in terms of accessibility (engine designs enabling optical access) and complexity (laser physics, optics, and signal processing expertise). Regression analysis, ANOVA, Design of Experiments (DOE) for chamber size versus emissions modeling.

- · Computational Models: Computational fluid dynamics (CFD) simulations provide a detailed predictive capability of the flow field, combustion, and emissions formation inside the engine. Different types of models can range from the complexity of the model (1-D to 3-D, single-zone, detailed chemical kinetics to just one species tracking), turbulence modeling (model), combustion modeling (model), chemical kinetics (levels of detail), or grid resolution. The simulated processes include the intake, combustion and exhaust processes in the engine system, and the system-level modeling simulates the entire engine system. Different types of differences: model fidelity (simple quasi-dimensional to more complex multi-dimensional) and calibration (quality of calibration data).

- Systematic reviews are conducted using a predefined methodology to search for and identify studies relevant to a specific clinical question, select studies that meet defined eligibility criteria, and synthesize results. Differences in search strategy (the breadth of the literature search), inclusion/exclusion criteria (criteria for selection of studies), and data extraction (data elements extracted from studies) are just a few of the variations. Meta-analysis pools data from several studies to provide a more accurate estimate of the effect of chamber size on emissions. What mod=1: 1 data reduction description: Statistical methods (different statistical methods) Study quality assessment (methods to assess quality of included studies) Quality assessment: Quality assessmentmod=2mod=2Details View on Journal site.

6.3 IDENTIFIED GAPS AND FUTURE DIRECTIONS

While much has been learned about the effects of combustion chamber size on engine emissions, there are still some important gaps in knowledge. First of all, very few studies have specifically looked at the emissions of particulate matter (PM) with respect to chamber size; most have focused on CO, HC, and NOx emissions. This includes the need for quantitative data on how various chamber geometries impact PM formation, size distribution, and the processes governing soot formation and oxidation. Second, most of the research today still deals with the engine operation in the steady-state, thus ignoring the effect of transient conditions (cold starts, accelerations) on emissions as a function of chamber design and fuel injection strategy. Thirdly, not as much is known about how alternative fuels (biofuels, hydrogen) interact with different chamber sizes, and whether existing chamber designs can accommodate new fuel formulations. Fourth, it has nonoptimized chamber design for advanced combustion strategies like RCCI and HCCI and very limited understanding on complex interaction of chamber geometry, fuel injection, and combustion phasing in these engines. Fifth, better, and more holistic CFD models are needed, especially for PM prediction, as well as experimental data for the validation of these models. Not the least, innovations in the geometries and materials have stagnated due to the exploration of new chamber configurations being one of the last frontiers toward cost-effective engine efficiency and emissions gains. Last but important,

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machines learning and AI techniques applied to optimize designs in the combustion chamber domain remains in its infancy, due to the absence of wide range of training datasets. Filling in these gaps through focused experimental studies, enhanced CFD modeling combined with AI-powered design strategies is a critical step to cleaner and more efficient internal combustion engines..

7. REGULATORY AND ENVIRONMENTAL CONTEXT

See reputable sources with details on the average means by which designers manufacture combustion chambers, and test engine emissions in internal combustion engines. This guidance and the associated processes are designed to assist companies in quantifying emissions, assessing their engines, and validating that their actions comply with the regulations. Industry standards that matter include:

· SAE International: SAE International publishes numerous engineering standards related to the automotive domain, including standards regarding engine performance testing, emissions, and fuels specifications. Appendix A provides a list of related test procedures including SAE J1349 (Engine Power Test Code), SAE J1995 (Engine Power and Torque Terminology) and SAE J1088 (Test Procedure for Small Utility Engine Exhaust Emissions), for example.

ISO Standards: The International Organization for Standardization (ISO) develops and publishes international standards about various topics related to engineering and manufacturing. ISO, among others, governs internal combustion engines with ISO 8178 (Reciprocating internal combustion engines — Exhaust emission measurement) and ISO 3046 (Reciprocating internal combustion engines — Performance) [12].

· Europe has established European Standards, denoted EN, regularly applied in the auto industry under the sponsorship of the CEN. EN 16842: EN standards for non-road mobile machinery testing emissions.

These standards come together to create guidelines to make sure the engines can meet performance and emissions standards while making it easier for trade and cooperation in the automotive industry. Emission standard comparison is shown in Table 6.

Table 6. Comparative emission limits across major global standards.

Standard	CO (g/km)	NOx (g/km)	HC (g/km)	PM (g/km)
EPA Tier 3	1	0.03	0.01	0.003
Euro 6	1	0.06	0.1	0.0045
China 6	1	0.035	0.068	0.0045
India BS VI	1	0.06	0.1	0.0045

8. CONCLUSION AND FUTURE DIRECTIONS

This paper reviews the effect of chamber volume on the emissions from internal combustion engines. The increase in turbulence and mixing with the use of the smaller nitrogen chambers help the fuel to burn more fully and this helps to reduce CO and HC emissions. However, higher peak temperatures can cause more NOx emissions. The bigger chambers can also lower NOx, but they cause unburnt combustion, and result in high CO and HC emissions.

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In the review, we learned how the serious compromises used to make combustion chambers less polluting. There is no one-size-fits-all answer as to the appropriate size and shape of the chamber or the loads under which it operates, and hitting the appropriate balance of performance, fuel efficiency and emissions is inevitably a complex mathematical optimisation problem.

The stan-size on Light-duty gasoline and diesel engines would have conflicting problems listed above, but still receive engine optimizing performance and emissions with the use of VVT, EGR (Exhaust Gas Recirculation) and turbocharging. A lower emissions contribution and more efficient engine can be obtained by switching to bioethanol.

It now needs to research the design of high-performance combustion chambers that contribute to the reduction of emissions while ensuring better engine performance. CFD methods provide better designs of the chamber and testing of various methods to burn the fuel. Future research needs to explore the relationships of a chamber scale to PM emissions control and seek improved strategies of PM regulation.

This review has several limitations. The literature review was restricted to English-language articles from January 2000 through May 2025. There could be a possibility of bias in the application of these criteria. The data generally contains only a subset of engines operated a particular way. These issues need to be addressed in further studies in order to provide a clearer picture of the influence of combustion chamber size on emissions from internal combustion engines. The room in the combustion chamber plays a major role in emissions for any internal combustion engine. It has become possible to create combustion chambers with less emissions whilst keeping the performance of an engine at the same or better levels by implementation of advanced engine technologies concepts and taking into account the trade-offs between engine emissions and performance through engine-design optimization. TASK 3: New chamber types and mixing approachesEmissions reduction and internal combustion engine efficiency should be done in new chamber types and mixing approaches..

8.1 INFLUENCE OF FUEL TYPE ON EMISSION BEHAVIOR

The combustion chamber design is one of the most critical parameters for the high-quality burning of fuels; as seen from Tabel 7, various fuels can significantly alter ICE emissions. Gasoline generally produces higher concentrations of CO and HC, while diesel produces higher concentrations of NOx and PM. Since CO and HC are reduced by employing ethanol and biodiesel as fuels, a good chamber designs can reduce them to a greater extent. Due to lower emissions, CNG is preferable for using in high-temperature chambers as burner operate differently with each fuel and combustion behavior, so the chamber should be designed to match flame speed, energy in the fuel and oxygen content..

Table 7. Influence of fuel type on major emission categories in ICEs.

Fuel Type	CO	HC	NOx	PM	Interpretation
Gasoline	↓	↑	↑	↓	Produces low CO due to relatively complete combustion but results in higher HC and NOx. Lower PM due to cleaner burning.
Diesel	↑	↓	↓	↑	Efficient lean combustion lowers HC and NOx, but incomplete vaporization increases PM. High CO from cold starts or rich zones.
Ethanol	↓	↓	↓	↓	Burns cleanly due to oxygen content; high octane allows high compression without NOx spike. Very favourable across all metrics.
Biodiesel	↓	↓	↓	↑	Low CO, HC, and NOx emissions due to oxygenated structure, but may increase PM due to higher viscosity and incomplete atomization.
CNG	↓	↓	↓	↓	Cleanest overall emissions. High methane content burns completely and cool, minimizing all pollutants.

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