Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 1 (2025)

GT-Power for Internal Combustion Engine Simulation: A Review

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Abstract

GT-Power, developed by Gamma Technologies, is a leading software for simulating internal combustion engines (ICE) and various powertrains. The software offers extensive capabilities, including detailed performance evaluation, combustion analysis, fluid dynamics, heat transfer, and emissions modeling. This review critically examines the functionality, applications, and key advantages of using GT-Power for internal combustion engine simulations, referencing case studies from academic research and industry. Key topics include engine performance optimization, hybrid powertrain development, real-time simulation, and emissions control strategies. While GT-Power is widely regarded for its accuracy and versatility, limitations are discussed, such as the need for high-quality input data and a steep learning curve. Prospects of the software to further automate the design optimization process, are also considered.

Keywords:GT-Power, Engine performance, internal combustion engine, modelling, simulationprocesses, emission

1. INTRODUCTION

Internal combustion engines (ICE) are continuously evolving in response to increasing efficiency demands and stricter emission regulations. Compression ignition (CI) engines, commonly known as diesel engines, have historically dominated heavy-duty and maritime transportation. More recently, they have also gained significant traction in light-duty vehicles [1]. Compression ignition engines are extensively used across various sectors, including automotive, agricultural, industrial, and transportation, due to their reliability, high thermal efficiency, and cost-effectiveness advantages. Key characteristics include ignition without spark plugs, throttle-less air supply, load control via fuel injection, high energy density, and lean air-fuel ratios, making them more thermally efficient than spark ignition (SI) engines [2]. Diesel engines rely heavily on fossil fuels, which account for 80% of global energy consumption. Diesel is particularly integral in transportation sectors, powering private vehicles, buses, trucks, and ships, among others. However, the combustion of diesel fuel in CI engines produces harmful emissions, including hydrocarbons (HC), particulate matter (PM), nitrogen oxides (NOx), and carbon monoxide (CO). Among these, black smoke and NOx are particularly detrimental, contributing significantly to environmental pollution. The environmental impact of these emissions has intensified efforts to find alternative fuels[2]. Additionally, the rapid depletion of petroleum-based fuel reserves underscores the urgency of transitioning to sustainable alternatives. Over the past few decades, researchers have explored fuels such as hydrogen, dimethyl ether (DME), biodiesel, and coal. However, challenges related to availability, cost-efficiency, safety, and supply have constrained these efforts.

Modern engine research increasingly integrates simulation approaches alongside experimental testing. While hardware experiments offer precise outcomes, they are often costly, time-intensive, and complex for interpreting cause-and-effect relationships. In contrast, simulation methods allow for controlled parametric studies, isolating variables to elucidate their effects more clearly. Validated simulation models are indispensable for studying new engine types or fuels, enabling efficient and detailed analyses [3]. Engine simulation software, such as GT-Power by Gamma Technologies, has become a cornerstone of engine development. This industry-standard tool supports thermodynamic simulations, combining fluid mechanics, combustion, heat transfer, and thermodynamics to optimize engine performance, fuel efficiency, and emissions. Widely used in academic and industrial settings, GT-Power facilitates early-stage design decisions, reducing reliance on physical prototypes. Key features include GT-ISE for managing simulation processes and GT-POST for analyzing and visualizing simulation data [4]. This review examines the capabilities, applications, and benefits of GT-Power for internal combustion engine simulations, referencing current research to highlight its value in advancing engine technology.

The next section of the paper discusses the fuel material used in the test rig for generating input data before the GT-Power application. Section 3 outlines the operational steps for GT-Power modeling, while Section 4 presents the governing equation for calculating the GT-Power output parameters. Sections 4 and 5 detail the capabilities, characteristics, and simulation processes of GT-Power, including other operational processes that complement the simulation system. Sections 6, 7, and 8 discuss the applications, advantages, and limitations of GT-Power software. Section 9 concludes the review paper.

2. FUEL MATERIAL

Diesel fuel refers to any liquid fuel designed for use in diesel engines, where ignition occurs through the compression of the air-fuel mixture without the need for a spark. The typical chemical composition of diesel fuel is represented by the formula $C12H23$, with variations generally ranging from $C10H20$ to $C15H28$ [3].Biodiesel is a renewable fuel alternative to conventional petroleum-based diesel fuel. It is a complex mixture of esters with different chain lengths and degrees of saturation and can be used blended (up to 20%) with diesel without major modifications in diesel engines. The quality of biodiesel is related to several physicochemical properties, such as ignition quality, heat of combustion, cold flow, oxidative stability, viscosity, density, and lubricity The process of producing biodiesel involves a chemical reaction between vegetable oils or animal fats and alcohols to produce esters in a process known as esterification [5-7]. However, additives and blends are substances or chemicals required to advance the quality of the produced biodiesel fuel. Biodiesel is also often blended with petroleum diesel to create a blend that improves the performance blend and reduces the emissions from the use of the blend. The percentage of biodiesel in a blend affects the resulting fuel properties such as cetane number, viscosity, and strength. Understanding the properties of additives and blends is important in the production and use of biodiesel as an alternative source. Additives are usually added in small amounts, but they play an important role in maintaining the quality and longevity of biodiesel. Without additives, the quality of biodiesel can deteriorate rapidly, reducing its efficiency as a fuel source. The selection of appropriate additives is therefore an important part of biodiesel production and can significantly influence the success of the final product[8].

3. METHODOLOGY

GT-Power is a one-dimensional simulation tool widely recognized as an industry standard by leading engine and vehicle manufacturers. It is employed to model the performance of internal combustion engines across a broad range of applications, including automobiles, trucks, motorcycles, motorsports, power generation, mining, construction, agriculture, and tractors. The software operates on one-dimensional gas dynamics principles, enabling accurate calculations of gas flow and heat transfer within engine cylinders, pipes, and associated components. GT-Power features two key modules: GT-ISE (Integrated Simulation Environment), which facilitates the creation, execution, and management of the simulation process, and GT-POST, a post-processing tool that provides access to all simulation-generated data for analysis and visualization[9].Simulating the performance of an internal combustion engine using the GT-POWER modeling tool involves several sequential steps. The process begins with taking input data from the selected test rig (diesel) engine. These measurements are then entered into the GT-POWER library, which contains a comprehensive database of engine components. To initiate the model development, users must navigate to the window menu and select "Tile with Template

Library”. This action displays the GT-POWER template library on the left side of the interface, providing access to a range of predefined templates and objects necessary for building the engine model.

To develop the model, specific templates and objects relevant to the project are dragged from the template library into the project workspace. These items may include both customizable templates and pre-defined objects available within the GT-POWER library[10]. A comprehensive list of required data for model construction is also provided within the library. Although not all listed items are needed for every simulation, this list serves as a practical starting point. During early design stages, the simulation process may help determine optimal values for key parameters. Key engine characteristics to include in the model encompass compression ratio, firing order, engine configuration (inline or V-type), V-angle (if applicable), and stroke cycle (2-stroke or 4-stroke). Cylinder geometry data such as bore, stroke, connecting rod length, pin offset, piston TDC clearance height, head bowl geometry, piston area, and head area are also critical inputs. Once the simulation is executed, GT-SUITE generates various output files containing the simulation results. These outputs are primarily analyzed using GT-POST, a post-processing application that facilitates data visualization, including animations and order analysis[11]. After completing the simulations, summary reports in tabular form can be created to present the key findings and simulation outcomes comprehensively. These computational results provide valuable insights into engine performance, supporting informed decisions in engine design and optimization[10].

3.1 The Main Steps of the Simulation[9]

- ✓ Build a 1-D model on a GT-ISE module (the model can be designed by dragging elements in the existinglibrary to the Main Map, then connecting them in order from the intake pipe, engine, to the exhaust).
- ✓ Setup the general input data of the engine (engine type, base size, engine speed, fuel type, reference conditions, cycle, etc.); obtained from the base engine experimental test results.
- ✓ Setup the elements input data (engine construction characteristics, heat transfer, combustion model, intake and exhaust valve specifications, etc.); obtained from the engine manufacturers' design data.
- ✓ Run simulations and check errors.
- ✓ Results are processed by the GT-post module (pilots, engine efficiency, fuel consumption efficiency, torque, power, etc.

3.2 Key Steps in the Simulation Process

The simulation process for engine modeling involves a series of structured steps to ensure accurate representation and analysis of engine performance. These steps encompass the construction of a one-dimensional model, configuration of both general and component-specific input data, execution of simulations, and comprehensive result analysis using specialized tools.

- Construction: - Develop a one-dimensional model using the GT-ISE module. The model is created by selecting elements from the existing library and arranging them on the Main Map. Components are connected sequentially, starting from the intake pipe through the engine and ending at the exhaust system.
- General Input Data Configuration - Define the engine's general input parameters, including engine type, base dimensions, operating speed, fuel type, reference conditions, and cycle. These inputs are typically derived from experimental test results of the base engine.
- Component-Specific Input Data Configuration - Specify detailed input parameters for individual components, such as engine construction characteristics, heat transfer properties, combustion models, and intake/exhaust valve specifications. This information is obtained from the engine manufacturer’s design data.
- Simulation Execution - Perform the simulation and monitor for errors during the process.
- Result Analysis - Use the GT-POST module to analyze simulation results. Key outputs include engine performance metrics such as efficiency, fuel consumption, torque, and power.

The elements in the model are organized sequentially in the following order: inlet environmental parameters, inlet runner parameters, inlet port parameters, inlet valve parameters, engine and cylinder parameters, turbocharger system, injector parameters, exhaust valve parameters, exhaust port parameters, exhaust runner parameters, and exhaust environmental parameters, among others.According toVenkateshmohan and Kumar [12], the first step in GT-Power simulation involves collecting data from a single-cylinder test rig. This process includes selecting 28 operational points based on the Real Driving Emissions (RDE) cycle to operate the engine and gather data. The data collected encompasses dynamic intake, exhaust, and in-cylinder pressures, as well as injection strategies, residuals, swirls, and emissions (CO, HC, and NOx).The subsequent step involves performing an initial quality check on the collected data. The primary aim of this step is to identify and address errors related to encoder accuracy, pegging, and thermal shock. Additionally, the quality of heat release data is evaluated to ensure reliability. Once this preliminary validation is complete, a three-pressure analysis (TPA) is conducted on the input data. TPA relies on the injection profile, and the measured intake, exhaust, and in-cylinder pressures, along with other operating parameters obtained from the test cell. The measured in-cylinder pressure is validated through a detailed, automated consistency check. TPA also provides trapped quantity data, which is challenging to measure directly within the test cell. Following TPA, cylinder pressure-only analysis (CPOA) is performed to further validate the TPA results. Inputs to the CPOA model include the trapped quantities from TPA and the measured pressure. If the trapped quantity predictions from TPA are accurate, the simulated pressure generated in CPOA should align with the results from TPA. After completing data validation, model calibration is conducted using 25 operational points. A design of experiments (DOE) approach is applied to adjust the combustion model multipliers across these 25 cases, refining the model for enhanced accuracy.Yahuza, et al. [3] conducted one-dimensional numerical analysis using the GT-ISE module within the comprehensive GT-POWER software suite to model and simulate a single-cylinder diesel engine. By leveraging GT-POWER's modeling capabilities, they developed a cycle simulation for a compression ignition engine using biodiesel-ethanol-diesel fuel blends. The engine specifications from the test rig were incorporated into the model to replicate the single-cylinder diesel engine. Experimental data on the physicochemical properties of the fuel and engine performance were used to validate the model and analyze combustion behavior.The combustion analysis model was developed in GT-ISE using its object-oriented structure, which is organized into a three-level hierarchy: Templates, Objects, and Parts. Templates serve as the foundational elements containing unpopulated attributes required by the model. These templates are transformed into objects, and when they are placed onto the project map as components or connections, they become parts, inheriting attributes from their parent objects. For the single-cylinder compression ignition engine, eleven templates were created: inlet environment, intake runner, intake port, intake and exhaust valves, cylinder, fuel injector, exhaust port and runner, outlet environment, and engine crank train. Once all the templates were prepared, the parts were positioned on the project map, and the components were interconnected, as depicted in Plate I. Each item on the map represents a distinct part, and GT-ISE automatically assigns names to these parts as they are added to the model as shown in Fig 1.

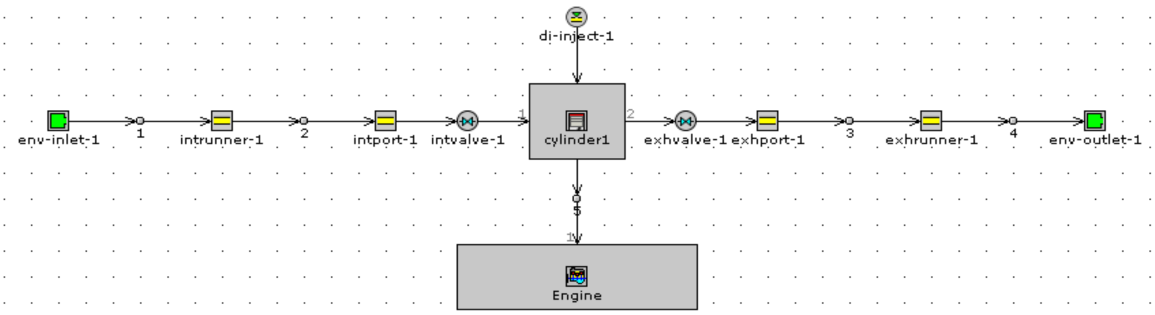

Fig 1: GT – ISE Model

Once the model was fully constructed, the case-specific inputs, simulation type, and desired outputs were defined within the settings menu of the GT-ISE interface. The simulation was executed by selecting the "Run Simulation" option on the GT-ISE toolbar, which also ensured that the model was automatically saved for future use. The simulation results were accessed and analyzed using the "Open GT-POST" button on the GT-ISE toolbar. This action prompted the selection of the `.gdx` file corresponding to the model's filename, automatically launching the GT-POST post-processing program in a new window for detailed result visualization and extraction.

3. GOVERNING EQUATION

Done, et al. [2]developed a model that utilized the principles of momentum, continuity, and energy conservation to solve the governing equations. A one-dimensional framework was employed, wherein the entire system was discretized into multiple small control volumes. Each flow split was assigned a distinct volume, and individual pipes were further divided into smaller segments. These volumes were interconnected through defined boundary conditions. The modeling process was grounded in three fundamental equations: the continuity equation, the energy equation, and the momentum equation. The first equation ensures mass conservation, the second governs energy conservation, and the third addresses momentum conservation. These equations collectively formed the foundation for the modeling methodology[13].

$$\frac{dm}{dt} = \sum_{boundaries} m \qquad (1)$$

$$\frac{d(me)}{dt} = -P\frac{dv}{dt} + \sum(mH) = h\,As\,(Tfluid - Twall)(2)$$

$$\frac{dm}{dt} = \frac{dpA + \sum_{boundaries}(mu) - 4Cf\frac{\rho u|u|dxA}{2D} - Kp(\frac{1}{2}pu|u|)A}{dx}(3)$$

The injector’s delivery rate can be calculated using Equation (4)

$$m_{Delivery} = nvp_{ref}NV_D\left(\frac{f}{A}\right)\frac{6}{(n)(Paulse\ width)} \qquad (4)$$

The Woschni’s (Eq. 5) was used to calculate convective heat transfer

$$h_c = \frac{k_1\,P^{0.8}W^{0.8}}{B^{0.2}TK_2}$$

(5)

The Wiebe function (Eq. 6) was used to calculate the combustion burn rate which is considered a function of (CA) crank angle.

Combustion (θ) = (CE) [1-$e^{(-WC)(\theta-SOC).^{(E+1)}}$]

(6)

Eq. 7 was used to calculate the specified thermal efficiency

$$n_i = \frac{pi}{mf\ \text{x}\ lower\ heating\ value}(7)$$

Eq. 8 was to calculate IMEP

$$\text{IMEP} = \frac{\text{Ib}}{\text{Displacement Volume}}(8)$$

Specific fuel consumption (indicated) (ISFC) was calculated by using Eq. 9

ISFC= $\frac{mf}{pi}$(9)

The FMEP was calculated using Eq. 10

$FMEP = 0.4 + (0.005*Pmax) + (0.009*Speed\ mp) + (0.009*Speed^2 mp)$(10)

The model was developed based on a four-stroke compression ignition (CI) diesel engine and encompassed several key components, including the engine cylinder, intake and exhaust ports, inlet and outlet environments, injection nozzle, intake valve, exhaust valve, and runner. The intake and exhaust ports were geometrically represented using pipes to accurately simulate their structure and functionality [13]. The model required detailed fuel properties in both the vapor and liquid phases to ensure accuracy. These fuel characteristics were derived from the GT-Power template fuel library, as illustrated in Fig. 2which consists of different sub-models such as environment inlet, inlet runner, inlet port, inlet valve, cylinder, diesel injector, exhaust valve, exhaust port, exhaust runner and environment outlet.

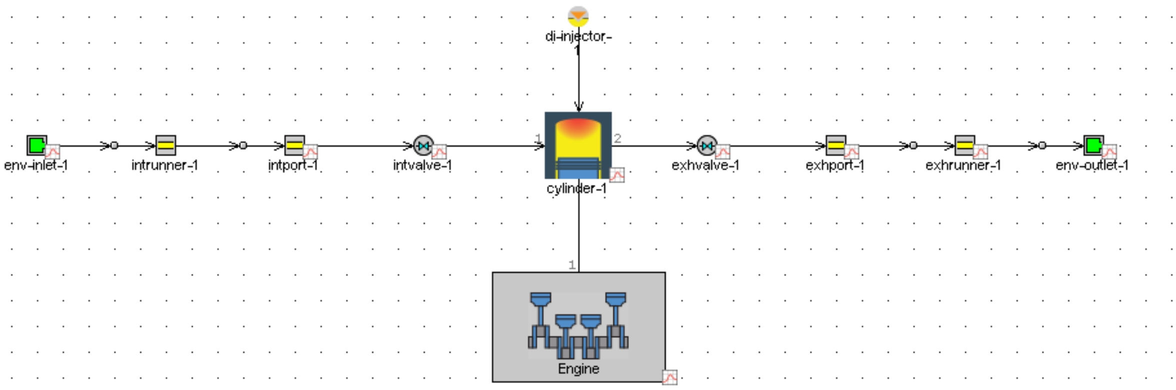

Fig. 2. Single-cylinder CI engine simulation model prepared on GT-Power

4. GT-Power Capabilities

GT-Power is a comprehensive simulation tool renowned for its capabilities in engine performance and combustion modeling, enabling detailed analysis of various engine configurations and streamlining the engine development process through virtual testing and optimization.

4.1 Engine Performance and Combustion Modeling

GT-Power enables detailed thermodynamic analysis and combustion modelling and it is used to model the performance of various engine configurations, including spark-ignition (SI), compression-ignition (CI), and hybrid systems. Through its advanced algorithms, GT-Power simulates complex engine operations such as intake, combustion, exhaust processes, and after-treatment systems. The software enables engineers to explore numerous design alternatives without the need for costly physical prototypes, thus saving time and resources. The software supports the simulation of both steady-state and transient performance, making it highly valuable for engine optimization.In their study,Ahmadipour, et al. [14], demonstrated the versatility of GT-Power for engine performance evaluation by exploring the optimization of a turbocharged diesel engine using GT-Power, showing significant improvements in break power and break torque output, and fuel efficiency with an increase in compression ratio under various operating conditions. The software's ability to simulate both steady-state and transient performance further enhances its utility in engine development. The software provided an opportunity to perform virtual tests under different operating conditions, significantly reducing the need for experimental iterations.

4.2 Fluid Flow and Heat Transfer Analysis

GT-Power is equipped with a robust fluid dynamics solver that can model and provide detailed analysis of airflow, fuel flow, and exhaust gas flow within the engine's intake and exhaust systems. It also simulates heat transfer processes, including convection, conduction, and radiation. These features are critical for optimizing engine cooling, fuel mixture preparation, and exhaust treatment systems.Dahham, et al. [15] utilized GT-Power to optimize the intake manifold design of a high-performance ethanol-gasoline engine, reducing pressure loss and improving combustion efficiency. Their research showed that the software's fluid dynamic models could accurately simulate the manifold's dimension and valve timing, allowing for a more efficient engine design. In similar research, the software was used to model EGR (exhaust gas recirculation) systems, optimizing flow patterns to reduce nitrogen oxide emissions (NOx) without sacrificing performance.

4.3 Emissions and After-Treatment Systems

GT-Power is a powerful tool for modelling emissions and after-treatment systems. With stringent emissions regulations, especially in the automotive industry, reducing pollutants such as NOx, CO_2, and particulate matter is essential, the software supports detailed analysis of exhaust emissions, including nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter (PM). GT-Power includes built-in models for simulating the behaviour of after-treatment systems such as catalytic converters, diesel particulate filters (DPFs), and selective catalytic reduction (SCR) in real-time. In a study byRamanjaneyalu [16],GT-Power was employed to optimize an SCR system for a heavy-duty diesel engine. By fine-tuning urea injection strategies and optimizing system configurations, significant reductions in NOx emissions were achieved, and the software helped in meeting the Euro VI emission standards while minimizing fuel consumption.

5. GT-POWER SIMULATION

GT-Power, developed by Gamma Technologies, is a one-dimensional simulation software widely used for modeling internal combustion (IC) engines. It predicts key engine performance parameters, including power, torque, airflow, volumetric efficiency, fuel consumption, turbocharger performance, and pumping losses, under both steady-state and transient conditions. Additionally, it supports engine and powertrain control analyses, accommodating a broad range of IC engine types. The software employs gas dynamics to model flow and heat transfer within engine components, enabling highly accurate simulations. Users build models in GT-Power through the GT-SUITE graphical interface by dragging and dropping components from an extensive database that includes cylinders, crankcases, pipes, and turbochargers. Components are interconnected using connection objects, and their properties are defined with customizable parameters. Simulation settings, such as convergence criteria and output plots, can be configured to meet specific objectives. The software excels in creating realistic engine models, requiring precise replication of real-world engine configurations, including details like pipe dimensions and angles. Beyond standard performance predictions, GT-Power integrates advanced physical models for analyzing emissions, acoustic properties of intake and exhaust systems, in-cylinder and pipe/manifold temperatures, and cylinder pressure measurements. It also supports control system modeling and facilitates the conversion of engine models into real-time simulations for software-in-the-loop (SiL) and hardware-in-the-loop (HiL) applications. Furthermore, GT-Power models can be integrated into system-level simulations within GT-SUITE, providing accurate, physics-based boundary conditions for vehicle-level analyses[3, 4, 12].According toVenkateshmohan and Kumar [12], GT-Power incorporates two primary combustion modeling approaches: Non-Predictive and Predictive combustion models, each tailored for specific simulation needs.

5.1 Non-Predictive Combustion Model

The non-predictive combustion model imposes a predefined burn rate that remains independent of in-cylinder conditions. This approach simplifies combustion modeling by focusing on fast simulation times, making it suitable for studying phenomena where burn rate characteristics are not critical, such as wave dynamics, turbocharging concepts, and exhaust configurations[4]. However, this model lacks the accuracy needed for analyzing parameters directly influenced by combustion dynamics, such as exhaust gas recirculation (EGR) and injection timing.

5.2 Predictive Combustion Model

In contrast, the predictive combustion model calculates the burn rate dynamically for each cycle, based on real-time in-cylinder conditions. While this approach requires longer simulation times, it provides deeper insights into processes that significantly impact combustion, such as variations in injection timing, EGR, and injection profiles[4]. To ensure accuracy, the predictive model must first be calibrated using experimental data. Phenomenological predictive models rely on zone-based combustion modeling, which divides the combustion process into either a single zone or multiple zones for more detailed analysis:

5.2.1 Single-Zone Model

This model represents combustion within a single, typically spherical zone, where processes such as fuel injection, evaporation, mixing, and burning occur simultaneously[17]. As combustion progresses, the zone expands to include the burned air-fuel mixture, maintaining uniform temperature and pressure throughout[17]. Single-zone models are ideal for analyzing primary combustion metrics, such as burn rate, rate of heat release (RoHR), and pressure traces. However, due to their lack of spatial resolution, these models are less effective for studying emission-related phenomena, including the formation of NOx and soot.

5.2.2 Multi-Zone Model

The multi-zone model divides the combustion chamber into several open systems, with each fuel packet tracked independently to monitor its trajectory, air entrainment, and evaporation[17, 18].Combustion equations are solved separately for each zone, incorporating localized temperature, pressure, and equivalence ratios[4]. This approach provides enhanced spatial resolution, offering superior predictive capabilities for both combustion performance and emission parameters compared to the single-zone model[19]. By accommodating these two combustion modeling methodologies, GT-Power offers flexibility in simulating engine dynamics while balancing computational efficiency and predictive accuracy.

5.3 Predictive Diesel Combustion Models in Gt-Power

GT-Power offers two advanced predictive combustion models for diesel engines: DI-Jet and DI-Pulse. Both models are multi-zone frameworks designed to simulate in-cylinder combustion and emission characteristics with high accuracy. While DI-Jet has been widely used, the newer DI-Pulse model delivers faster computation times while maintaining or exceeding the predictive accuracy of its predecessor[4].

5.3.1 DI-Jet Combustion Model

The DI-Jet combustion model employs a quasi-dimensional, multi-zone approach, developed by Gamma Technologies, to provide detailed predictive combustion simulations for diesel engines. This model divides the injected fuel into multiple axial slices, each containing five radial zones, with new slices generated at every time step. The mass of fuel within each slice depends on the instantaneous injection rate integrated over the time step, and the mass is evenly distributed among the radial zones[4]. Each radial zone is further subdivided into subzones representing liquid fuel, an entrained vapor-air mixture, and burned gas. Over time, the liquid fuel zone entrains air, transferring fuel mass to the unburned subzone, where combustion reactions proceed based on localized conditions of temperature, pressure, and mixture strength. Burned products are subsequently transferred to the burned subzone. Emission products, including NOx and soot, are calculated independently for each zone, based on its specific conditions, and are then integrated to determine overall emissions. This zonal resolution significantly improves the accuracy of emission predictions compared to single-zone models, which average states like pressure and temperature across the entire cylinder[4].

5.3.2 DI-Pulse Combustion Model

The DI-Pulse combustion model, also developed by Gamma Technologies, is a newer, phenomenological multi-zone approach designed for diesel engines with single or multi-pulse injections. It predicts combustion and emission parameters based on the in-cylinder pressure and temperature profiles, mixture composition at intake valve closing (IVC), and the injection rate profile[4, 20].

Although DI-Pulse operates approximately 5% slower than non-predictive models, it is significantly faster than the DI-Jet model. This improved computational efficiency allows for a more practical application in complex simulations without compromising accuracy. The model tracks each injection pulse individually, monitoring its evaporation, mixing, and combustion processes. Accurate input of the injection rate profile is critical for reliable simulation results.

DI-Pulse divides the cylinder volume into three thermodynamic zones:

1. Main Unburnt Zone - Contains the trapped gases at IVC.

2. Spray Unburnt Zone - Consists of fuel and gases entrained during injection.

3. Spray Burnt Zone - Represents the combustion products.

The model incorporates four calibration parameters: entrainment, ignition delay, premixed combustion rate, and diffusion combustion rate multipliers to fine-tune predictions against experimental data. This zonal partitioning (details below) enhances the model's ability to simulate combustion dynamics and emissions with high spatial resolution[4]. By leveraging these combustion models, GT-Power enables precise simulation of all combustion phases, facilitating detailed analysis of engine performance and emissions for advanced diesel engine designs.

5.4 Fuel Injection

The DI-Pulse model accommodates both single and multi-pulse injection events without restrictions on the number of pulses. Each injection pulse is independently monitored and incorporated into the spray unburnt zone.Consequently, achieving precise injector modeling is crucial for ensuring simulation accuracy.

The spray penetration length, denoted as 'S,' for a pulse at a time 't' following the injection event is determined using Eq.11beforethe breakup and Eq.12 after the breakup occurs[20].

$$S = u_{inj}\,.\,t.\left[1 - \frac{1}{16}\left(\frac{t}{t_b}\right)8\right] \;; when\ \frac{t}{t_b} \le 1 \qquad (11)$$

$$S = u_{inj}\,.\ t_b.\frac{15}{16}\left(\frac{t}{t_b}\right) \;; when\ \frac{t}{t_b} \ge 1$$

(12)

Here, U_{inj} represents the injection velocity at the nozzle tip, and t_b denotes the time required for the spray to break up into droplets. The breakup time, t_b, and the spray tip velocity, U_{inj}, are calculated using Eq. 13 and Eq. 14, respectively.

$$t_b = \sqrt{\frac{2\,.pi}{pg}}.\frac{d_n}{C_{d^*}\,u_{inj}} \qquad (13)$$

where ρg is the density of the gas, ρi is the density of the liquid fuel, Cd is the coefficient of discharge of the injector nozzle and dn is the diameter of the nozzle.

$$u_{inj} = c_d\sqrt{\frac{2\,\Delta P}{pi}} \qquad (14)$$

Where ΔP is the pressure difference across the injector nozzle.

5.4.1 Entrainment Model

During fuel injection into the cylinder, the spray entrains fresh air, residual gases, and fuel from preceding pulses. The entrainment process is modeled using the principle of momentum conservation, as described by Eq. 15[20].

Initialsparymomentum* = *Finalentrainementmixturemomentum

$m_{inj}.u_{inj} = (m_{inj} + m_{air-entrained}).u\ ; where\ u = \frac{dS}{dt}$(15)

Here, m_{inj} represents the initial mass of the injected fuel packet, $m_{air\text{-}entrained}$ denotes the mass of air entrained into the packet, and u is the final velocity of the resulting air-fuel mixture. Consequently, the mass of air entrained is strongly influenced by the injection velocity, as expressed in Eq. 16.

$$m_{air-entrained} = \frac{m_{inj}.u_{inj}}{u}$$

(16)

The rate of entrained fuel-gas mixture is modelled as shown in Eq. 17.

$\frac{dm}{dt} = -C_{ent}.m_{inj}.u_{inj}.\frac{du}{dt}$(17)

Centis the entrainmentmultiplier can be used for the calibration of the model.

5.4.2 Evaporation

The subsequent phase in the modeling process involves the evaporation of fuel within the entrained mixture. A control volume is defined around the droplet, and the energy balance equation is applied, as represented in Eq. 18. The droplet's change in internal energy is determined by the combined effects of convective heat transfer from the surrounding hot entrained gas and the energy loss due to evaporation[20].

$$m_d.C_{pd}.\frac{dT}{dt} = \frac{dQ_c}{dt} + \frac{dQ_e}{dt}$$

(18)

Where md is the mass of the droplet, cpd is the specific heat capacity of the droplet.

Eq. 19below defines the rate of convective heat transfer:

$\frac{dQ_c}{dt} = h.\pi.d_d^2.T_g - T_d$(19)

Where d_d is the diameter of the droplet, T_g is the temperature of the entrained gases,and T_d isthe temperature of the droplet.

The heat absorbed from the control volume due to enthalpy change is given by Eq. 20.

$\frac{dQ_e}{dt} = -\frac{dm_d}{dt}.\Delta H_{v\ d}$(20)

Where ΔH_{vd} is the latent heat of vaporization of the droplet, dm_d/d_t is the rate of dtevaporation of the droplet.

5.4.3 Ignition Delay

Ignition delay refers to the interval between the onset of fuel injection and the initiation of combustion. This delay is modeled individually for each injection pulse and is influenced by factors such as exhaust gas recirculation (EGR), the bulk cylinder temperature, and the cetane number of the fuel, as expressed in Eq. 21. The calibration of the model can be fine-tuned using the multiplier Cign.

$\tau_{ign} = C_{ign}.\rho^{C_{ign2}}.e^{\frac{C_{ign3}}{T}}.f(EGR)$(21)

As temperature and pressure vary continuously with the crank angle, the ignition delay is calculated using the relationship proposed by[21], as described in Eq. 22.

$\int_{t_{soi}}^{t_{soi}+t_{id}} \frac{dt}{\tau(p,T)} = 1$(22)

5.4.4 Premixed Combustion

Premixed combustion occurs when ignitable conditions are achieved within the cylinder. During this phase, the air-fuel mixture formed after the ignition delay period drives the combustion process. Key influencing factors include temperature, air-fuel ratio, exhaust gas recirculation (EGR) fraction, and the kinetic rate constant. To calibrate the model, a multiplier, Cpm can be applied. The mathematical representation for modeling the premixed combustion phase, as described by[20],is provided in Eq. 23.

$\frac{dm}{dt} = C_{pm}.m.(t - t_{ign}).f(k, T, \lambda EGR)$(23)

Here, t represents the time elapsed since the fuel packet was injected, t_{ign} denotes the ignition delay, k is the kinetic rate constant for the combustion reaction, and m is the mass of the air-fuel mixture formed during the ignition delay period.

5.4.5 Diffusion combustion

Once the premixed combustion phase concludes, the reaction rate becomes governed by the availability of the fuel-air mixture. The burning rate during diffusion-controlled combustion is influenced by factors such as the exhaust gas recirculation (EGR) level, oxygen concentration, cylinder volume, and the mass of the mixture. To fine-tune the model, a diffusion combustion multiplier, C_{df}, can be applied. The equation used to model the diffusion combustion phase, as outlined by[20],is presented in Eq. 24.

$\frac{dm}{dt} = C_{df}.m.\frac{\sqrt{k}}{\sqrt[3]{V_{cyl}}}.f(EGR, [o_2])$(24)

where V_{cyl} is the cylinder volume, and m is the mass of the air-fuel mixture available at the diffusioncombustion stage.

5.5 Model Calibration

To calibrate predictive combustion models, engine burn rate data derived from experimental tests is essential. However, directly measuring the burn rate during engine operation poses significant challenges. Instead, cylinder pressure is commonly measured as a proxy.

In GT-Power, the relationship between cylinder pressure and burn rate is utilized through two complementary simulations: a "reverse run" and a "forward run" [4]. The reverse run estimates the burn rate from measured cylinder pressure, while the forward run predicts cylinder pressure based on a known burn rate. For combustion model calibration, the reverse run simulation is typically employed.GT-Power calculates the fuel burn rate by dividing the cylinder into two zones[4]. The first zone, referred to as the unburnt zone, comprises the unburnt air-fuel mixture, the fuel being injected at a given moment, and residual gases present at the intake valve closure (IVC). The second zone, also known as the burnt zone, is progressively populated as the mixture in the unburnt zone undergoes combustion. The rate at which the mixture transitions from the unburnt to the burnt zone is defined as the burn rate[4].GT-Power employs two methods for estimating the burn rate through reverse run simulations: Three Pressure Analysis (TPA) and Cylinder Pressure Only Analysis (CPOA)[4]. Both approaches require cylinder pressure data as a function of crank angle, obtained from experimental measurements. A detailed explanation of these methods is provided below.

5.5.1 Three Pressure Analysis (TPA)

TPA calculates the burn rate for specific operating conditions using measured pressures from the intake, exhaust, and cylinder[4, 20]. This method relies on a reverse-run approach, iteratively determining the amount of fuel transferred from the unburned to the burned zone until the simulated cylinder pressure aligns with the measured values. Initial estimates of volumetric efficiency, trapping ratio, and residual gas quantities are derived from the measured port pressures and average temperatures imposed on the system's boundaries[4, 20]. TPA has two variations: TPA steady, which uses single-cycle data resolved by crank angle, and TPA multicycle, which incorporates data over multiple cycles. The multicycle approach offers an advantage in accounting for cyclic variations in the combustion process[4].

5.5.2 Cylinder Pressure Only Analysis (CPOA)

CPOA estimates the burn rate solely from cylinder pressure data. While the burn rate calculation process is similar to TPA, a key distinction lies in the requirement for input values: volumetric efficiency, trapping ratio, and residual gas quantities must be manually provided in CPOA, as they cannot be estimated from other data[20]. This method's primary limitation is the challenge of accurately determining the trapping ratio and residuals during engine testing, which may compromise calibration accuracy[4, 20].

Accurate modeling of the injection rate and timing is crucial for reliable combustion model calibration[20]. The primary advantage of a common rail direct injection (CRDI) system lies in its ability to maintain constant injection pressure under varying engine operating conditions. However, injection pressures are often adjusted to optimize engine efficiency and emissions, with minimal pressures used during idling and maximum pressures at high speeds and loads. Pressure fluctuations, caused by the high-pressure (HP) pump and the injection process, add complexity to the system. While the CRDI system dampens these fluctuations, they persist and significantly influence subsequent injections, especially when multiple injection strategies are employed with short intervals between injections[22]. For accurate fuel system modeling in GT-Suite, pressure fluctuations must be considered. High-pressure components, such as the HP pump and rail, should ideally be modeled in detail. However, to balance model complexity and simulation time, the HP pump and rail are often simplified, while the injector is modeled with higher fidelity. This simplification may introduce inaccuracies in the system's behavior.

The accuracy of combustion model calibration also heavily depends on the precision of test cell data [20]. Before using cylinder pressure data for burn rate analysis, common errors such as encoder errors, pegging errors, and thermal shock effects must be identified and corrected. To analyze and preprocess test cell data, a graphical data evaluation and visualization software such as AVL Concerto, is employed. The graphical data evaluation and visualization software facilitates data browsing, calculation, report generation, and batch processing. Its prebuilt macros support standard calculations such as heat release analysis, zero-line pressure correction, and filtering, while user-defined scripts enable custom data validation and visualization[23].

5.6 Common Errors in Pressure Data

Identifying and addressing common errors in pressure data is crucial for ensuring the accuracy and reliability of engine simulations and performance analyses.

5.6.1 Encoder Error

Encoder errors arise from inaccuracies in phasing the pressure transducer signal with the crank angle encoder. Misalignment leads to significant errors in heat release curve shape and magnitude, ultimately distorting thermodynamic insights into engine performance [24]. A crank angle error of 1° can result in up to a 10% error in heat release and a 5–25% error in instantaneous pressure[25].

Encoder error can be detected using two methods:

- ✓ TDC Sensor - A sensor mounted on the injector or spark plug generates a voltage signal based on piston movement, ensuring accurate determination of the top dead center (TDC). This method is preferred as it is unaffected by errors like pressure pegging or intra-cycle drift ([24].
- ✓ Motored Engine Pressure Trace - In an idealized motored engine, peak cylinder pressure occurs precisely at compression TDC due to the balance between compression and expansion work. However, real engines exhibit losses from heat transfer, crevice effects, and blow-by, causing peak pressure to deviate slightly, typically within 1° before TDC[20, 24].

5.6.2 Pegging Error

Piezoelectric pressure transducers, widely used in engine testing, generate a charge proportional to pressure changes. This signal is converted to voltage and requires "pegging" against a known reference pressure during each cycle. A transfer function is derived during this process and applied throughout the cycle to maintain measurement accuracy[26]. The general form of the transfer function is given in Eq. 25.

$$P(\theta) = P_{peg} + Gain\ (V(\theta) - V(\theta_{peg}))(25)$$

Where $Ppeg$ is the pegged pressure,$Gain$ is the sensor gain value in bar/volt, which is fixedfor a given sensor, $V(\theta)$ is the voltage in Volts at a given crank angle θ and $V(\theta peg)$ is the voltage at the crank angle where the pressure is being pegged.

Incorrect pressure pegging affects several key parameters, including instantaneous and cumulative heat release, crank angle at peak pressure, burned mass fraction, bulk charge temperature, and the polytropic coefficient [26]. There are two ways to check for pegging errors:

- ✓ Polytropic Coefficient - The polytropic coefficient (\(n\)) reflects the specific heat ratio of gases and heat transfer across cylinder walls. For direct-injection (DI) diesel engines, during the early compression stroke (-90° to -40° before firing TDC), the polytropic coefficient typically falls within the range of 1.35 to 1.37 [27]. The pegged pressure must align with this range for accurate calculations. Variations in dilution also influence the polytropic coefficient.
- ✓ Pressure Shift - In engines with untuned intake systems, the cylinder pressure at the intake bottom dead center (BDC) should match the intake manifold pressure. A maximum deviation of 200 mbar between these pressures is acceptable [20].

5.6.3 Thermal Shock Errors

During the combustion stroke, the release of significant heat flux can temporarily alter the offset value of piezoelectric sensors, a phenomenon referred to as thermal shock. Although most sensors are designed to recover quickly (within the same pegging cycle), prolonged recovery can cause intra-cycle drift, leading to inaccuracies in pressure measurements[24]. Thermal shock can be identified by evaluating the Average Exhaust Absolute Pressure (AEAP) between 240° and 320° after firing TDC. For reliable measurements, the standard deviation of AEAP should not exceed 4 kPa[24].

6. APPLICATIONS OF GT-POWER SOFTWARE IN ENGINE DESIGN AND ANALYSIS

Numerous studies have utilized GT-Power software for modeling, analysis, and optimization of engine performance and combustion characteristics:

6.1 Real-Time Simulation and Model-Based Design

GT-Power also supports real-time simulation, allowing integration with control systems through hardware-in-the-loop (HIL) and software-in-the-loop (SIL) platforms. This capability is essential for validating control strategies and evaluating engine performance under realistic driving conditions. It is particularly valuable for the development of advanced control algorithms in both ICE and hybrid systems. Tippur Chandrashekar [28]highlighted the successful use of GT-Power in real-time engine system development, emphasizing the software's accuracy in simulating dynamic engine behavior and its effectiveness in fine-tuning control strategies.

6.2 Exhaust System Design

Mohiuddin, et al. [29]designed and optimized an exhaust manifold using GT-Power, comparing its performance with an existing system. Results demonstrated that the redesigned exhaust manifold reduced back pressure, enhancing overall engine performance. The study emphasized that achieving specific flow characteristics is crucial for optimal exhaust system performance.

6.3 Wärtsilä W20V34SG Engine Analysis

Campblell, et al. [30]conducted a thermodynamic analysis of the Wärtsilä W20V34SG engine using a 1-D model in GT-Power. The study evaluated the impact of cooled and dehumidified ambient air (ranging from 9.5°C to 15.5°C) at constant pressure (1 bar) and relative humidity (100%). Simulations aimed to determine the maximum allowable air temperature at the cooling coil outlet without exceeding a cylinder pressure safety limit of 186 bar. With the brake mean effective pressure (BMEP) varied from 20 to 23.45 bar, the analysis concluded that the maximum outlet temperature should not exceed 13.8°C under the specified conditions.

6.3 Diesel-to-Dual-Fuel Conversion

Dong, et al. [9]modeled a Cummins diesel engine in GT-Power to explore the feasibility of converting it to dual-fuel operation using compressed natural gas (CNG) as the primary fuel and diesel as the pilot fuel. The simulation revealed less than 5% deviation in torque, power, and brake-specific fuel consumption (BSFC) between the modeled results and standard manufacturer test data under 100% load. The dual-fuel system showed a 3.6% increase in BSFC at full load compared to the baseline diesel engine while maintaining equivalent brake power. The alternative CNG fuel ratio achieved 75%, improving fuel economy and reducing environmental pollution.

6.4 Engine Performance at Varying RPM

Done, et al. [2]investigated the combustion, performance, and emissions of a single-cylinder compression ignition engine using GT-Power across engine speeds of 2400, 3000, 3600, and 4000 RPM. The results showed that increasing engine speed led to higher cylinder pressure, cumulative heat release rate, torque, brake power, and brake mean effective pressure (BMEP), as well as increased NOx concentrations. Conversely, hydrogen and CO emissions decreased with rising RPM.

6.5 Injection Timing and Compression Ratio Optimization

Nabi, et al. [13]developed a GT-Power model to analyze the performance and combustion characteristics of a diesel engine. The study evaluated engine speeds ranging from 800 to 2500 RPM, varying injection timings from 15° after top dead center (aTDC) and compression ratios from 13:1 to 25:1. Optimal performance was observed at an engine speed of 1700 RPM, a compression ratio of 20:1, and an injection timing of 10° to 15° before top dead center (bTDC).

6.6 Single-Cylinder Diesel Engine Performance

Galal, et al. [31]employed GT-SUITE 6.2 software to model a 407 cc single-cylinder diesel engine for performance analysis. The study compared simulation results with analytical methods and identified the highest brake and indicated power outputs at 3000 RPM.

7. KEY ADVANTAGES OF GT-POWER

GT-Power is known for its accurate predictions of engine performance and emissions. It offers a wide range of customizable models, making it suitable for various engine configurations and powertrains. Its accuracy has been validated by numerous studies, as discussed above, where GT-Power simulations closely matched experimental results during engine testing.

The software's ability to perform comprehensive engine simulations significantly reduces the need for costly and time-consuming physical prototypes. By enabling virtual tests and optimizations in early design stages, GT-Power accelerates the development process and minimizes experimental overhead.

GT-Power can be integrated with other simulation tools such as MATLAB/Simulink, AVL Cruise, and ANSYS, which enhances its utility in multi-disciplinary projects. This interoperability allows for more comprehensive system-level simulations, ensuring that engines and powertrains are optimized not just in isolation, but as part of the entire vehicle.

8. LIMITATIONS AND FUTURE DIRECTIONS

Despite its numerous advantages, GT-Power has certain limitations. The software's complexity may present a steep learning curve for new users, requiring detailed knowledge of engine thermodynamics and fluid dynamics. Additionally, the accuracy of simulations heavily depends on the quality of input data and assumptions made during model setup.Future developments in GT-Power may focus on enhanced integration with artificial intelligence (AI) and machine learning algorithms to automate engine optimization processes. This could significantly reduce the time required for simulation and further improve engine design.

9. CONCLUSION

This review studydemonstrates that GT-Power is a versatile tool for traditional ICE applications as well as modern hybrid and real-time system development. It advances engine design, optimizes performance, assesses environmental impacts, and contributes to improvements in fuel economy, emissions reduction, and control optimization. The software's capabilities in engine performance, fluid dynamics, heat transfer, and emissions control make it indispensable for engineers seeking to optimize engine design and meet regulatory requirements. Although the software presents some challenges, such as a steep learning curve, its accuracy and adaptability ensure its continued relevance in engine development. Future improvements, such as the integration of AI, could further enhance the efficiency of the design process.

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