A Critical Review on Thermal Simulation of LNG Driven IC Engines

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Abstract

Thermal modeling and simulation of IC engines have attracted considerable attention from the research community in the last three decades. An accurate understanding of the IC engine's heat gradient would help enhance the engine's efficiency. Researchers have used software developed by multiple vendors. Using the Using not only help in better understanding but will also aid in reducing the design time and research effort of engineers. The simulation would also aid engineers in studying engine performance without using expensive prototyping and physical testing. This will bring the cost of design and hence the total product cost. An effort has been made in this work (i) to study the various approaches proposed by researchers in studying engine performance by performing the thermal simulation (ii) to figure out research gaps and (iii) to provide future directions. The research contribution would help academicians, researchers, and practitioners pursue further research in the thermal simulation of IC Engines.

Keywords

LNG Engine, Performance analysis, Simulation, Thermal Simulation, Internal Combustion Engine, IC Engine

1. Introduction

The piston is a critical component of the reciprocating Internal combustion engine (IC Engine). The piston will be performing reciprocating motion continuously within the engine cylinder. The piston rings would help achieve an air-tight condition and facilitate combustion (Balahari et al., 2017; Sathish et al., 2016; Ikpe et al., 2020). The piston crown will carry the gas pressure during working. The piston would help transfer force from the expanding gases within the engine cylinder to the crankshaft with the help of a piston rod and connecting rod (Sonar et al., 2015, Prasad et al., 2016). Fuel will be converted into gases during the combustion process. The gases will impact the piston and cause it to execute the reciprocating motion, which is converted into the rotary motion of the crankshaft (Kumar et al., 2017). The reciprocating piston will be subjected to its inertia forces due to reciprocation, friction forces generated by the continuous rubbing of the piston and the cylinder wall, and the forces of the gases generated during combustion (Gadde et al. 2017). Thus, the piston will be subjected to high temperatures (2500^0K) and high-pressure gradients during work and experience continuous fatigue and wear and tear (Reddy et al. 2013). The high-temperature gradients would also result in thermal stresses and an expansion of the piston material and cause the material to lose its valuable properties (Gupta et al. 2014). The forces and the torques acting on the piston were also formulated as a function of the angles of the crank and the connecting rod (Nigus 2015).

Vishal et al. (2016) explored performing static stress analysis of pistons made of two aluminum alloys under different pressure load conditions. The investigation revealed that AL-GHY-1250 alloy fared better over 4032 for various pressures. Low deformation in A4032 was mainly due to higher yield strength and ultimate tensile strength. Manisaikamal (2017) studied thermal analysis of pistons having concave and convex shapes and concluded that both heat distribution and the deformations in the pistons having concave profiles were higher than in pistons with convex profiles. The low heat distribution in the pistons will increase the life of pistons and piston rings.

2. Literature review

Many researchers have contributed to the thermal simulation studies of IC engines for better understanding. Mojtaba Babaelahi (2015) proposed a new thermal model using polytropic compression and expansion processes. The model was successfully employed for predicting the thermal efficiency of sterling engines.

2.1 Governing Equations

Heat transfer predictions in IC engines are made using the Governing equations derived from steady flow boundary layer analysis.

$$h = a\frac{k}{B}\mathrm{Re}^{0.7} + b\frac{T^4 - T_w^4}{T - T_w} \tag{1}$$

Equation (1) is used for computing heat transfer co-efficient in Anand's (1963) model.

In Equation (1), **a** is constant, which varies from 0.35 to 8. The value of the constant **a** depends upon the intensity of motion within the cylinder. K is the thermal conductivity of the gas in the engine cylinder. **B** is the diameter of the cylinder. $\mathbf{R_e}$ is the Reynolds number and depends upon the speed of the piston. Here **b**, is a constant equal to 4.3 X 10^{-9} W/m^2 K^4 in SI units. Also, here **T** is the temperature of the gas, and $\mathbf{T_w}$ is the temperature of the wall. The unsteady thermal boundary layer model has the following assumptions.

1. Planar, cylindrical, and spherical boundary layers are included.
2. Isentropic compression and expansion in the region outside the thermal boundary region are excluded

The energy equation may be derived as equation (2). To solve this equation (2,), initial conditions and boundary are required.

$$\frac{\partial \phi}{\partial t} = \frac{1}{\rho c_p}\frac{\partial}{\partial r}\left(k\frac{\partial \phi}{\partial r}\right) + \left(\frac{\sigma}{r}\alpha - u\right)\frac{\partial \phi}{\partial r} \tag{2}$$

In equation (2), α is the thermal diffusivity.
The total mass in the boundary layer between the surface (r_0) and a certain point in the boundary layer is given by

$$m = \int_{r_0}^{r} \rho A dr \tag{3}$$

In equation (3), $A = r^\sigma$ is the area for the different coordinate systems.

The velocity in the direction of r is given by equation (3)

$$u = -\frac{1}{\rho A}\frac{dm}{dt} = -\frac{1}{\rho A}\frac{d}{dt}\int_{r_0}^{r} \rho(r')A(r')dr' = -\frac{1}{\rho r^\sigma}\frac{d}{dt}\int_{r_0}^{r} \rho(r')r'^\sigma dr' \tag{4}$$

The energy equation (3) can be used where combustion occurs.

The main contribution of this work is that polytropic expansion/compression processes replaced the adiabatic expansion/compression processes. This was mainly done to improve the accuracy of prediction. Suitable changes were made to the governing differential equations to reflect mass loss from working to buffer spaces and heat loss from expansion to compression spaces because of the thermal conductivity of the displacer. The model also considers the effect of non-ideal heat recovery of the regenerator and the hydraulic pressure drop in the heater, cooler, and regenerator. The model also considers the mechanical friction between the piston and the cylinder. This model was also made to correct piston back pressure in terms of piston velocity, using the principle of finite speed thermodynamics (FST). The model was named Polytropic Analysis of Sterling Engine with various losses (PSVL) and was then used to predict the sterling engine's thermal efficiency. The results were then compared with previous thermal models and experimental results. Hosseinzade (2015) developed a new thermal model for sterling engines. The model uses Adiabatic analysis and FST to predict sterling engines' thermal efficiency. The model considers the finite speed of the piston and mechanical friction while predicting the brake horsepower (BHP), indicated horsepower (IHP), and the engine's thermal efficiency. The magnitude of errors was 69.7%, 33. 6%, and 14.9% while computing the engine's BHP, IHP, and thermal efficiency, respectively. The thermal model was successively validated and optimized in five different scenarios.

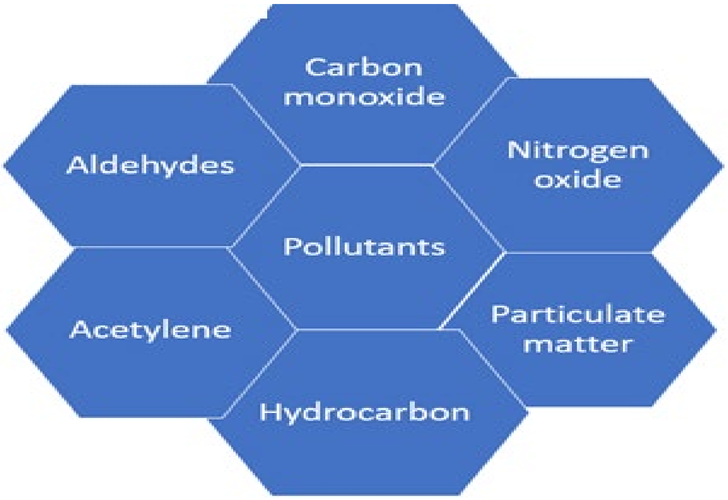

Fig. 1 Pollutants of the Combustion process

Mahmood et al. (2022) investigated the performance of a Ford-Philips 4-215 engine by developing a thermal model by considering the effect of different factors such as engine rotational speed, engine pressure, heater temperature, and piston stroke on technical (energy and exergy) and economic (cost savings and payback period). The results of the model were validated using experimental data. They concluded that increasing engine pressure and heater temperature would enhance the engine capacity and efficiency. They also observed that increasing the engine rotational speed and the stroke of the piston will first shorten the payback period and make it longer.

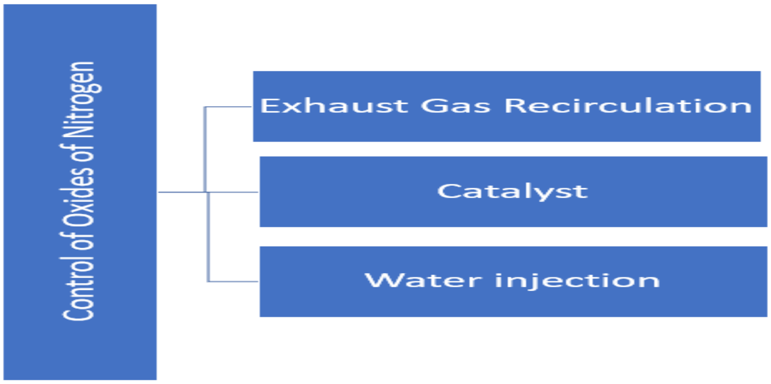

Fig 2. Methods used for controlling oxides of Nitrogen

They used the Linear programming method and technique for ordering preference by similarity to ideal solution (TOPSIS) to design engine parameters. While looking from an energy and economic perspective, engine parameters were designed to give maximum electric power and a minimum payback period of 260.46 kW and 6.10 years, respectively.

While optimizing energy, exergy, and economic objective functions, the experiment revealed the maximum output power and efficiency are evaluated at 258 kW and 44.5%, respectively, at a 5-year payback period. Chenhao et al. (2022) studied a modified sterling engine and proposed Incorporated Pressure Drop-modified Simple Model (IPD-MSM). The investigation revealed that the model could give accurate predictions at high pressure and high-frequency conditions compared to other adiabatic models, such as CAFS and ISAM. They also studied the thermodynamic properties of Helium, Hydrogen, and Helium and Xenon mixtures. The study showed when the percentage of xenon reaches 2%, in Helium and Xenon mixtures, the highest output power and thermal efficiency are possible.

Internal combustion engines' significant challenges are low efficiencies and high emissions (Figure 1). One survey projected that IC engines would be in the long-term (Serrano 2017). Engineers and researchers from the automobile industry are trying hard to tackle both efficiency and emission-related problems. Various researchers for tackling emission-related issues have proposed many techniques. These include three-way catalysts (Zhang et al. 2017), diesel oxidation catalysts (Fayad et al. 2017), selective catalytic reduction systems (Leskovjan et al. 2018), and particulate matter filters (Jiang et al. 2018). These approaches have been implemented and tested in spark and compression ignition engines. The catalytic converters are mainly used as after-treatment systems. The main issue with these catalytic converters is that they are highly inefficient during the startup and warmup stages of the working cycle. When the temperatures reach 2500C-3000C, these systems activate and convert the harmful emissions (Zhu et al., 2018, Mahadevan et al., 2017). Much research is expected from researchers regarding the thermal management of catalytic converters. Researchers have recently explored that hybrid electric vehicles (HEV) could be used to make IC engines more efficient. One researcher showed how kinetic energy could be recuperated during braking (Chan 2017). However, thermal management is equally important even in HEV because exhaust temperatures are low, and catalytic converters will be inefficient. Another issue with the after-treatment devices is that their interaction during working may bring down the system performance. Especially when there are multiple after-treatment devices are there in the system. For example, the diesel particulate filter regeneration temperature will be higher than the Diesel oxidation catalyst light-off temperature. Thus, the heat released by the Diesel oxidation catalyst will make diesel particulate filter regeneration more efficient (Nakane et al. 2005). Many researchers studied exhaust emission analysis during the cold start and warm-up stages. Many researchers have observed the exhaust emissions and found they contain large quantities of hydrocarbon and carbon monoxide (Nithyanandan et al., 2010, Roy et al., 2016). Exhaust emissions during the cold start phase of both petrol and diesel engines have reported high quantities of both hydrocarbons and carbon monoxide. Researchers have measured the amounts of hydrocarbons from 220 ppm to 28000 ppm. Similarly, researchers found that exhaust emissions during a cold start will have carbon monoxide concentrations from 950 ppm to 8400 ppm. This is partly due to in-efficient combustion and in-efficient catalyst (Deng et al. 2011, Li et al. 2009, Fonseca et al. 2011). Jianbing Gao et al. (2019) explored the articles related to thermal management of catalytic converters (Figure 2) to decrease engine emissions such as carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter, to meet stringent emission regulations. They also studied other thermal management methods such as burners, reformers, and electrically heated catalysts.

2.2 Simulation tools

Thermal management would not only help in improving the performance of engines but also in reducing emissions. In the conventional design, components individually may not guarantee an optimum overall system design. The system's actual performance will be known only after prototyping and testing. This is how design defects are identified in the later stages of the design process, making it expensive. Also, the traditional design process is sequential, inflexible, and costly.

Computer-aided Engineering (CAE) helps engineers analyze and test automobile designs quickly and at a reduced cost. This would also help to do away with costly physical prototyping (Mikelsons et al. 2017, Wu et al. 2014, Fitzgerald et al. 2010). Simulation software would assist in analyzing the complexity both at the component level as well as system level. Sometimes, various simulation tools will have to be used for better clarity. Thus, holistic system analysis is only possible through the modern design process. Therefore, holistic vehicle simulation would allow for concurrent component development and testing, reducing the product development time (Reyneri et al. 2002, Casoli et al. 2014). For performing simulation, it would be helpful to consider an automobile consisting of submodules such as an IC engine, electric motor, power transmission system, control system, HVAC system, vehicle cooling system, and cabin thermal system. The models for predicting vehicle speed can be classified into backward facing and forward-facing models. The backward-facing models assume that the vehicle follows the reference speed (Vagg 2015) and calculates the force required to achieve this by considering drag force into consideration (Murgovski et al. 2015, Ruan et al. 2016, Vagg et al. 2016, Tian et al. 2018, Musardo et al. 2005, Mohan et al. 2013, Shojaei et al. 2012). These models are simple and easy to implement. Forward-facing models use speed reference and feedback obtained from modeled vehicles to control the torque demand of the engine. As such, these models represent the real-world scenario (Nuesch 2014).

Vehicle body thermal modeling methods mainly include data-driven approaches, which are easy to implement and help in real-time modeling and control of applications. The main problem with this model is that they are not stable and precise. The mathematical models are very close to the modeled system and give accurate results. But they are complex and computationally expensive (Austin et al. 2001, Wang 2010, Piovano et al. 2016).

A thermal fluid simulation model would help accurately predict the behavior of coolant and oil for performance measurement. They are also helpful in system-level optimization. The most used are the 1D and 3D CFD approaches. ID tools are simple and inexpensive. 3D CFD approaches are complex and computationally expensive (Setlur et al. 2005, Ap et al. 2003, Wagner et al. 2002).

The refrigerant subsystem consists of components such as a compressor, heat exchanger, thermal expansion valves, and evaporator. The inputs given to the model are compressor speed and displacement, air flow rate, temperature, relative humidity, and evaporator inlet condition. A simulation tool for analyzing the air-conditioning system was proposed by Davis (1972).

The co-simulation technique helps thermal modeling and energy management and captures interactions between different system modules. The model would help compute the fuel consumption over a wide range of operating conditions (Wang et al., 2015, Wang et al., 2011). Co-simulation tools can be used in two different configurations. The model exchange module would help the user to export a model from one platform and run it on another platform. In co-simulation mode, the simulation of each component will be done by its numerical solver; however, a global server would control the information exchange between the different models and the simulation order (Chen et al., 2018). The issue with the co-simulation models is that they are computationally expensive. Li et al. (2015) co-simulated CarSim with a Simulink anti-lock braking controller capable of estimating optimum tire slip ratio at a given pressure.

3. Conclusion

An attempt has been made in the present research to study the different approaches proposed by researchers for performing effective thermal management using simulation. IC Engines are not efficient and have high emissions. Many schemes are proposed to make IC engines efficient and reduce emissions containing carbon monoxide, hydrocarbons, nitrogen oxides, etc. However, much research is expected from researchers in the thermal management of catalytic converters to decrease engine emissions such as carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter, to meet stringent emission regulations.

Researchers will also have to work toward reducing emissions and particulate matter, especially during the cold starting and warming up phases of IC Engines. With the advent of computer-aided engineering, simulation software is being used in industries to predict thermal efficiency, stresses, and deformations. Vehicle body thermal modeling methods mainly include data-driven approaches, which are easy to implement and help in real-time modeling and control of applications. A thermal fluid simulation model would help accurately predict the behavior of coolant and oil for performance measurement. The co-simulation technique helps thermal modeling and energy management and captures interactions between different system modules. Various researchers have attempted to evaluate an IC engine's performance at the component and system levels through simulation. There is a need to make the simulation software more robust and to make them more reliable. There is a need to develop cost-effective, accurate, and reliable co-simulation models to make IC engines efficient and minimize emissions.

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