Numerical simulation of performance and emission of marine diesel engine under different gravity conditions

Xiuwei Lu and Peng Geng

Abstract
A computational fluid dynamics model of the marine diesel engine was established and validated, and the simulation studies were carried out using this model. Different gravity conditions were set in the computational fluid dynamics model to investigate their effect on marine diesel emissions and performance. By comparing the simulation results under different basic grid sizes, 1.2 mm was selected as the basic grid size of the computational fluid dynamics model. The model uses the experimental data including cylinder pressure, heat release rate, and nitrogen oxides (NO\textsubscript{x}) emissions to calibrate and validate the model. The simulation results are very close to the experimental data, and slight errors are also within the allowable range. In particular, when considering the heat transfer of the combustion chamber wall, the simulation results of the heat release rate are closer to the experimental data. The simulation results show that gravity has a slight effect on cylinder pressure and heat release rate, and has a certain degree of effect on fuel spray and atomization. The penetration length of the fuel is proportional to the gravity, and the maximum deviation of the Sauter mean diameter of the droplet is 25.74%. The spray and atomization process of fuel directly affects combustion and emissions. The maximum deviation of NO\textsubscript{x} emissions is 6.03%, which is reduced from 7.46 to 7.01 g/kW\textsubscript{h}. Finally, the three-dimensional simulation results of temperature, equivalence ratio, and NO\textsubscript{x} emission of different crank angles under different gravity conditions are compared.

Keywords
Gravity, Sauter mean diameter, marine diesel engine, NO\textsubscript{x}, computational fluid dynamics

Introduction
As the quality of atmospheric environment continues to deteriorate, people continue to have concern about environmental issues. Pollutant emissions from marine diesel engines, especially NO\textsubscript{x} and soot, have drawn increasing attention. The International Maritime Organization (IMO) imposes limits on the NO\textsubscript{x} emissions from marine diesel engines by developing and publishing Tier-III regulations.\textsuperscript{1,2} The introduction of the Tier-III standard has caused a considerable impact on plenty of shipping countries and shipping companies. The Tier-III standard is reduced by 76% compared to the Tier-II standard, which means more stringent regulations are enforced to reduce marine diesel NO\textsubscript{x} emissions. At present, the mainstream NO\textsubscript{x} emission reduction technologies include exhaust gas recirculation (EGR), selective catalytic reduction (SCR), natural gas engines, and so on, all of which have made breakthrough in the reduction of NO\textsubscript{x} emissions.\textsuperscript{3–5}

Gravity condition
Ocean-bound vessels are significantly affected by marine meteorological conditions. Not only does the harsh and constant-changing marine meteorological conditions affect the performance of marine diesel engines, but also the emission of pollutants. The effect of gravity on marine engines has always been a focus of scholars and engineers. However, due to the complexity of the engine, the research on this point is still rare.

Merchant Marine College, Shanghai Maritime University, Shanghai, China

Corresponding author:
Peng Geng, Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China.
Email: penggeng@shmtu.edu.cn

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
environment affect the comfort level of personnel, it also causes disruption to the operation of the equipment. The hull caused by the waves is in a state of being overweight or weightless for a short time. People have long been aware of the effects that gravity has on the combustion process. However, due to the complexity of the combustion process, the classical combustion theory described by mathematical formulas tends to overlook gravity as an influencing factor. Such experimental facilities as drop towers and weightless aircraft can obtain weightlessness for a short period. Through these devices, many countries have conducted weightless combustion experiments on various combustible materials. The establishment of the International Space Station has promoted the weightless combustion experiment based on which many positive results have been obtained. Gravity can have effect on heat transfer, mass transfer, flame propagation, and flame stability during the process of combustion. Under normal gravity conditions, the flame shows a “droplet” shape with a center of gravity, while the flame is of “circular” shape under weightless conditions. Besides, gravity could affect chemical reaction, thus resulting in different combustion products. In general, combustion exhibits the following characteristics under weightless conditions. First, it is more conducive to the study of stationary and low-speed flow combustion under circumstance where natural convection almost disappears. Second, gravity sedimentation is almost non-existent, which facilitates the study of combustion under stable and free-suspension conditions. Third, the disappearance of buoyancy leads to an increase in combustion in time and space scales, which will be conducive to the observation of combustion.

A range of physical and chemical changes experienced by a droplet before burning play an important role in engine combustion. Combustion is directly associated with to emissions. There is a possibility that ignition would not occur until several crank angles after the start of injection. Once ignition occurs, the fuel that has been injected and mixed with air undergoes the premixed combustion process. When the combustible mixture as prepared in advance has been consumed, mixing-controlled combustion occurs. As the name suggests, burning in this combustion process is subject to control by the fuel–air mixing process. Droplet combustion is commonly found in diesel engines. Despite plenty of studies focusing on diesel spray combustion, none of them takes into account the effect of gravity. The University of Tokyo, Japan, took the lead in conducting research into the combustion of n-heptane droplets under the context of microgravity.

**Simulation software**

Due to the rapid development of computer technology, it is made increasingly convenient to study engine performance and emissions by means of numerical simulation. Traditional experimental methods are faced with the difficulty in observing the effects that gravity has on the performance and emissions of combustion plants. Engine numerical simulation technology is capable to simulate a variety of different engine operating conditions, especially those that are difficult to simulate in traditional experiments. As an engine computational fluid dynamics (CFD) simulation software, CONVERGE shows massive advantages that make it most commonly in practice.

In order to calculate the spray in a simulation, CONVERGE introduces drop parcels into the domain at the injector location at a user-specified rate. Parcels represent a group of identical drops (e.g. same radius, velocity, temperature, etc.) and are used to statistically represent the entire spray field. With the concept of drop parcels applied, CONVERGE leads to a significant reduction of the computational time required by a simulation involving spray.

In CONVERGE, a drop’s velocity, \( v_i \), is obtained using its equation of motion

\[
\rho_l V_d \frac{dv_i}{dt} = F_{di}
\]

where \( \rho_l \) indicates the liquid density, \( V_d \) denotes the drop volume, and \( F_{di} \) is determined by the sum of the drag force and the gravitational body force as

\[
F_{di} = F_{drag,i} + F_{g,i} = C_D A_f \frac{\rho_g |U_i|}{2} U_i + \rho_l V_d g_i
\]

\( A_f = \pi r^2 \) represents the drop’s frontal area, \( \rho_g \) indicates the gas density, and \( U_i \) refers to the drop-gas relative velocity expressed as

\[
U_i = u_i + u'_i - v_i
\]

where \( u_i \) and \( u'_i \) represent the local mean and turbulent fluctuating gas velocities, respectively, and \( g_i \) indicates the gravitational acceleration. Therefore, the equation of motion can be rewritten as

\[
\frac{dv_i}{dt} = \frac{3 \rho_g}{8 \rho_l} C_D \frac{|U_i|}{r} U_i + g_i
\]

which is used in CONVERGE to update drop velocities at any given time-step.

In summary, the velocity of the fuel droplets subject to impact from gravity. The difference in droplet
velocity causes change to the statistics and distribution of parcel in CONVERGE. In this article, a validated model is applied to explore the effect of different gravity conditions on the performance and emissions of marine diesel engines.

Simulation model

Brief description of the CFD model

The CFD model of Perkins Rolls-Royce marine four-stroke engine (2306C-E14TAG3) was constructed and validated with experimental data. Based on this model, research is conducted. The main technical parameters of the engine are presented in Table 1.

CONVERGE 2.4, commercial CFD software, is applied to facilitate simulation. The CFD model geometry is drawn according to the shape of the engine combustion chamber. Figures 1 and 2 illustrate the geometry corresponding to the top dead center (TDC) and bottom dead center (BDC), respectively. The characteristics of the CFD model are as follows. First, the combustion chamber consists of the piston, the cylinder head, and the cylinder wall only. Second, with the symmetry of the combustion chamber, the model is calculated using the engine sector (60°). Third, the cylinder head is simplified to a flat surface. Fourth, the moment is taken when the intake valve and the exhaust valve are closed altogether as the starting point of the simulation. Fifth, the exhaust valve opening time is taken as the end point of the simulation. Finally, only the compression, combustion, and expansion strokes are calculated. Not only does this setting reduce the time required for, it also reduces the need for computing resources. Moreover, a smaller grid size can be used to improve simulation accuracy.

Various turbulence models are available in CONVERGE (e.g. Standard $k – \varepsilon$, Rapid Distortion RNG $k – \varepsilon$, RNG $k – \varepsilon$, Realizable $k – \varepsilon$, $k – \omega$ SST). In order for a better simulation of the gas motion in the cylinder under high Reynolds number, the Renormalization Group (RNG) model is applied as the Reynolds-averaged Navier–Stokes (RANS) turbulence model. The fuel atomization and spray process have a considerable impact on engine performance and the final combustion products. Fuel atomization and spray involves a complex process where gas–liquid two-phase flows are coupled to each other. Spray droplets are subject to multiple processes from injection burning. Table 2 below shows the fuel atomization and spray process

| Table 1. Main technical parameters of the engine. |
|-----------------------------------------------|
| Technical parameters                        |
| Cylinder number                              | 6 |
| Bore (mm)                                    | 137 |
| Stroke (mm)                                  | 165 |
| Power (kW-h)                                 | 396 |
| Speed (r/min)                                | 1500 |
| Displacement (L)                             | 14.6 |

Figure 1. Geometric models at BDC.

Figure 2. Geometric models at TDC.
models applied in this article. As for the numerical simulation of marine diesel engines, n-heptane and n-tetradecane are commonly taken as surrogate fuels for heavy fuel oil. In this article, n-heptane is taken as surrogate fuel. The n-heptane reaction mechanism (42 species and 168 reactions) provided by CONVERGE is utilized. The detailed chemical kinetics model SAGE was selected to construct the combustion model. An extended Zeldovich mechanism and Hiroyasu soot model were applied to predict NO\textsubscript{x} and soot emissions, respectively. The diesel engine speed is 1500 r/min, and the power is 396 kW under 100% load. The fuel consumption rate measured by the experiment is 204.8 g/kW·h.

Best base grid size

The governing equations used in CFD simulation are partial differential equations. The solution to the partial differential equation is to discretize the solution region into a mesh in the first place. Then, the physical parameters at the mesh node are solved. Finally, the physical parameters between the nodes are obtained by interpolation. CONVERGE is also reliant on the same method to solve partial differential equations, for which the number of meshes is closely related to the simulation results. The grid control methods in CONVERGE include base grid, adaptive mesh refinement, and fixed embedding. Both adaptive mesh refinement and fixed embedding are performed to further refine the mesh based on the base grid. Therefore, the size of the base grid determines the total number of meshes required for the CONVERGE simulation. Despite the theoretical proportionality that the number of meshes has to the accuracy of the simulation, the number of grids determines not only the computational time but also the need for computational resources. In addition, the iteration error caused in the solution process increases as the number of meshes is on the rise increases. Therefore, it is essential to determine how to choose an appropriate grid number in calculation accuracy and calculation cost for CFD simulation. Figures 3 and 4 present the comparison of the simulation results of cylinder pressure and heat release rate (HRR) in the absence of adaptive mesh refinement and fixed embedding, respectively. Figure 5 shows a more intuitive comparison of maximum combustion pressure ($P_{\text{max}}$), $P_{\text{max}}$ position, NO\textsubscript{x} emissions, and computational time consumption for different base grid sizes.

As shown in Figures 3–5, when the base grid size reaches 1 mm, the cylinder pressure, the HRR, and the NO\textsubscript{x} emission approach the experimental data. When the basic mesh size is further set to 0.9 mm, the simulation results barely change. The trend of the compression and expansion strokes shows basically no changes, which suggests that they are irrelevant to the choice over the base grid. Close to TDC, the most complex stage of physical and chemical processes, however, the result is affected significantly by base grid size. Therefore, in order to ensure accuracy of calculation

| Table 2. Atomization and spray model used in simulation CONVERGE.39 |
|---------------------------------|-------------------------------|
| Spray model physical process   | Model options                |
| Spray breakup                  | Kelvin–Helmholtz and         |
|                                | Rayleigh–Taylor model         |
| Drop drag                      | Dynamic drag models           |
| Collision model                | NTC model                     |
| Collision outcomes model       | O’Rourke, Post                |
| Drop turbulent dispersion      | O’Rourke model                |
| Drop/wall interaction          | Rebound/slide model           |
| Evaporation model              | Multi-component vaporization  |

Figure 3. Comparison of cylinder pressures of different base grid.

Figure 4. Comparison of HRR of different base grid.
and reduce the time for calculation. In this article, the base grid is set to 1.2 mm, while adaptive mesh refinement and fixed embedding are conducted to refine the grid near TDC. Throughout the calculation process, the 2-scales adaptive mesh refinement based on velocity and temperature gradient was performed in the solution region. Fixed embedding is applied to nozzle, piston, and cylinder head. Not only does such grid control approach ensure sufficient calculation accuracy and less computational time for the compression and expansion stroke, it also facilitated the capture of in-cylinder details during the spray and combustion process. With no consideration given to other factors like the combustion model, atomization model, and mechanism, such a grid strategy can achieve an excellent trade-off between simulation accuracy and calculation time.

**Model calibration verification**

Figures 6 and 7 present the comparison performed between simulation results and experimental data. As shown in Figure 6, the trend of cylinder pressure and HRR is consistent with the experimental data. The errors of critical data are indicated in Table 3. As shown Figures 6 and 7, though the cylinder pressure error is 4.4% when the expansion process is complete, it remains within the acceptable limits.

**Correction of HRR**

There is a significant difference between the simulation results and the experimental data of HRR, especially the maximum value of the simulation results that is considerably higher compared to the experimental value, which is due to that the HRR obtained by the experimental method is affected by the heat transfer loss of the combustion chamber wall surface, and that this part of the heat transfer loss is neglected at the time of conventional CONVERGE simulation. The HRR of the combustion chamber wall as output of CONVERGE is shown in Figure 8, while Figure 9 presents the comparison between the simulation HRR.
and the experimental data after subtraction the wall HRR. As revealed by Figure 9, after consideration given to the wall HRR, the simulated HRR peak value approaches the experimental data more. In summary, the errors of cylinder pressure, NO\textsubscript{x} emission, and HRR are validated as acceptable, which verifies the model.

### Results and discussion

A marine four-stroke diesel CFD model was applied to investigate the effect of different gravity on engine performance and emissions. When the engine worked, the state of the fluid in the cylinder showed a rapid change. It is difficult to observe the effect of gravity on engine performance and emission using the conventional experimental methods. CFD models can be applied to observe the details that are difficult to capture in traditional experiment, and to gain understanding as to the process of combustion and formation of emissions.\textsuperscript{51}

Figure 10 presents the comparison of cylinder pressure and HRR under different gravity conditions (0,
+9.8, and −9.8 m/s²). As shown in Figure 10, gravity has barely any effect on the cylinder pressure but a certain impact on the HRR. The difference of HRR at −3°CA reaches its maximum. The difference is

that 0 m/s² is roughly 10.3% higher than +9.8 and −9.8 m/s². The different in NOₓ and soot emission is shown in Figure 11, which reveals that the NOₓ emission of 0 m/s² is approximately 6% higher than +9.8 and −9.8 m/s², with the rate of NOₓ formation being the highest. The production of soot was maximized at 13°CA. The peak value position of −9.8 m/s² lags 0.2°CA with respect to +9.8 and 0 m/s², and the amount of emission is roughly 1.1% higher. Nevertheless, the soot emissions at 0 m/s² by the end of the expansion stroke were minimized. The parameters of performance and emission are compared under different gravity conditions, as shown in Table 4.

The penetration length (PL) and Sauter mean diameter (SMD) of the fuel are shown in Figures 12 and 13, respectively. Different gravity conditions tend to impact on SMD and PL during the process of atomization and breakup. The same Blob injection model was applied under different condition of gravity simulation (the initial droplet diameter defaults to the same nozzle diameter). As shown in Figure 13, PL shows a declining trend as gravity is reduced. This trend is made

Figure 10. The comparison of cylinder pressure and HRR under different gravity.

Figure 11. NOₓ emission under different gravity: (a and b) NOₓ emission and (c and d) soot emission.
SMD is the most used indicator to evaluate the quality of fuel atomization. It refers to the ratio of the volume to the surface area of the atomized oil droplets. The smaller the SMD, the faster the evaporation rate of the droplets, and the better the atomization quality of the oil droplets. As shown in Figure 12, the SMD prior to burning is consistent with the diameter of the nozzle. SMD will lead to significant fluctuations after the start of combustion ($10^{/9.8}$CA). The SMD in the absence of gravity is shown to be the minimum.

Figure 13. The comparison of penetration length under different gravity.

More noticeable in the middle and late process of atomization. SMD is the most used indicator to evaluate the quality of fuel atomization. It refers to the ratio of the volume to the surface area of the atomized oil droplets. The smaller the SMD, the faster the evaporation rate of the droplets, and the better the atomization quality of the oil droplets. As shown in Figure 12, the SMD prior to burning is consistent with the diameter of the nozzle. SMD will lead to significant fluctuations after the start of combustion ($10^{/9.8}$CA). The SMD in the absence of gravity is shown to be the minimum.

Equivalent ratio, temperature, and NO$_x$ distribution cloud maps provide more support for the analysis of two-dimensional results. The equivalent ratios, temperatures, and NO$_x$ of contours at different crank angles (11–17$^{/9.8}$CA) are shown in Figures 14–16. The marine diesel engine is fitted with a six-nozzle injector, and the CFD model is 1/6 of the combustion chamber. The turbulence causes the fuel to be distributed clockwise after hitting the cylinder wall in the injection direction. As shown in Figure 15, the temperature in the combustion chamber rises at a fast pace when combustion occurs. A sharp increase in temperature causes the evaporation rate of the droplets to exceed burning rate. The difference between the evaporation rate and the burning rate results in the formation of a substantial amount of oil and gas mixture. Therefore, as shown in Figure 14, the equivalence ratio is high at the front surface of the spray, particularly near the wall surface. According to Figures 14 and 15, the equivalence ratio on the flame surface of the diffusion combustion shows a gradual decline as the combustion rate is on the rise. NO$_x$ production is directly associated with oxygen concentration and temperature. NO$_x$ is mainly produced in the areas with high temperature and abundant oxygen. It is easy to observe that the amount of NO$_x$ produced is high in a region with appropriate equivalent ratio and temperature.

As shown in Figures 14–16, the difference in equivalence ratio, temperature, and NO$_x$ under different gravity conditions is self-evident. Figure 12 shows the effect of gravity on SMD. SMD bears an inverse proportionality to the evaporation rate of the fuel droplets. The effect of gravity on SMD is the root cause of the difference in equivalence ratio, temperature, and NO$_x$ distribution. Except for 0 m/s$^2$, regardless of whether it is $+9.8$ or $-9.8$ m/s$^2$, the existence of gravity causes the temperature in the core region of the cylinder to be higher, the distribution to be wider, and the NO$_x$ formation area to be expanded significantly.

Table 4. Comparison of parameters under different gravity.

|                  | 0 m/s$^2$ | $-9.8$ m/s$^2$ | $+9.8$ m/s$^2$ |
|------------------|-----------|----------------|----------------|
| HRR at $-3^{/9.8}$CA (J/S) | 263.56 | 250.63 | 263.37 |
| Soot emission at $13^{/9.8}$CA (mg) | 3.68 | 3.70 | 3.66 |
| NO$_x$ emission at $50^{/9.8}$CA (mg) | 5.02 | 5.05 | 4.99 |
| NO$_x$ emission at $50^{/9.8}$CA (g/kW·h) | 7.46 | 7.01 | 7.05 |

HRR: heat release rate.

Figure 13. The comparison of penetration length under different gravity.

Figure 12. The comparison of SMD under different gravity.

Table 4. Comparison of parameters under different gravity.

Conclusion

In this article, experimental data are used to calibrate and validate the CFD model. Cylinder pressure, HRR, and NO$_x$ emissions are well consistent with
Figure 14. The equivalent ratio in different crank angle under different gravity.

Figure 15. The temperature in different crank angle under different gravity.
experimental data. Based on this CFD model, the simulation results of three gravity models are analyzed. The effects of performance and emissions on four-stroke marine diesel engines are investigated, which leads to the following results:

a. The validity of the model has been confirmed. There is almost no error in the cylinder pressure, and the NO\textsubscript{x} emission error is 1.84%. The HRR in the absence of wall heat transfer is different from the experimental value by \(-10.58\%\), and the difference of HRR after consideration given to the wall heat dissipation value is 5.82% compared to the experimental value. In the process of CFD simulation, the correction of HRR is vitally important.

b. Gravity conditions have little effect on HRR, and soot production is basically irrelevant to gravity. The effect of gravity on the NO\textsubscript{x} emissions of marine diesel engines can be maximized to 6.03%. The contours of temperature and NO\textsubscript{x} emission are different for different gravity. This can explain the different results for marine diesel engine emission characteristics under different gravity.

c. Under three gravity models, there are differences observed in fuel atomization and spray. SMD fluctuates considerably after the process of combustion starts. This tends to be affected by the evaporation rate of the fuel droplets and in-cylinder temperature. PL is proportional to the gravity, which is because the natural convection almost disappears with the disappearance of gravity. Moreover, turbulence intensity in the cylinder will be reduced.

d. Due to the difference in fuel spray and atomization, the equivalence ratio distribution is different which is the range of equivalence ratio distribution under non-gravity conditions is smaller. The temperature field remains distributed in line with the contour of the equivalence ratio. NO\textsubscript{x} is generated in high temperature and oxygen-rich regions, and the difference in temperature and equivalence ratio is also contributory to the difference in NO\textsubscript{x} distribution in the absence of gravity conditions.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.
Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors thank Natural Science Foundation Committee of China (No. 51709163), China Postdoctoral Science Foundation (No. 2018T110382), Shanghai Sailing Program (No. 17YF1407500), for the financial support.

ORCID iD
Peng Geng https://orcid.org/0000-0002-1703-5715

References
1. International Maritime Organization. Report of the Marine Environment Protection Committee on its fifty-eighth session—Revised NOx Technical Code. Technical Report, 17 October 2008. London: International Maritime Organization.
2. Blasco J, Durán-Grados V, Hampel M, et al. Towards an integrated environmental risk assessment of emissions from ships’ propulsion systems. Env Int 2014; 66: 44–47.
3. Raptotasios SI, Sakellaris NF, Papagiannakis RG, et al. Application of a multi-zone combustion model to investigate the NOx reduction potential of two-stroke marine diesel engines using EGR. Appl Energy 2015; 157: 814–823.
4. Abagnale C, Cameretti MC, De Simio L, et al. Numerical simulation and experimental test of dual fuel operated diesel engines. Appl Ther Eng 2014; 65: 403–417.
5. Geng P, Cao E, Tan Q, et al. Effects of alternative fuels on the combustion characteristics and emission products from diesel engines: a review. Renew Sustain Energy Rev 2017; 71: 523–534.
6. Lorenz H. Trägheitskraft an frei fallenden Docht flammen. Phys Zeitschr 1934; 25: 529–530.
7. Zhang X. Research advances on microgravity combustion. Adv Mech 2004; 4: 507–528.
8. Kumagai S and Isoda H. Combustion of fuel droplets in a falling chamber. Symposium on Combustion 1956; 6: 726–731.
9. Cochran TH. Combustion experiments in a zero-gravity laboratory. New York: AIAA, 1981, 73 pp.
10. Berlad AL, Huggett C, Kaufman F, et al. Study of combustion experiments in space. NASA-CR-134744, 1974, https://ntrs.nasa.gov/search.jsp?R=19750010196&h=Study+combustion+experiments+space&q=N%3D0%26Nt%3DAll%26Nt%3DSkylab%2520experiment%2520M479%2520zero%2520gravity%2520flammmability
11. NASA, 2015, https://spaceflightsystems.grc.nasa.gov/SOPO/ICHO/IRP/MSG/BASS/NASA
12. Ramachandra PA, Altenkirch RA, Bhattacharjee S, et al. The behavior of flames spreading over thin solids in microgravity. Combust Flame 1995; 100: 71–84.
13. Egorow SD, Yu BA, Klimin LP, et al. Fire safety experiments on MIR orbital station. NASA, CP-10174, 1995, pp.195–199. https://ntrs.nasa.gov/search.jsp?R=19960008416
14. Ito K and Fujita O. Research of ignition and flame spread of solid materials in Japan. NASA, CP-10174.1995, 201–206. https://ntrs.nasa.gov/search.jsp?R=19960008417
15. Kaldeich B. Combustion experiments during KC-135 parabolic flights. Patent 1113-SP, ESA, 1989.
16. Coward HF and Jones GW. Limits of flammability of gases and vapors. Washington, DC: US Bureau of Mines (Bulletin 627), 1952.
17. Zhang L and Liu Y. Research status and outlook of microgravity combustion in space station. Mann Spacefi 2015; 21: 603–610.
18. Zhang X and Hu W. The fire safety problems of manned spacecraft. Mann Spacefi 2006; 12: 5–11.
19. Friedman R, Gokoglu SA and Urban DL. Microgravity combustion research: 1999 program and results. Greenbelt, MD: NASA, 1999.
20. Hu W. Microgravity science and application. Bull Chin Acad Sci 1990; 2: 95–100.
21. Sun X, Liang X, Shu G, et al. Effect of different combustion models and alternative fuels on two-stroke marine diesel engine performance. Appl Ther Eng 2017; 115: 597–606.
22. Heywood JB. Internal combustion engine fundamentals. 2nd Edition. McGraw Hill, 2018, pp.18–21.
23. Zhou X, Li T, Lai Z, et al. Modeling diesel spray tip and tail penetrations after end-of-injection. Fuel 2019; 225: 358–369.
24. Zhou X, Li T, Lai Z, et al. Similarity of split-injected fuel conditions. Energy Conv Manag 2018; 220: 654–670.
25. Zhou X, Li T, Wei Y, et al. Scaling spray combustion processes in marine low-speed diesel engines. Fuel 2019; 258: 116133.
31. Duan J, Liu F, Yang Z, et al. Study on the NOx emissions mechanism of an HICE under high load. *Int J Hydro Energy* 2017; 42: 22027–22035.

32. Vuilleumier D, Taritas I, Wolk B, et al. Multi-level computational exploration of advanced combustion engine operating strategies. *Appl Energy* 2016; 184: 1273–1283.

33. Li Y, Li H, Guo H, et al. A numerical investigation on methane combustion and emissions from a natural gas-diesel dual fuel engine using CFD model. *Appl Energy* 2017; 205: 153–162.

34. Poorghasemi K, Saray RK, Ansari E, et al. Effect of diesel injection strategies on natural gas/diesel RCCI combustion characteristics in a light duty diesel engine. *Appl Energy* 2017; 199: 430–446.

35. Li Y, Li H and Guo H. A numerical investigation on NO2 formation reaction pathway in a natural gas-diesel dual fuel engine. *Combust Flame* 2018; 190: 337–348.

36. Prakash Duvvuri P, Sukumaran S, Kumar Shrivastava R, et al. Modeling soot particle size distribution in diesel engines. *Fuel* 2019; 243: 70–78.

37. Zhu H and Duan J. Research on emission characteristics of hydrogen fuel internal combustion engine based on more detailed mechanism. *Int J Hydro Energy* 2019; 44: 5592–5598.

38. Rahimi Boldaji M, Gainey B and Lawler B. Thermally stratified compression ignition enabled by wet ethanol with a split injection strategy: a CFD simulation study. *Appl Energy* 2019; 235: 813–826.

39. CONVERGE_2.4_Manual. Chapter 12 (Discrete Phase Modeling), Convergent Science, 318–322.

40. Zhou S, Gao R, Feng Y, et al. Evaluation of Miller Cycle and fuel injection—direction strategies for low NOx emission in marine two-stroke engine. *Int J Hydro Energy* 2017; 42: 20351–20360.

41. Pang KM, Karvounis N, Walther JH, et al. Numerical investigation of soot formation and oxidation processes under large two-stroke marine diesel engine-like conditions using integrated CFD-chemical kinetics. *Appl Energy* 2016; 169: 874–887.

42. Thangaraja J and Kannan C. Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels—a review. *Appl Energy* 2016; 180: 169–184.

43. Chen W, Shuai S and Wang J. A soot formation embedded reduced reaction mechanism for diesel surrogate fuel. *Fuel* 2009; 88: 1927–1936.

44. Maroteaux F and Noel L. Development of a reduced n-heptane oxidation mechanism for HCCI combustion modeling. *Combust Flame* 2006; 146: 246–267.

45. Stratsianis V, Kontoulis P and Kaiktsis L. Effects of fuel post-injection on the performance and pollutant emissions of a large marine engine. *J Energy Eng* 2016; 142: e4016001.

46. Struckmeier D, Tsuru D, Kawauchi S, et al. Multi-component modeling of evaporation, ignition and combustion processes of heavy residual fuel oil. *SAE Technical Paper* 2009-01-2677, 2009.

47. Liu X, Wang H, Wang X, et al. Experimental and modeling investigations of the diesel surrogate fuels in direct injection compression ignition combustion. *Appl Energy* 2017; 189: 187–200.

48. Ra Y and Reitz RD. A combustion model for IC engine combustion simulations with multi-component fuels. *Combust Flame* 2011; 158: 69–90.

49. Hiroyasu H and Kadota T. Models for combustion and formation of nitric oxide and soot in direct injection diesel engines. *SAE Technical Paper* 760129, 1976.

50. Heywood JB. Experimental and theoretical study of nitric oxide formation in internal combustion engines. *Combust Sci Techno* 1970; 1: 313–326.

51. Lamas MI, de Dios Rodriguez J, Castro-Santos L, et al. Effect of multiple injection strategies on emissions and performance in the Wärtsilä 6L 46 marine engine. A numerical approach. *J Clean Prod* 2019; 206: 1–10.

52. Mugele R and Evans HD. Droplet size distributions in sprays. *Ind Eng Chem* 1951; 43: 1371–1324.

53. Li W, Wu K, Zhang Y, et al. Comparative study on micro-spray characteristics of diesel and biodiesel. *Automob Appl Techno* 2017; 18: 4–6.