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Review

Strategies to Reduce Emissions from Diesel Engines under Cold Start Conditions: A Review

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Abstract: Reducing diesel engine emissions under cold start conditions has become much more valuable as environmental issues become more important. Regarding diesel engine emissions under cold start conditions, this review summarizes the emission mechanisms and specifically focuses on the research progress of four reduction strategies: biodiesel utilization, intake heating, injection optimization, and aftertreatment technologies. In general, adding biodiesel and Di-Ethyl-Ether (DEE) could provide the benefit of reducing emissions and maintaining engine performance. Intake heating and appropriate injection strategies could also effectively reduce emissions under cold start conditions. Unlike normal operating conditions, lean nitrogen oxide traps (LNT) or electrically heated catalysts (EHC) should be utilized in the aftertreatment of diesel engines to minimize emissions under cold start conditions. By offering the valuable information above, this review could be a helpful reference in reduction strategies for diesel engines under cold start conditions in both academia and industry.

Keywords: cold start; diesel engine; emissions; reduction strategies; aftertreatment technology

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1. Introduction

Over the past few decades, energy efficiency and pollution prevention have become global focuses as environmental deterioration becomes more severe [1–4]. It is becoming increasingly critical to find effective strategies to minimize automobile emissions [5–7]. Although the market for electric vehicles is expected to grow, several factors, such as high cost, limited charging stations, and short cruising range, still prevent many people from adopting these technologies. Meanwhile, because of the features in excellent efficiency and durability, diesel engines are still widely used and have become a major source of energy consumption and environmental pollution today [8,9]. Hence, the engine cold start condition, closely related to a series of emission problems, has attracted much attention from scholars [10,11].

For diesel vehicles, a large number of nitrogen oxides (NO_X), hydrocarbons (HC), and carbon monoxide (CO) emissions will be generated during start-up, so auxiliary power units (APU), direct combustion heaters, and other components are usually increased to reduce the time and space transfer time of diesel engine start-up and reduce emissions during the start-up process [12].

The diesel engine's temperature is consistent with the ambient temperature during cold starts. Incomplete combustion is unavoidable due to the relatively low temperature of the in-cylinder air–fuel mixer [13–16]. In the meantime, the low oil temperature will generally result in inadequate lubrication between the engine block parts [17]. Zare et al. [18] compared the emissions between cold and hot (starting after the engine was preheated) start conditions from a turbocharged six-cylinder diesel engine fueled with oxygen-containing fuel. The results indicated that a cold start produces roughly twice as much nitrogen oxide and five times as much particulate matter (PM) 2.5 as a hot start. Pacaud et al. [19] found

that as ambient temperature increases from −2 °C to 32 °C, the CO and HC emitted by a diesel engine could decrease by 87.5% and 75%, respectively. Tang et al. [20] found that the emissions of heavy vehicles were relatively high during cold starts. NO_X emissions, in particular, could account for 40% to 90% of the total engine working process during a cold start. Feng et al. [21] demonstrated that the aftertreatment system performance of a diesel engine could be adversely affected under cold start conditions. It showed that the conversion efficiency of CO, HC, and NO_X were 63%, 79%, and 86% under cold start conditions, about 10% to 16% lower than the hot start. Deng et al. [22] comprehensively considered low temperature, air pressure, and preheating; simulated the operation of a specific diesel engine in a low-temperature environment; and conducted an outdoor vehicle experiment to verify the results. The results showed that when the temperature was reduced by 9.5 °C, the cold start time of the diesel engine increased by 1.67 s, and the overall pollutant emissions also increased.

With the increasing strictness of diesel emission laws and regulations worldwide, reducing diesel engine emissions under cold start conditions is of great significance. For example, the European emission standards for diesel engines are shown in Table 1 [23]. Compared with the Euro 3 emission standards for passenger cars, the Euro 6 emission standards put forward higher standards for the HC and NO_X emissions of diesel engines. In particular, the NO_X emission limit decreased by 64% from the original 0.50 g/km to 0.08 g/km. PM emission limits decreased from 0.50 g/km to 0.05 g/km, with a 90% decrease. Furthermore, Europe replaced the previous New European Driving Cycle (NEDC) test with the World Light vehicle Test Cycle (WLTC). It began phasing in Real Drive Emission (RDE) test requirements in 2017 to limit emissions from measurements in actual use.

Table 1. EU emission standards for vehicles with compression ignition engines [23] (Reprinted with permission from Ref. [23]. Copyright 2022 DieselNet).

Stage	Date	CO	HC + NO_X	NO_X	PM	PN
		g/km				#/km
Euro 1 †	1992.07	2.72 (3.16)	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	0.7	-	0.08	-
Euro 2, DI	1996.01	1.0	0.9	-	0.10	-
Euro 3	2000.01	0.64	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	0.30	0.25	0.025	-
Euro 5a	2009.09	0.50	0.23	0.18	0.005	-
Euro 5b	2011.09	0.50	0.23	0.18	0.005	6.0×10^{11}
Euro 6	2014.09	0.50	0.17	0.08	0.005	6.0×10^{11}

†: Values in brackets are conformity of production limits.

Furthermore, China's emission requirements for new passenger cars and light-duty commercial vehicles have been revised to China 6 norms. Tables 2 and 3 illustrate the emission restrictions for China 3 to China 5 and China 6 [24]. Among these, the China 6 emission standards were proposed in 2016 and implemented in 2021, aiming to reduce HC by 50%, NO_X by 40%, and PM by 33% compared with Euro 6. Compared with the China 3 standard implemented in 2007, the NO_X emission limits of China 6b standards Class I, Class II, and Class III decreased from 0.50 g/km, 0.65 g/km, and 0.78 g/km to 0.035 g/km, 0.045 g/km, and 0.050 g/km, respectively. Starting in July 2023 (China 6b's implementation date), RDE compliance rules apply to compression ignition engines accompanying updated NO_X and PN limitations. Moreover, a conformance factor of emission restrictions applies to both the urban portion of the journey and the overall trip. RDE data must be observed and recorded before July 2023.

Table 2. China 3 to China 5 emission standards for vehicles with compression ignition engines [24] (Reprinted with permission from Ref. [24]. Copyright 2023 DieselNet).

Stage	Category	Class	CO	HC + NO_X	NO_X	PM	PN
			g/km				#/km
China 3	Type 1		0.64	0.56	0.50	0.050	
	Type 2	I	0.64	0.56	0.50	0.050	
		II	0.80	0.72	0.65	0.070	
		III	0.95	0.86	0.78	0.100	
China 4	Type 1		0.50	0.30	0.25	0.025	
	Type 2	I	0.50	0.30	0.25	0.025	
		II	0.63	0.39	0.33	0.040	
		III	0.74	0.46	0.39	0.060	
China 5	Type 1		0.50	0.230	0.180	0.0045	6×10^{11}
	Type 2	I	0.50	0.230	0.180	0.0045	6×10^{11}
		II	0.63	0.295	0.235	0.0045	6×10^{11}
		III	0.74	0.350	0.280	0.0045	6×10^{11}

Table 3. China 6 emission standards [24] (Reprinted with permission from Ref. [24]. Copyright 2023 DieselNet.)

Stage	Category	Class	CO	HC	NMHC	NO_X	N_2O	PM	PN
			g/km						#/km
China 6a	Type 1		0.700	0.100	0.068	0.060	0.020	0.0045	6×10^{11}
	Type 2	I	0.700	0.100	0.068	0.060	0.020	0.0045	6×10^{11}
		II	0.880	0.130	0.090	0.075	0.025	0.0045	6×10^{11}
		III	1.000	0.160	0.108	0.082	0.030	0.0045	6×10^{11}
China 6b	Type 1		0.500	0.050	0.035	0.035	0.020	0.0030	6×10^{11}
	Type 2	I	0.500	0.050	0.035	0.035	0.020	0.0030	6×10^{11}
		II	0.630	0.065	0.045	0.045	0.025	0.0030	6×10^{11}
		III	0.740	0.080	0.055	0.050	0.030	0.0030	6×10^{11}

The above findings show that the emissions will be much higher during cold starts. Moreover, it is more urgent to reduce pollutant emissions to meet the increasingly stringent regulations for diesel engines worldwide. Therefore, it is significant to implement effective strategies to minimize diesel engine emissions under cold start conditions [25–27]. The rest of the paper is organized around this theme, as follows: The emission processes are introduced in Section 2. Section 3 mainly introduces the reduction strategies. Section 4 presents the conclusions and further scope. This paper could provide valuable insights into strategies to minimize diesel engine emissions under cold start conditions and would also be a helpful reference for the future development of diesel engine research in both academia and industry.

2. Emission Mechanisms under Cold Start Conditions

Changes in the quality of the air–fuel mixture, combustion, and other factors lead to a decrease in diesel engine emissions under cold start conditions compared to normal operating situations [28–30].

In general, obtaining a homogeneous air–fuel mixture during cold start conditions is more difficult since it is challenging to atomize and evaporate the fuel with a low intake temperature, which would likely result in incomplete combustion [31]. In addition, under cold start conditions, the viscosity the lubricating oil could be greatly increased, leading to a deterioration in the thermal efficiency and the wear of engine components. In detail, under cold start conditions, the basic mechanisms for the main kinds of emissions, such as NO_X, CO, HC, and PM, are described as follows.

The NO_X emissions from diesel engines mainly comprise NO and NO_2 [32]. During the combustion process, the major source of NO is the oxidation of nitrogen elements, the relevant chemical formulas of which are shown in Equations (1)–(3):

$$N_2 + O = NO + N \quad (1)$$

$$N + O_2 = NO + O \quad (2)$$

$$N + OH = NO + H \quad (3)$$

In addition, NO_2 roughly occupies 10% to 30% of the total NO_X emitted by diesel engines. Equation (4) presents the rapid conversion to NO_2 after NO forms in the engine combustion chamber. In the meantime, NO can be produced by Equation (5) if no cooler fluids are present to stop the chemical reaction [33,34]. Hence, for the cold start process of a diesel engine, a part of the generated NO_2 could be eliminated due to the low intake temperature and would be less likely to be converted into NO again. Therefore, the ratio of NO_2 to NO would be significantly higher than that of normal engine operating conditions.

$$NO + HO_2 \rightarrow NO_2 + OH \quad (4)$$

$$NO_2 + O \rightarrow NO + O_2 \quad (5)$$

Regarding the mechanism of CO emissions from diesel engines, it is closely related to some typical chemical reactions in hydrocarbon combustion, as presented in Equation (6). Here, R denotes the hydrocarbon radical.

$$RH \rightarrow R \rightarrow RO_2 \rightarrow RCHO \rightarrow RCO \rightarrow CO \quad (6)$$

Afterwards, CO could be oxidized to CO_2 by the reaction shown in Equation (7). Moreover, as shown in Equation (8), the oxidation reaction rate is related to a factor k^+_{CO}. Hence, it should be noted that under cold start conditions, k^+_{CO} would be smaller due to a lower T, which makes the rate of CO oxidation slower. Consequently, the diesel engine cold start stage will have higher CO emissions.

$$CO + OH = CO_2 + H \quad (7)$$

$$k^+_{CO} = 6.76 \times 10^{10} \exp\left(\frac{T}{1102}\right) \mathrm{cm}^3/\mathrm{gmol} \quad (8)$$

Regarding the mechanism of HC emissions, the fuel spray undergoes a substantial pyrolysis of its compounds. Hence, the diesel engine exhaust contains a complicated mixture of unburned and partially oxidized HC [35,36]. Under cold start conditions, HC emissions would increase significantly, which can be attributed to two main reasons. First, the inhomogeneous air–fuel mixture would worsen HC emissions because some fuel remains in the injector-nozzle sac volume, escaping combustion. Second, a lower cylinder wall temperature would also enhance HC emissions due to wall quenching during the combustion under cold start conditions.

PM is typically regarded as another primary emission and is a severe issue for diesel engines, mainly composed of dry soluble organic fraction, soot and sulfate [37]. During engine operation, a small amount of fuel remains unburned and easily condenses, producing various PM sizes. Especially under cold start conditions, insufficient fuel combustion will be more frequent and greatly promote PM formation due to low intake temperature. Verma et al. [38] investigated the formation of PM during cold and hot starts of a diesel engine. It was found that the size of primary PM was reduced by 2.1~6.5% under cold start conditions, which may be due to the fast oxidation rate of particulate matter during cold starts, thus inhibiting the surface growth of particulate matter.

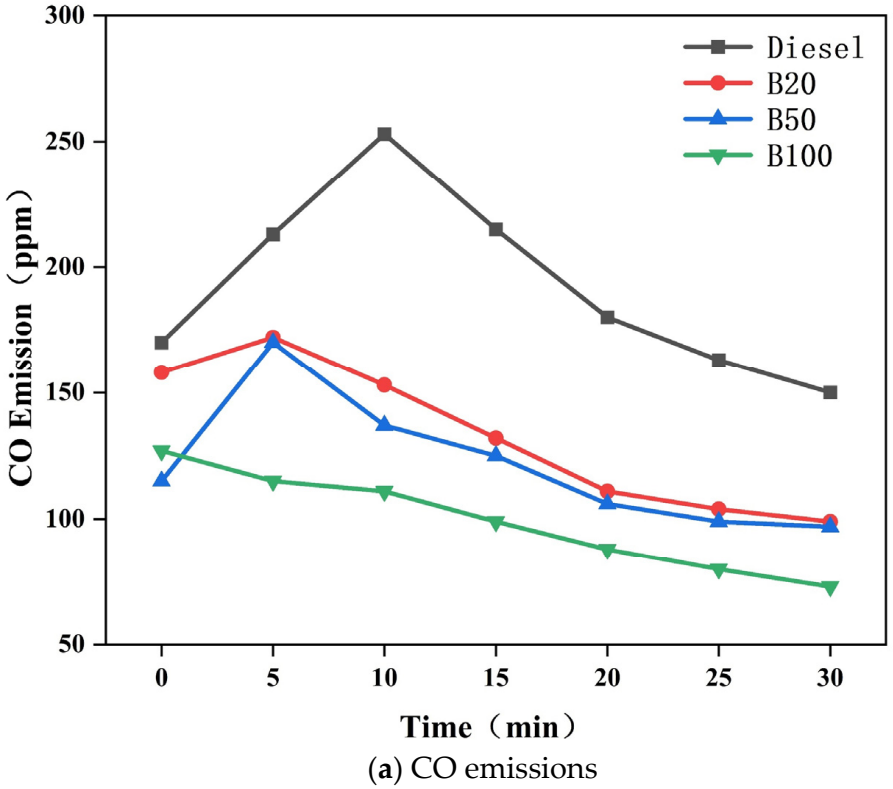
3. Emission Reduction Strategies

Based on the existing research, the emission reduction strategies of diesel engines under cold start conditions mainly include the following four aspects: biodiesel utilization, intake heating, injection optimization, and aftertreatment technologies.

3.1. Biodiesel Utilization

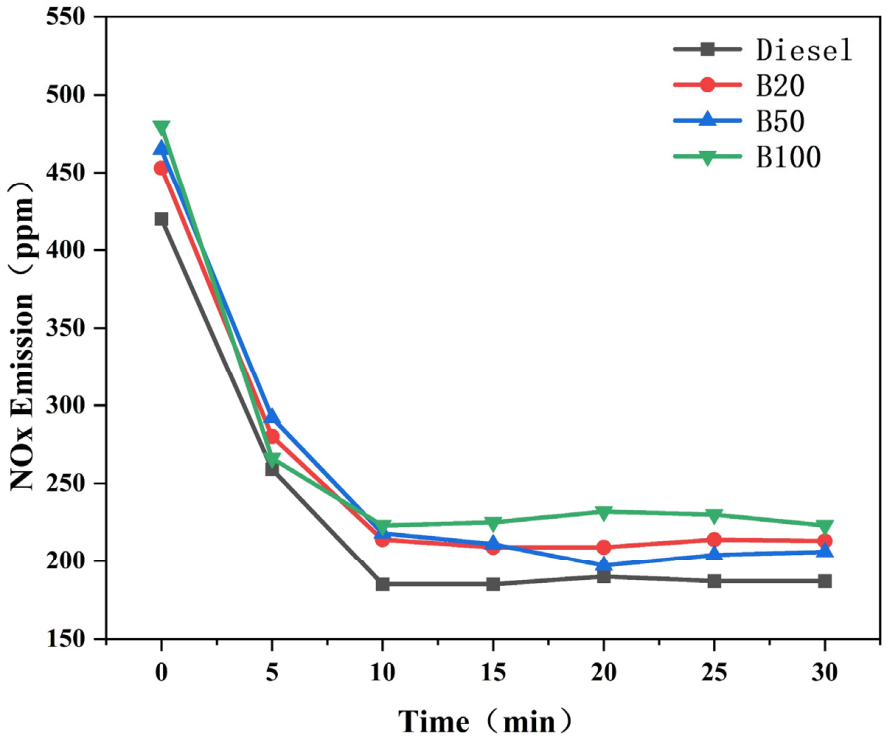
Due to biodiesel having lower sulfur and aromatic hydrocarbon contents than diesel, it has been a hot research topic in recent years with the potential to minimize harmful engine emissions [39]. Furthermore, biodiesel can be mixed with diesel and used in diesel engines in any proportion. Although biodiesel might cause a small problem in liquidity under low-temperature conditions, it is still a good choice for reducing emissions under cold start conditions of diesel engines [40,41].

Many researchers have conducted emission experiments using biodiesel on different types of diesel engines during the cold start stage. Roy et al. [42] analyzed the characteristics of CO, NO_X, and HC emissions on a four-cylinder diesel engine running on diesel, biodiesel (B100), and diesel–biodiesel blends (B20, B50) under five-minute cold start circumstances at 1000 rpm. As illustrated in Figure 1, CO emission using B100 has a considerable reduction compared to pure diesel, which can be linked to the cold flow properties of biodiesel. However, biodiesel is an oxygen-containing fuel with a high oxygen concentration in the combustion area of the cylinder chamber, which could cause early heat release time and the early formation of nitrogen oxides in the cylinder. Hence, no remarkable difference can be found in the emissions of NO_X and HC by fueling with pure diesel and biodiesel.

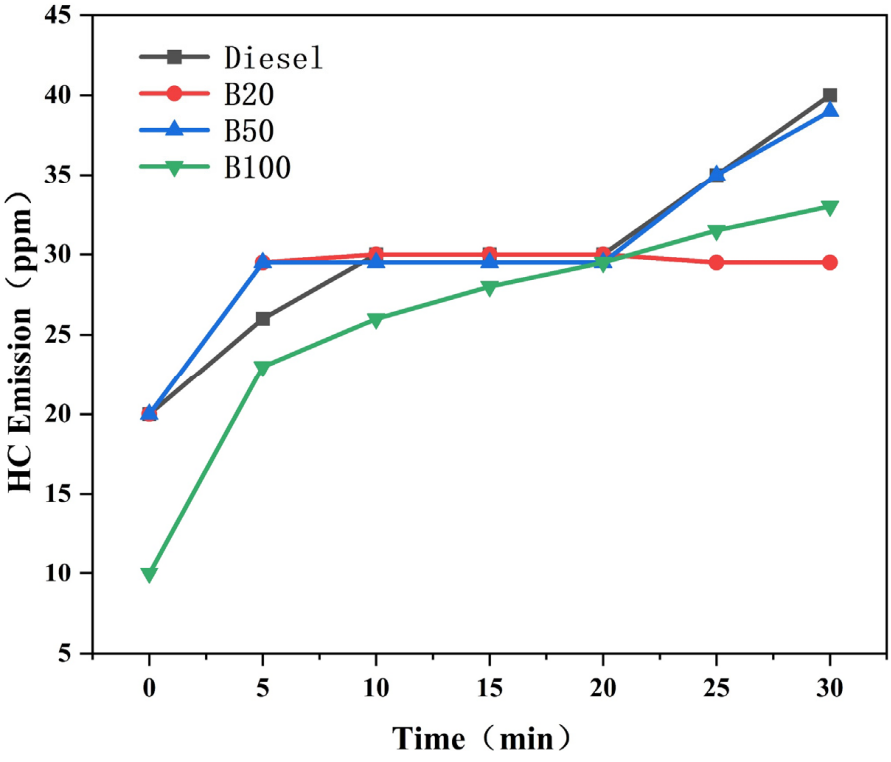


(**a**) CO emissions

Figure 1. *Cont.*



(**b**) NOx emissions

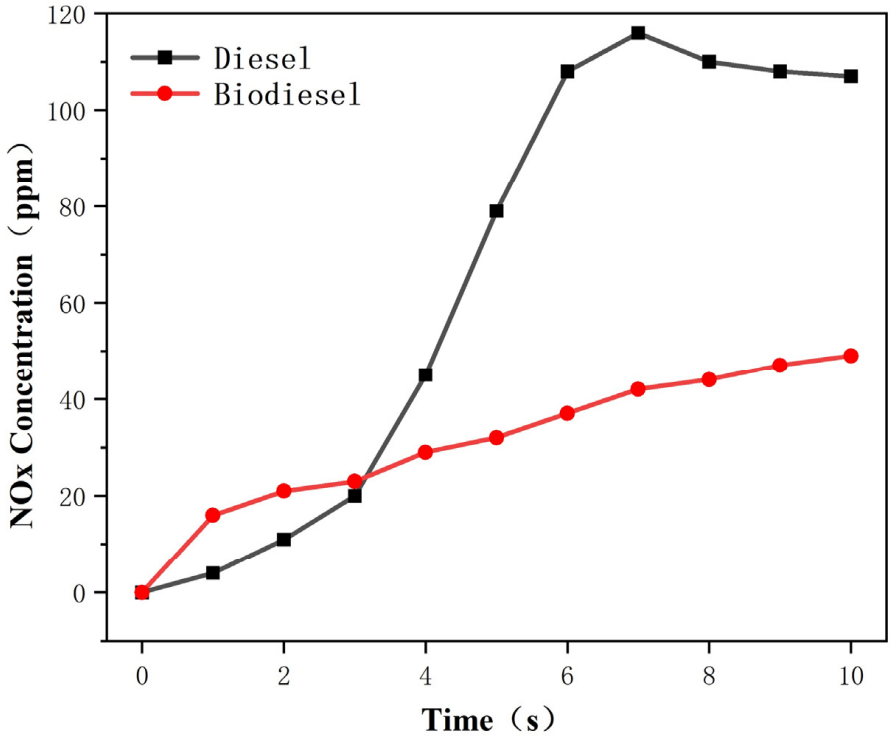


(**c**) HC emissions

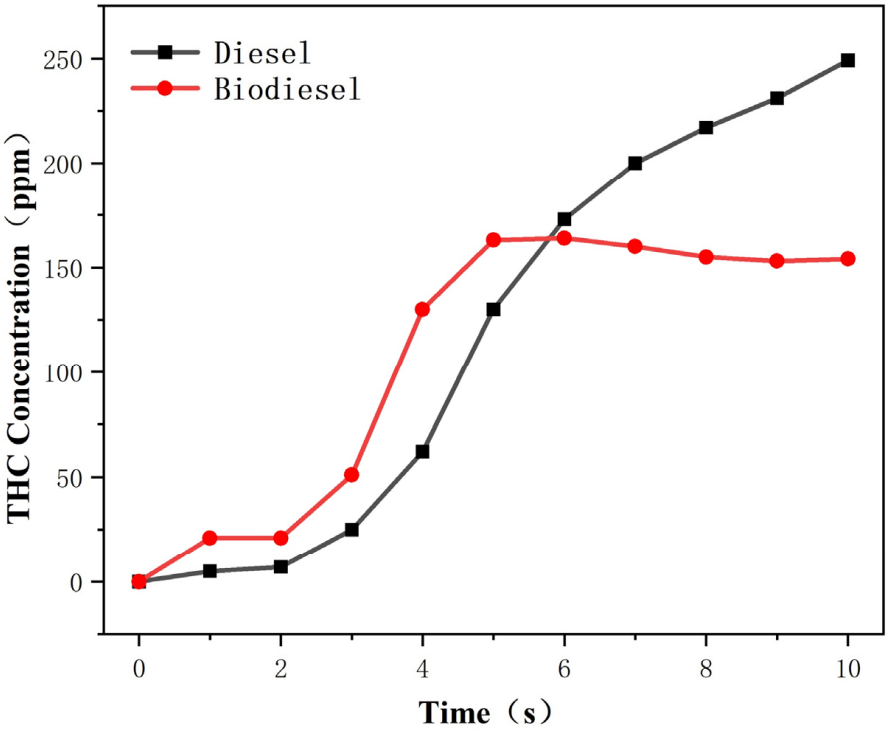
Figure 1. CO, NO_X, and HC emissions over warm-up from cold start [42] (Adapted with permission from Ref. [42]. Copyright 2016 Elsevier).

Armas et al. [43] investigated the cold start transient emissions of a turbocharged direct injection diesel engine with a common rail system and an exhaust gas recirculation system, utilizing animal fat biodiesel and conventional diesel (biodiesel accounting for 5.83%).

Figure 2 describes the instantaneous emissions of NO_X, THC, and CO in the transient process of the cold start. It shows that the instantaneous NO_X emission of biodiesel is continuously lower than that of conventional diesel within 10 s after starting the diesel engine, while THC and CO emissions begin to be lower than that of conventional diesel around 6 s.

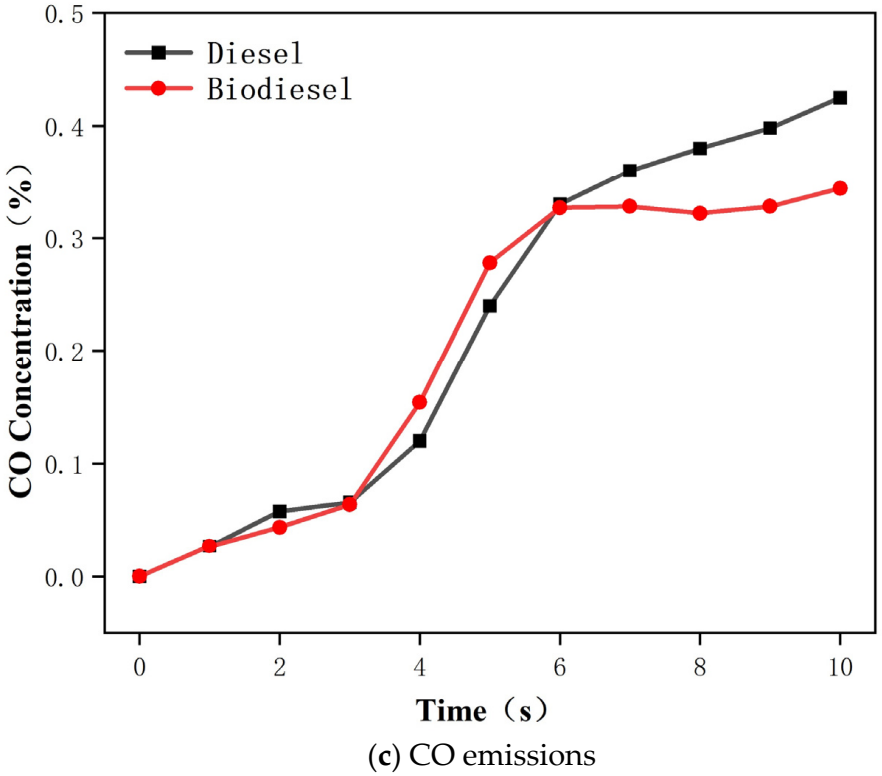


(**a**) NOx emissions



(**b**) THC emissions

Figure 2. *Cont.*



(**c**) CO emissions

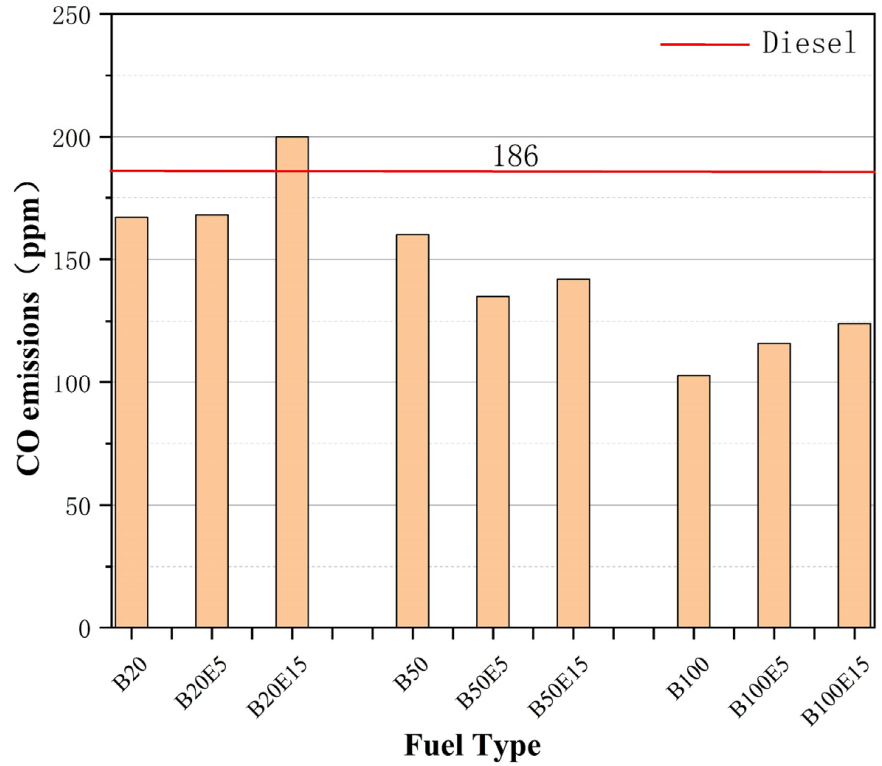
Figure 2. CO, NO_X, and HC emissions from a cold start [43] (Adapted with permission from Ref. [43]. Copyright 2013 Elsevier).

In addition, it should be noted that under cold start conditions, engine performance in terms of emission and combustion would be partially offset due to the high viscosity of biodiesel. Tinprabath et al. [44] studied the impact of cold circumstances on the properties of diesel, winter diesel, diesel–biodiesel blends, winter diesel–biodiesel blends, and pure biodiesel spray. The study indicated that the discharge coefficients would decrease by increasing the fraction of biodiesel in the fuel blends. Hence, some researchers demonstrated that using diesel–biodiesel blends and adding some other components is a practical solution to optimize the cold start performance of diesel engines.

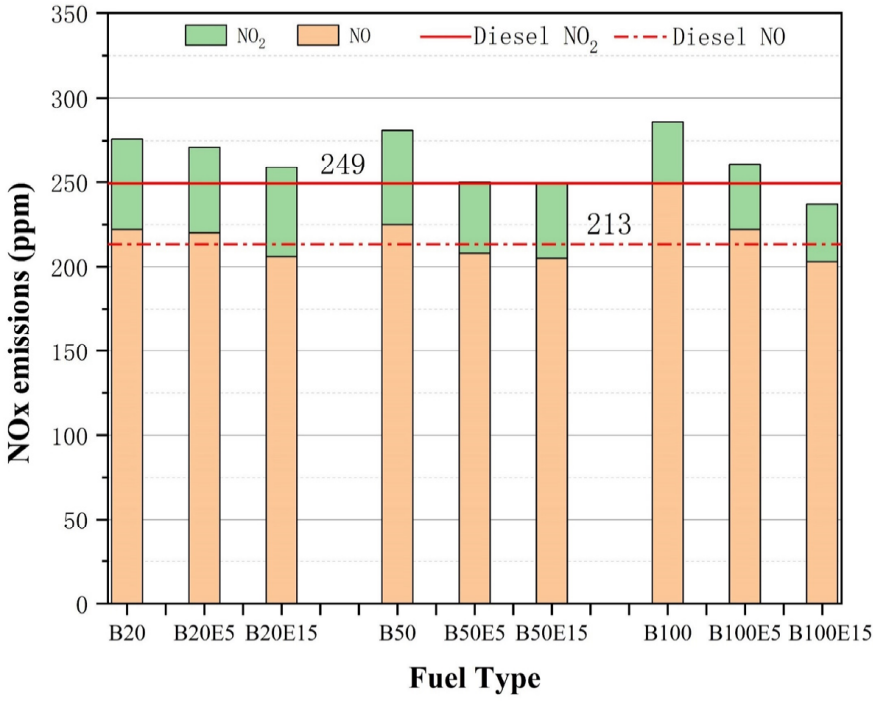
For instance, Clenci et al. [45] investigated the performance of diesel engines equipped with different proportions of diesel and biodiesel mixtures in a −20 °C cold start process. The experimental results showed that the start-up performance of diesel engines is significantly reduced. When the biodiesel ratio reaches 50%, the diesel engine cannot start properly, but it can be recovered by adding Di-Ethyl-Ether (DEE) to the fuel.

Pourhoseini et al. [46] took a single-bar, air-cooled, four-stroke direct injection diesel engine as the research object and optimized the cold flow performance of biodiesel by adding iron nanoparticles to B20. The experiment showed that when the engine starts at 0 °C, adding iron nanoparticles to biodiesel could reduce the viscosity of the mixed fuel by 14%. In the meantime, CO and HC emissions are reduced by 42% and 54%, respectively.

Roy et al. [42] optimized the emissions of a diesel engine during cold start by adding ethanol (5% and 15% by volume) to B20, B50, and B100 in the experiment. As shown in Figure 3, it is obvious that adding ethanol could greatly reduce HC emissions and partially lower NO_X emissions. However, it will deteriorate CO emissions, owing to the lower cetane number and the higher heat required for vaporization due to the addition of ethanol.

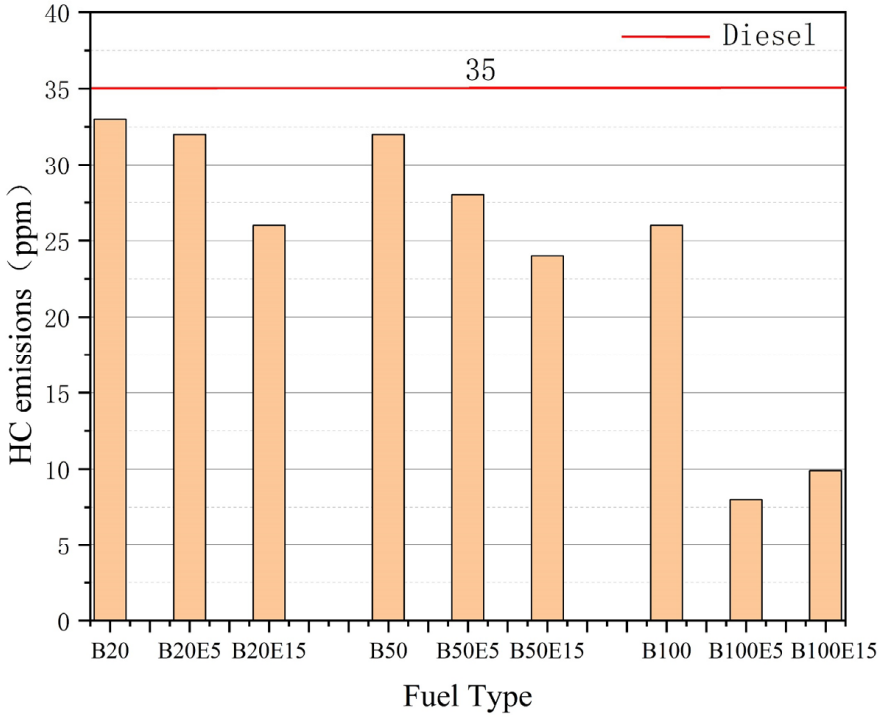


(**a**) CO emissions



(**b**) NOx emissions

Figure 3. *Cont*.



(**c**) HC emissions

Figure 3. CO, NO_X, and HC emissions in cold start after ethanol addition [42] (Adapted with permission from Ref. [42]. Copyright 2016 Elsevier).

Using an optical constant-volume chamber to record the chamber pressure, Xu et al. [47] measured the soot mass distribution of acetone–butanol–ethanol (ABE) and mixed diesel fuel. The experimental results showed that with the decrease in the initial ambient temperature, the soot generation gradually decreased due to the weakening of the combustion process. Huang et al. [48] studied the low-temperature combustion and emission characteristics of different fuels (D100, D70B30) under different exhaust gas recirculation (EGR) ratios from a small diesel engine. The experimental results showed that EGR had a significant impact on the cold start emission of biodiesel. When the EGR ratio is about 25%, the soot, NO_X, CO, and HC emissions from the combustion process of D70B30 reach their best states.

3.2. Intake Heating

The intake heating strategy is a feasible solution to reduce diesel engine emissions under cold start conditions. An appropriate intake temperature positively impacts diesel engine emissions under these conditions [49–51].

Glow plugs are often used as an auxiliary device for the cold start of small- and medium-sized diesel engines [52]. Broatch et al. [53] investigated a compact, cutting-edge, turbocharged DI diesel serial engine with an EGR cooler. For the measurement of gaseous emissions, a HORIBA 7100DEGR exhaust gas analyzer was used, which is shown in Figure 4. The experimental results showed that the heater plug could effectively increase the intake temperature and enhance the combustion process under cold start conditions. With the help of glow plugs, HC, CO, and NO_X emissions were significantly reduced, and PM was just slightly increased.

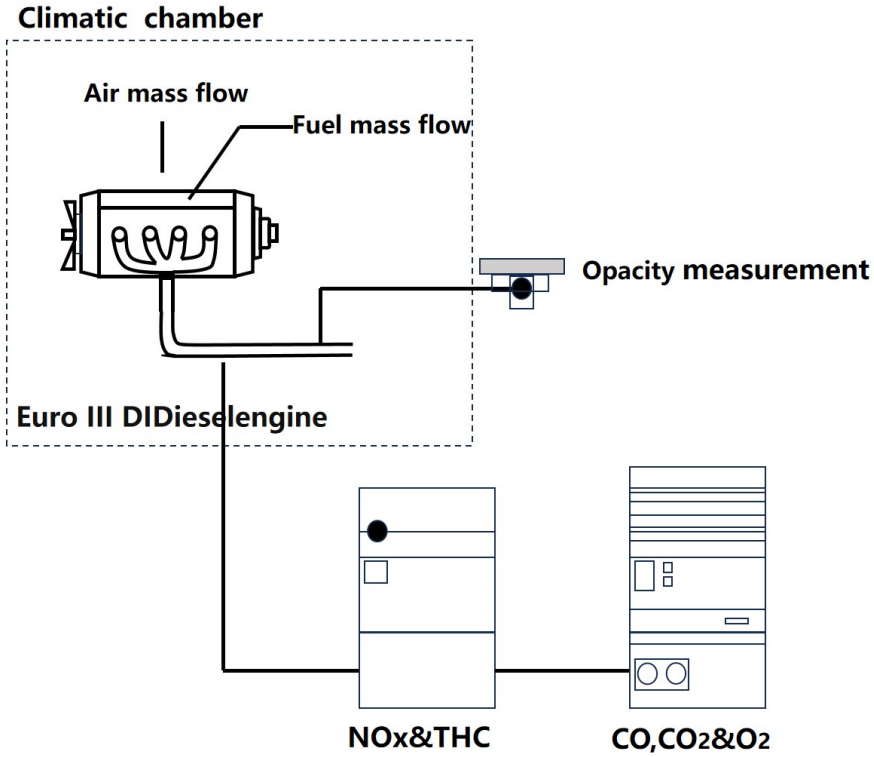


Figure 4. Exhaust gas measurement set up [53] (Adapted with permission from Ref. [53]. Copyright 2008 Elsevier).

Merkisz et al. [54] studied how intake heating affects diesel engine performance under cold start conditions by employing different lengths of glow plugs, as shown in Figure 5. It was found that HC and CO emissions will be significantly reduced after using glow plugs. Moreover, compared with the standard preheating plug, increasing the length of the preheating part by 4mm can reduce the amount of CO, HC, NO_X, and particulate matter emitted by 12.9%, 9.3%, 14.3%, and 9.8%, respectively, because with the increase in the glow plug length, the intake heating effect is further enhanced.

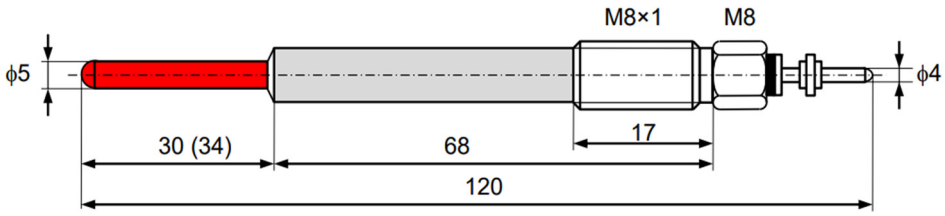
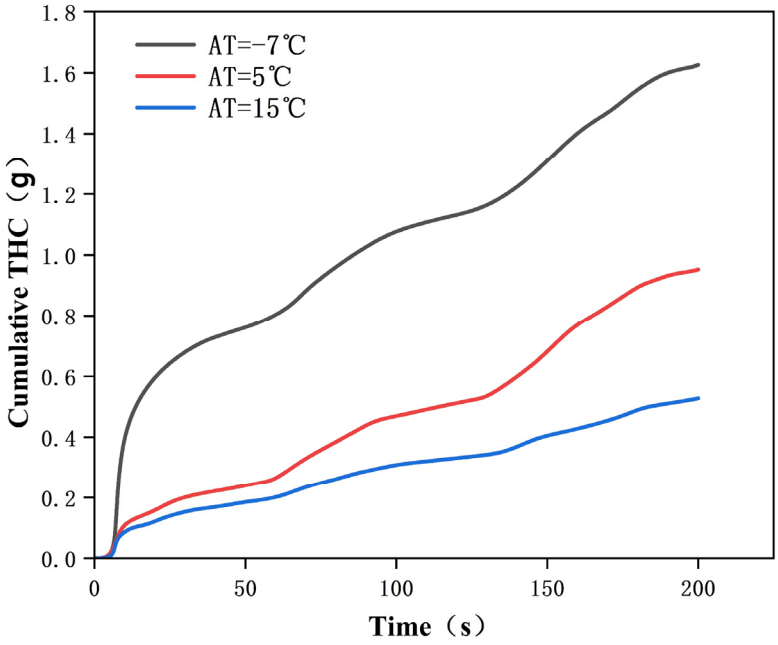


Figure 5. Dimensions of a standard glow plug [54]. Reprinted from Ref. [54].

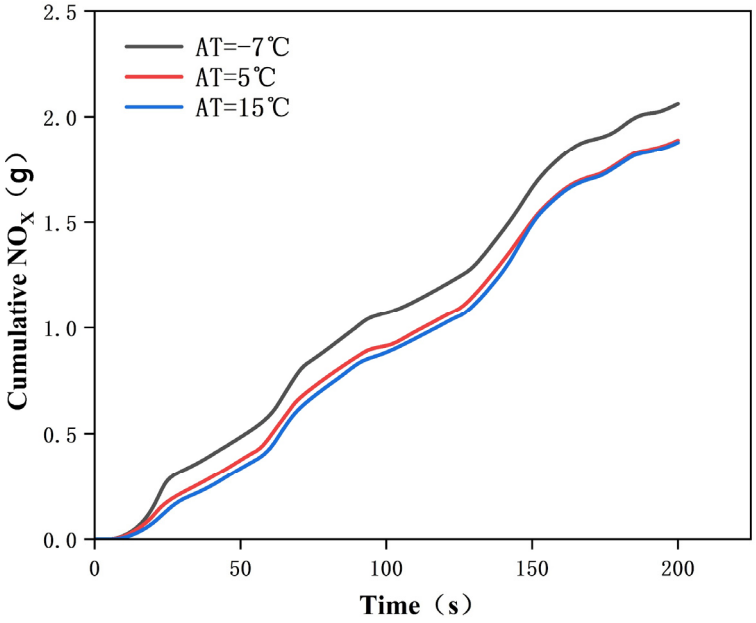
For large diesel engines, using an intake air-heater to increase the intake temperature is another practical way to control emissions under cold start conditions [55]. Vivegananth and Ramesh [56] proposed a method to improve the cold start capability of low-compression ratio diesel engines by recompressing the intake air. By pumping hot air into the intake manifold at the end of the compression stroke, the pressurization temperature increases, and the gas temperature becomes sufficient to meet the required combustion conditions. Ramadhas et al. [28] took a six-cylinder, turbocharged, common rail direct injection diesel engine and performed a cold start experiment at −20 °C. The intake temperature of the diesel engine could be increased by installing an intake heater between the intake manifold and the turbocharger. The experimental results showed that the cold start time of the diesel engine was shortened when the intake temperature increased to

5 °C. The emissions of NO, HC, and PM were reduced by more than 50% during idle operating conditions.

Ramadhas et al. [57] conducted an experiment on a turbocharged diesel engine under the condition of −7 °C. For intake heating, an intake air heater was connected between the intake manifold and the turbocharger. Figures 6–8 demonstrate that with the increase in the intake temperature from −7 °C to 15 °C, HC and NO_X emissions could be reduced by 55% and 10%, respectively. Heating the intake air may result in a significant decrease in PM concentration. The PM in the NEDC cycle could be lowered from 1/4 to 1/5 during the cold start-up stage.



(**a**) HC emissions



(**b**) NOx emissions

Figure 6. Cumulative emissions of HC and NO_X at different intake temperatures [57] (Adapted with permission from Ref. [57]. Copyright 2018 Taylor & Francis).

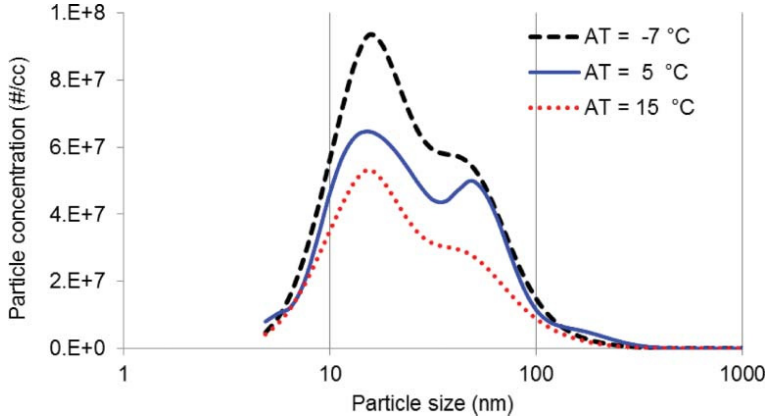


Figure 7. Size distribution of PM at different intake temperatures [57] (Reprinted with permission from Ref. [55]. Copyright 2018 Taylor & Francis).

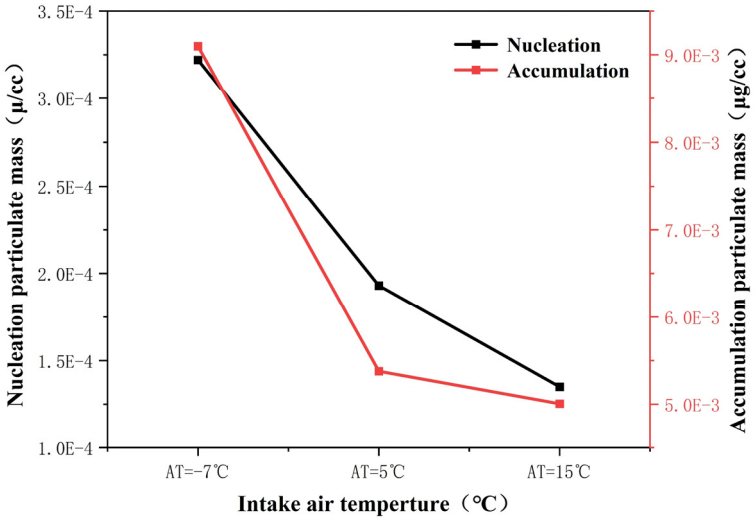


Figure 8. Mass of PM at different intake temperatures [57] (Adapted with permission from Ref. [57]. Copyright 2018 Taylor & Francis).

Kaltakkran et al. [58] proposed a technique for storing thermal energy with phase change materials (PCMs). Using coolant waste heat as the heat source, the latent and dominant warmth stored in the PCM is transferred to the diesel engine intake manifold, potentially raising the intake temperature at cold start. Under the condition of 6 °C, the experimental results showed that the cold start time was reduced by 68.2%. Meanwhile, CO and HC emissions could be reduced by 27.5% and 44%, respectively.

Lujan et al. [59] proposed a method to reduce diesel engine emissions during cold starts by recycling diesel exhaust preheating to increase intake air temperature. The experiment was carried out on a 2.0 L four-cylinder turbocharged diesel engine. By using high-pressure EGR connected to the intake manifold, the effect of intake heating is satisfied at an ambient temperature of −7 °C, the unburned HC is reduced by 65%, the CO is reduced by 10%, and the fuel consumption is reduced by 10% compared to the standard model. Similarly, Galindo et al. [60] used a low-pressure EGR to recover exhaust gas for intake heating in a Euro 6 turbocharged diesel engine at −7 °C. The results showed that the preheating time was reduced by about 60 s compared to a diesel engine without EGR. Moreover, the intake temperature was increased by about 30 °C, and the CO emissions were reduced by about 12%.

3.3. Injection Optimization

The diesel engine's emissions can also be reduced by adjusting the injection pressure, timing, and frequency to optimize fuel injection [61]. Therefore, an appropriate injection strategy would be essential under for diesel engines under cold start conditions. According to the study of Mohan et al. [62], enhanced fuel atomization and lower HC, CO, and PM emissions could be achieved by increasing the injection pressure from diesel engines during cold start conditions. Through experiments in a constant volume combustion chamber (CVCC), Yang et al. [63] demonstrated that injection pressure and flames can be successfully controlled with a slower start-up speed and a cool intake temperature.

Zare et al. [64] demonstrated that injection delay would cause a sharp decrease in NO_X during the cold start on a six-cylinder common rail engine. Liu et al. [65] studied an air-assisted, direct injection, two-stroke spark ignition diesel engine at a cold start of 9 °C. The HC emissions of the diesel engine could be significantly decreased by delaying the ignition period, as shown in Figure 9. Compared with the injection of 10 °CA, the HC emissions of the diesel engine are reduced by 34% at the 40 °CA injection condition. This is mainly because it is beneficial for the combination and evaporation between air and fuel by an appropriate injection timing, accelerating the preheating process to reduce emissions during cold start. Duan et al. [66] tested different ABE ratios on diesel engines to study the impact of fuel injection timing on diesel engine emissions. The results showed that the soot quality, CO, and HC of diesel engines all decreased, while NO_X emissions increased. This is because the advanced injection time increases the mixing time of fuel and fresh air, which is conducive to the formation and uniform distribution of the premix. Ge et al. [67] conducted experiments using different injection strategies under a common-rail, direct-injection diesel engine fueled with diesel and ethanol. By using a multiple-injection approach and adjusting the phase angle between the main injection and pre-injection, the results showed that the optimal injection strategy could reduce the emissions of NO_X and smoke by 32.32% and 46.88%, respectively.

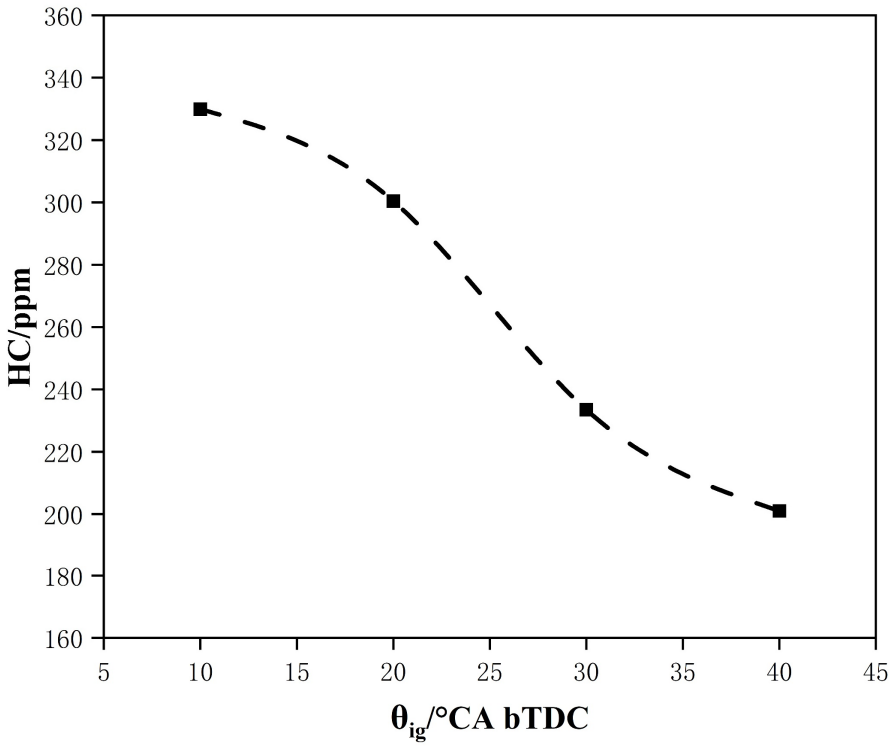
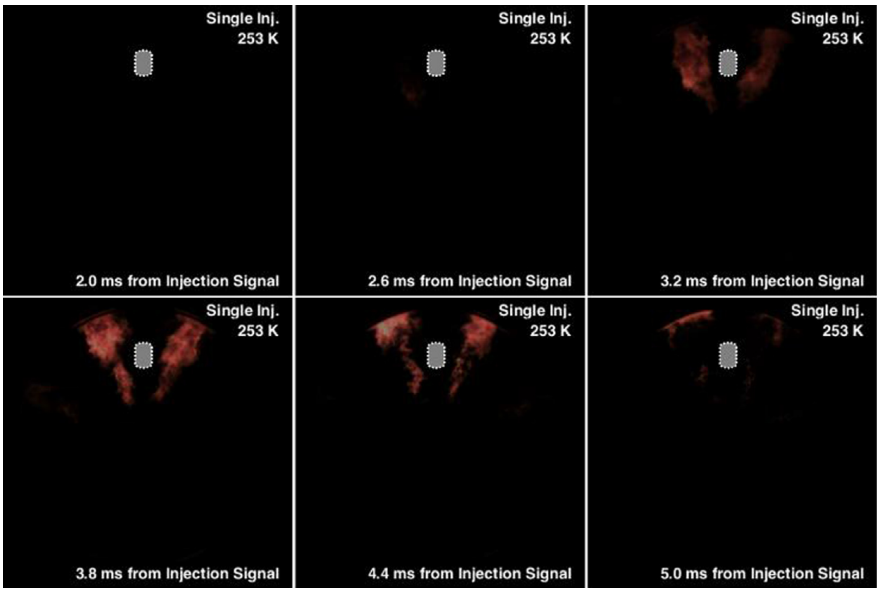
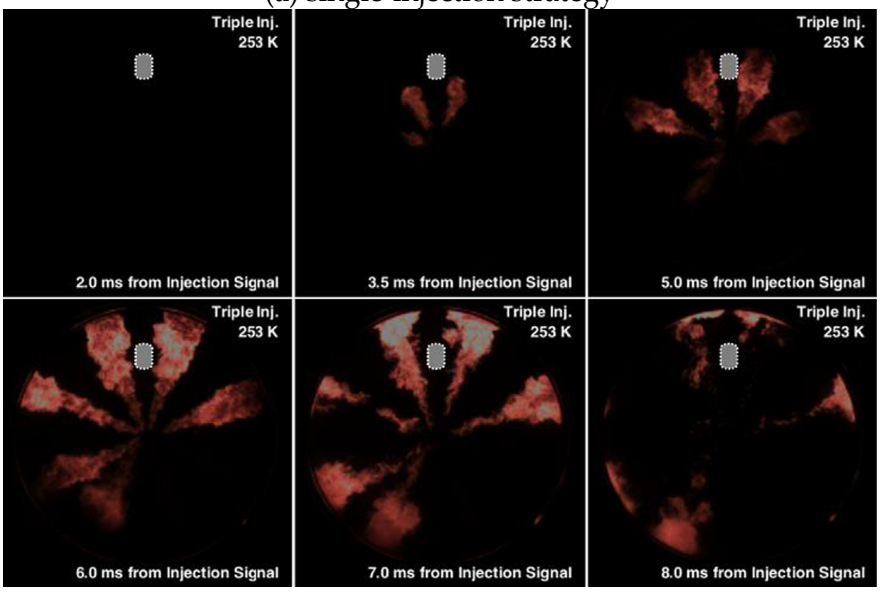


Figure 9. Cold start HC emissions at different ignition times [65] (Adapted with permission from Ref. [65]. Copyright 2016 Elsevier.)

Regarding the injection frequency, Hwang et al. [61] demonstrated that the multiple-injection technique outperforms the single-injection strategy regarding cold start performance by conducting a diesel spray test in a CVCC. Park et al. [68] comprehensively analyzed various injection strategies to improve the diesel combustion process at 253 K ambient temperatures. It was found that with the single-injection strategy, visible combustion reactions can only be seen near the electric heater plug at a 253 K temperature, as shown in Figure 10a. Therefore, Figure 10b shows that a triple-injection strategy can be adopted to help effectively improve the combustion process, which would reduce engine emissions. This is mainly because multiple injections with a small number of droplets can strongly optimize fuel vaporization and atomization.



(**a**) single-injection strategy



(**b**) triple-injection strategy

Figure 10. Combustion process for different injection strategies at 253 K [68] (Reprinted with permission from Ref. [68]. Copyright 2019 Elsevier).

3.4. Aftertreatment Technologies

The existing research on aftertreatment technologies focusing on the cold start of diesel engines mainly focuses on reducing NO_X emissions. The common aftertreatment

technologies mainly include diesel oxidation catalysts (DOC), particle oxidation catalysts (POC), selective catalytic reduction (SCR), diesel particulate filters (DPF), etc. [69]. The advanced solutions mainly include lean nitrogen oxide traps (LNT) and electrically heated catalysts (EHC) in the cold start stage of the diesel engine.

LNTs are commonly used to reduce NO_X during cold start-up of diesel engines due to adsorption storage followed by catalytic treatment [70]. Millo and Vezza [71] demonstrated that LNTs have a good NO_X storage capacity and can effectively reduce the total NO_X emissions during the test on a 2.0 L diesel engine. Theis et al. [72] evaluated a low-temperature NO_X adsorber and indicated that LNT could achieve a good result in reducing NO_X emissions when diesel engines are cold started.

The standard method of LNT is to adsorb and store the emissions first, then release the stored pollutants after catalytic reduction [73,74]. In this way, LNTs could perform NO_2 aftertreatment via a periodic adsorption–catalytic reduction in which NO in the exhaust gas is converted to NO_2 and reacted with NO_X storage materials, like barium metal, to create nitrate (NO_3) [75,76]. The stored NO_X can react with reducing agents such as HC and CO enriched in the exhaust gas on platinum group metals (PGM).

Under cold start conditions of diesel engines, it is challenging to operate DOC and selective catalytic reduction (SCR) normally [68]. For example, SCR technology combined with urea injection could achieve a good effect on NO_X emission only when the exhaust temperature reaches at least 200 °C [77–79]. Therefore, to reach an effective operating temperature under cold start conditions, an EHC is employed and intended to heat the DOC and SCR.

Compared with conventional heating of the catalyst using engine exhaust, EHC technology has two main advantages in cold start conditions. One is that, when integrated with a diesel engine's aftertreatment system, EHCs can directly transport the thermal energy generated by automotive batteries or onboard generators to heat the catalytic with greater efficiency and precision [80,81]. The other key advantage is that the precious metals used in the catalyst could be decreased using EHCs, thus reducing the cost of the aftertreatment system [82]. In addition, Pace et al. [83] demonstrated that EHCs could be activated more efficiently by recovering waste energy, thereby increasing effective thermal efficiency and mitigating engine CO emissions.

Duan et al. [84] installed EHCs at the DOC entrance and used the World Harmonized Transient Cycle (WHTC) to study the influence of EHCs on exhaust temperature and emission characteristics. The results showed that after the EHC was turned on, the time required for exhaust temperature to reach 138 °C was shortened by 767 s, and the time required for achieving 200 °C was reduced by 418 s. The conversion efficiency of CO and HC each increased by 92.8% and 50.8% during the cold start preheating process. The coupling diagram of EHC and DOC is shown in Figure 11.

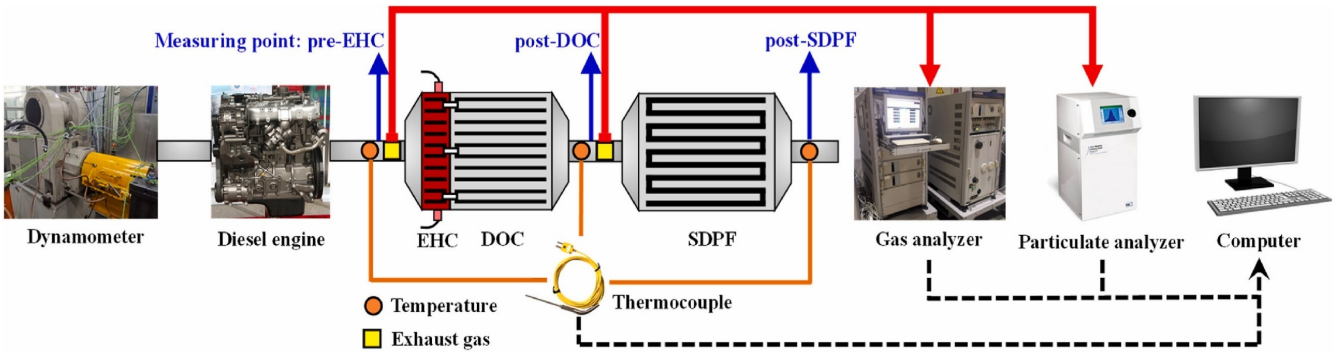


Figure 11. Schematic of the experimental system [84] (Reprinted with permission from Ref. [84]. Copyright 2022 Elsevier).

Kang et al. [85] took a diesel engine integrated with a passive NO_X absorber (PNA), EHC, DOC, and SCR catalyst integrated into a DPF (SDPF) and SCR as the research object to compare the effects of different catalyst loads on PNA emission characteristics. The results showed that compared with coupling EHCs before DOC, the NO_X conversion rate increased by 16.61% during cold start by coupling EHCs after DOC.

4. Conclusions

One of the most important transitory processes directly connected to engine emission levels is the cold start procedure for diesel engines. Hence, this paper aims to review the key strategies used to lessen diesel engine emissions under cold start conditions. The main conclusions of this paper can be drawn as follows:

(1) Under cold start conditions of diesel engines, it is very difficult to form a homogenous air–fuel mixture, leading to increases in nitrogen oxide, hydrocarbon, and carbon monoxide emissions of more than 85%, 75%, and 60%.
(2) By increasing the proportion of biodiesel in the diesel–biodiesel blends, diesel engine emissions could be gradually decreased under cold start conditions. When using pure biodiesel, CO emissions are reduced by 45% and HC emissions by 25%, but NO_X emissions rise slightly. Moreover, adding DEE could be a practical solution to further improving the cold start performance of diesel engines fueled with diesel–biodiesel blends.
(3) The cold start performance for diesel engines can be effectively increased using intake heating, and emissions can be decreased. Glow plugs and intake air heaters are normally used for small-to-medium diesel engines and large diesel engines, respectively. An effective intake heating system can reduce cold start time by more than 68%.
(4) Changing injection strategies, including injection pressure, timing, and frequency, would lead to different combustion conditions in diesel engines. An appropriate injection strategy would reduce emissions under cold start conditions.
(5) Under cold start conditions of diesel engines, it is hard for the DOC, DPF, and SCR to operate normally. Hence, the advanced approaches of aftertreatment technologies under cold start conditions are primarily LNTs and the use EHCs to preheat conventional post-processing equipment. EHCs can improve the cold start stage of conventional post-processing technology. The conversion efficiency of CO and HC can be more than 92% and 50%, and the conversion efficiency of NO_X is more than 16%.

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Abbreviations

ABE	Acetone–Butanol–Ethanol
APU	Auxiliary Power Unit
CVCC	Constant Volume Combustion Chamber
DEE	Di-Ethyl-Ether
DOC	Diesel Oxidation Catalysts
EHC	Electrically Heated Catalyst

HC	Hydrocarbon
LNT	Lean Nitrogen Oxide Traps
NEDC	New European Driving Cycle
PCMs	Phase Change Materials
Pt	Platinum
PGM	Platinum Group Metals
PM	Particulate Matter
PNA	Passive NOx Absorber
RDE	Real Drive Emission
SCR	Selective Catalytic Reduction
SDPF	SCR catalyst integrated into DPF
WHTC	World Harmonized Transient Cycle
WLTC	World Light vehicle Test Cycle

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