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Investigation of transient deterioration mechanism and improved method for turbocharged diesel engine

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ABSTRACT

The object of this paper is to reveal the mechanism of combustion process and pollutant emission deterioration during transient operation and propose an improve method to reduce transient smoke opacity as much as possible while keep NO_x formation below steady state condition. The paper reveals the transient operation deterioration mechanism from the following three levels: First, the combustion parameters response level (also known as boundary condition response level); Second, combustion process level (chiefly refer to apparent heat release rate, in-cylinder pressure, combustion phasing and combustion duration etc.); Third, in-cylinder micro-analysis level (chiefly refer to air fuel mixing energy ME). The main contributor of performance deterioration is boundary conditions deviation which caused by inconsistent response delay due to turbocharger lag. The consequence of boundary condition deviation is air-fuel mixing energy (ME) reduction. The improved method is to increase air-fuel mixing energy to compensate the negative effect cause by turbocharged lag. This work increases ME by means of advancing injection timing. The results indicates that: The BTE increases 2.2% and smoke decreases 12.1% as the injection timing advances 2 °CA, compared with the level under original injection timing. Therefore increasing ME can alleviate transient operation deterioration by improving the quality air-fuel mixture formation.

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1. Introduction

The characteristics of engine transient operation is boundary condition response delay comparing to steady state [1,2]. The response delay leads to a poor in-cylinder physical condition which is the cause of deterioration of fuel economy and pollutant emission [3–5]. Many corporations and institutes have attached great importance on transient working condition due to increasingly stringent fuel consumption and emission regulations [6].

The turbocharger lag of turbocharged engine causes of air supply delay into cylinder. The air supply delay changes oxygen concentration field, temperature field and equivalence ratio in combustion chamber in contrast to steady state. The boost pressure delay reduces the amount of oxygen that influences both engine performance and emissions.

From the perspective of engine performance, Zhang et al. [7] investigated diesel engine combustion deterioration under transient operation. They found that the combustion phasing delay is chiefly due to air supply delay which results in increasing smoke formation and fuel consumption. Galindo et al. [8] introduced a heat transfer model to predict engine performance under steady as well as transient conditions. They utilized this model to discuss the thermal energy saving under load transient. Glewen et al. [9] investigated the reason that transient performance deviates the steady state in a light duty diesel engine. They announced that mass air flow (MAF) and manifold absolute pressure (MAP) have little effect on engine performance at low load condition with low temperature combustion strategies. However, the intake valve closed (IVC) temperature and excess oxygen fraction in EGR is the main reason of transient performance deviation. Rakopoulos et al. [10] developed a detailed two-zone transient combustion model to predict the nitric oxide (NO) and soot emissions. They found that mass moment of inertia, cylinder wall insulation and exhaust valve opening timing are the sensitive factors of influencing NO and soot emission. Alberer et al. [11] propose a control maneuver called in-cylinder oxygen concentrations before (O2,BC) and after combustion (O2,AC) which can apply a nonlinear optimization through

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Nomenclature

EGR	exhaust gas recirculation
NOx	nitrogen oxide
CO	carbon dioxide
3D	three dimensional
CFD	computational fluid dynamics
ECU	engine control unit
A/D	analog to digital
ATDC	after top dead center
AFR	air-fuel ratio
γ	loading rate
δ	lag coefficient
ψ	deterioration coefficient
P_{max}	maximum pressure in cylinder
BSFC	brake specific fuel consumption
MFB10	crank angle location of 10% mass fraction burned
MFB50	crank angle location of 50% mass fraction burned
HRR	heat release rate
Φ	air-fuel equivalence ratio
ME	driving energy of air-fuel mixing
FDE	fuel driving energy
ODE	oxygen driving energy
DPSF	dominant period of soot formation
DPSO	dominant period of soot oxidation
T	temperature
BTE	brake thermal efficiency

choosing optimal trajectories to certain oxygen target quantities corresponding to particular transient torque. Turner et al. [12] presented a breakup model to imitate the transient fuel spray process which acquire acceptable agreement to experimental data meanwhile reduced the dependency on empirical parameters choosing. Eagle et al. [13] studied the transient spray process with high pressure injection through high-speed imaging.

The boundary conditions deviation due to inconsistent response delay under transient condition definitely affects the pollutant emissions [14–16]. Therein soot and NO_x deserve special concern due the trade-off correlation. Generally, NOx production decreases under transient operation because air supply delay cause oxygen concentration decrease which destroy the condition of NO_x formation. On the other hand, the lack of oxygen increases the goal equivalence ratio and rich regions which causes a poor soot emission [17–19]. In addition the increasing rich regions also increases the amount of UHC and CO emission. Fillipi et al. [20] declared that the spike soot emission occurred at the initial stage of sudden load increase from idle state. Furthermore as the load increased rapidly the average particulate size increased correspondingly. Eastwood et al. [21] compared the results of NOx and soot emissions between steady state and transient operation. They presented a mathematical algorithm to predict the discrete emissions departure from quasi-steady-state. Alex Darlington, Keith Glover and Nick Collings [22] suggested an air-path based model to predict the in-cylinder gas composition. They kept the in-cylinder burned fraction above particular threshold by controlling the position of EGR valve which have a noticeable effect on reducing transient NO_x emission. They reduced the spike of soot formation through limiting the maximal fuel quantity to keep the air-fuel ratio above threshold. Rakopoulos et al. [23] claimed that turbocharger lag plays a dominant influence on combustion deviation which results in elevated soot emission. The lack of air and its mismatched of fuel injection led to excess smoke opacity. The pollutant emission deteriorated and transient operation period extended in a steeper acceleration process.

The specific fuel consumption (SFC) is the function of load transient and it can deteriorate exceed 30% comparing to steady-srtate. The excessive pumping-loss is the main contributor of SFC deterioration. Tufail et al. [24] proposed a control strategy that aimed at minimizing the transient specific fuel consumption. The constructed SFC prediction empirical model is combined with engine operating strategy to constraint the pumping-loss. Yang et al. [5] quantified the correlation between torque increase time, fuel economy and engine-out emissions. They indicated that fuel consumption and smoke opacity increased significantly with rapid or steep torque increasing. Extended the torque increasing time is capable to reduce the smoke opacity at the expense of high specific fuel consumption. Besides, the NO_x concentration bear no relation to torque increasing time. Atkinson et al. [25] proposed a model-based rapid transient calibration system to reduce transient fuel consumption and emission.

Further minimizing fuel consumption and pollutant emission during transient condition requires full-scale optimization among fuel injection, air supply by turbocharger, match of combustion boundary conditions and in-cylinder physical condition etc [26,27]. A great amount of mathematic model have been proposed including heat release rate model, in-cylinder pressure model, torque model and emission model [28,29]. Finesso et al. [28] raised a real-time mean - value engine model to simulate the engine performance including heat release rate, combustion pressure, torque output and pollutant emission. The key thermodynamic properties including air quantity, EGR rate and air-fuel ratio can be obtained through look-up tables, correlations and empirical parameters. Nikzadfar et al. [30] developed an extended mean value model (EMVM) to optimize the diesel engine performance and emissions during transient operation. The dynamic and static modules were used to simulate the actual diesel engine. The results showed that the EMVM had a better capacity to predict the combustion process and actual emission under load transient. Grahna et al. [31] drawn calculated set points into engine management system (EMS). The set points were obtained through a given dynamic driving cycle with the object of increasing fuel economy and preventing emission maximal values exceeding regulation limits. Finesso et al. [32] constructed an efficient model to calculate in-cylinder combustion temperature and NOx production. They adopted a three-zone thermodynamic model to calculate combustion temperature. Meanwhile the NOx formation is computerized through second-order polynomial equations. Tian et al. [33] applied mean value model to calculate transient torque for engine real time control.

The object of this paper is to reveal the mechanism of combustion process and pollutant emission deterioration during transient operation. In addition, an improve method is proposed to reduce transient smoke emission as much as possible while keep NOx formation below steady state condition. The paper reveals the transient operation deterioration mechanism from the following three levels: First, the combustion parameters response level (also known as boundary condition response level); Second, combustion process level (chiefly refer to apparent heat release rate, in-cylinder pressure, combustion phasing and combustion duration etc.); Third, in-cylinder micro-analysis level (chiefly refer to air fuel mixing energy ME). The main contributor of performance

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