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Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review

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ABSTRACT

The call for reduction in pollution has been mandated by government's policies worldwide. This challenges the engine manufacturer to strike an optimum between engine performance and emissions. However with growing technology in the field of fuel injection equipment, the task has become realizable. For past few years it has been the hot topic to improve combustion and emissions of compression ignition engines through optimizing the fuel injection strategies. Choosing between various injection strategies are potentially effective techniques to reduce emission from engines as injection characteristics have great influences on the process of combustion. For example, increasing the fuel injection pressure can improve the fuel atomization and subsequently improve the combustion process, resulting in a higher brake thermal efficiency, producing less HC, CO, PM emissions, but more NO_x emission. Pilot injection help in reducing combustion noise and NO_x emissions and immediate post injection may help in soot oxidation and late post injection helps in regeneration of diesel particulate filter. This article aims at a comprehensive review of various fuel injection strategies *viz* varying injection pressure, injection rate shapes, injection timing and split/multiple injections for engine performance improvement and emissions control. Although every strategy has its own merits and demerits, they are explained in detail, in view of helping researchers to choose the better strategy or combination for their applications.

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1. Introduction

Diesel engines are the most efficient energy conversion devices; however they have one serious drawback: the amount of exhaust emissions like NO_x and particulate matter (PM) is comparatively larger than that of gasoline engines. According to

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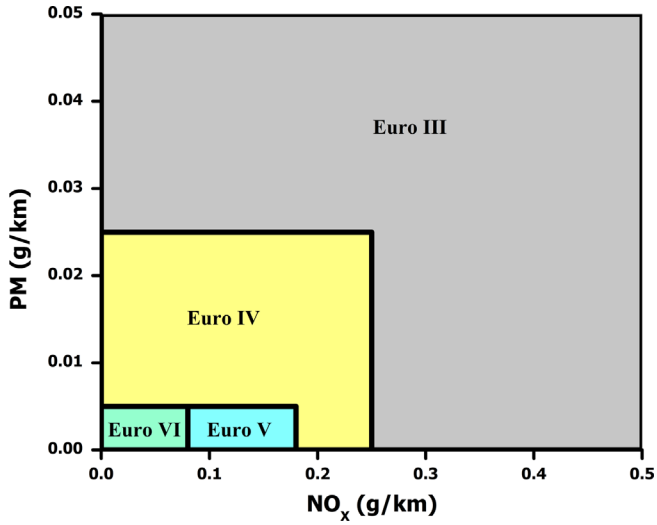

Fig. 1. European emission standards for passenger diesel cars.

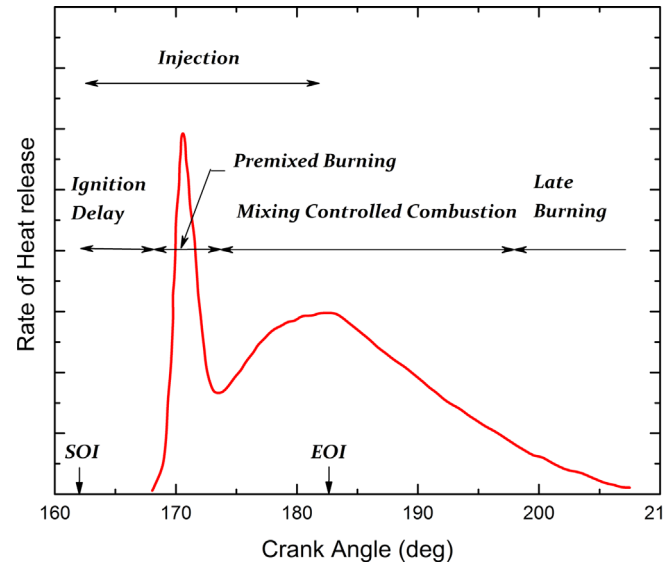

Fig. 2. Typical heat release rate curve of a CI engine (redrawn from [9]).

various reports [1–7], the exhaust emissions from engines have undesirable effects on human health. The reduction of environmental pollutions from diesel engines is regulated by federal government regulations. In order to improve the air quality standards, regulations on emissions from mobile sources have become stringent drastically in USA, Japan, Europe and other Asian countries over the decade. The European emission standards implement progressive and increasing stringent emission norms on passenger diesel cars [8] shown in Fig. 1. These regulations have pressed the automobile industries to explore substitutes to conventional fuel injection systems and have enthused attention in development of various fuel injection strategies.

The emissions formed are dependent upon the engine design, power output and working load. The complete combustion of fuel leads to major reductions in the formation of exhaust emissions. Complete combustion is a result of careful matching of air–fuel mixture and accuracy in the injection process. In order to reduce NO_x and PM formation it is necessary to understand the mechanisms of its formation.

1.1. NO_x and PM formation

Generally, the combustion process in a typical CI engine can be classified into four major phases [9], as shown in Fig. 2, the heat release rate curve of a CI engine.

The four phases are ignition delay, premixed burning, mixing controlled combustion and late burning phase. The period from the start of fuel injection to the start of combustion is the ignition delay. During the premixed combustion phase, a rapid heat release from the combustion of fuel which premixes and accumulates during the ignition delay period takes place. A relatively slower and controlled mixing combustion takes place after the initial rapid premix burning, which is primarily governed by the fuel atomisation, mixing of fuel vapour with air and chemical reactions. In the late combustion phase, the heat release rate slows down to a lower rate extending itself into the expansion stroke.

During the premixed combustion phase, poly aromatic hydrocarbons are formed which are the precursors of soot, due to the lack of air and fuel rich environment. The controlled mixing combustion phase takes place in two spatially separated stages. In the first stage, the fuel passes through a high fuel-rich premixed reaction zone and then in the second stage the fuel burns out in the turbulent diffusion flame at the jet periphery. Thus, for both combustion phases—initial premixed and controlled mixing; the fuel mixes with air, and gets vaporized and heated to ignition temperature. Then the fuel gets partially oxidized in a rich premixed reaction, and then completes combustion in a near-stoichiometric diffusion flame. The fuel rich premixed combustion produces partially burned products which lead to formation of soot. Though most of the soot burns out with the remaining fuel at the late combustion phase, a small part is not oxidized and converts to exhaust emission. Oxides of nitrogen (NO_x) are formed in the high-temperature regions in the hot product gases, and the rate of production increases exponentially with temperature. The NO_x and particulates are traded off against each other in several characteristics of engine design. High temperatures inside the combustion chamber help in reduction of particulates at the expense of high NO_x formation. At the same time low temperature inside the combustion chamber leads to less NO_x formation but increases the likelihood of high particulates formation. Thus a trade-off between NO_x and PM formation is more important to minimize both emissions [10].

1.2. Injection strategies

There are several ways to reduce NO_x and PM emissions. In some cases exhaust gas recirculation (EGR) is used to reduce NO_x emissions [11–14], but it increases the PM emissions and also increases the soot deposits on engine components and decreases the durability of the engines. In EGR, the exhaust gas displaces the fresh air entering the combustion chamber; as a consequence lower amount of oxygen in the intake mixture is available for combustion. Reduced oxygen available for combustion lowers the effective air–fuel ratio. The specific heat of intake mixture also increases by addition of exhaust gas, which results in reduction of flame temperature. Thus combination of lower oxygen content and reduced flame temperature reduces the rate of NO_x formation while increases the PM emissions accompanied by power loss [15]. The other ways to reduce emissions are by implementing various exhaust gas after treatment devices such as diesel particulate filter (DPF) and selective catalytic reduction (SCR). DPF is able to capture and remove diesel particulate matters and soot, while SCR can convert NO_x emissions to nitrogen and water by catalytic reactions. Though after treatment devices promises to reduce NO_x and PM emissions to a greater extent [16–23], but results in high capital and maintenance cost. Though there are many emission reduction techniques available, reducing the pollutants at source is the most beneficial method. The modern electronic fuel injection

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