Full Length Article

Modelling and understanding deposit formation and reduction in combustion engines – Application to the concrete case of internal GDI injector deposit

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ABSTRACT

Deposits, which form within various parts of internal combustion engines, can affect normal engine operation and result in diverse negative effects. Versatile research over the last decades revealed that the formation and reduction of deposits is the result of a complex interaction between the physical boundary conditions at the place of interest and of the fuel properties. To appropriately catch this complexity, an abstract, generalized kinetic model for deposit formation and reduction mechanisms is developed within this publication. It accounts both for the chemical and physical properties of the fuel mixture on a single component basis and for the physical boundary conditions at the site of interest. Due to an included explicit time dependence, it is also able to describe the effect of boundary condition changes and hence dynamic engine operation. In the second part of this publication the model is applied to the concrete case of internal deposit formation of a GDI injector during continuous engine operation, where the fuel flow drift caused thereby is used as the measure for the deposit amount. The deposit formation tendencies within the engine map, i.e. various engine speed and load points, are investigated and the results are interpreted by evaluating the impact of the operation point changes on the deposit kinetics. In a last step, selected desposit formation and reduction phenomenons during engine operation are discussed, which show the necessity for a model with a component basis of both fuel and deposit composition.

1. Introduction

The physical boundary conditions in various parts of combustion engines and the presence of fuel and lubricant together enable the formation of deposits [1]. These deposits can cause various and distinct problems during engine operation, dependent on their exact position within the engine. As a consequence, efforts to understand and avoid deposit formation in internal combustion engines were made by many authors during the last decades, where their research differs concerning various aspects. One of these aspects is the site of the deposit, where in principle all components of the engine which have contact to fuel or

lubricant are involved. The methodologies to investigate the deposits are distinct as well [2]. They range, without claiming completeness, from component and principle tests [3], over spray investigations [4], elemental analysis of deposits [5], measurement and simulation of the impact of fuel flows on the deposit formation [1,6] to real-time engine measurements [7,8]. For all named methodologies, the focus can again be different and include for example the elemental composition of deposits [3], the impact of fuel composition on deposit formation rates [5,8], the deposit caused injector flow-drift [8,9,7], the impact of deposits on emissions, fuel efficiency, performance [10,11,5] and spray [12] or the optimization of engine components concerning some of the

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named points [9]. Additionally many authors try to correlate certain operation strategies, fuel properties and physical boundary conditions at the place of deposit formation with deposit formation rates. The correlation of the T90 temperature, i.e. the temperature where 90% of the total fuel volume is evaporated, with the injector tip temperature is addressed [2,13], as well as the impact of a so-called soak period after the engine is stopped [2,14,10].

All publications have in common that under certain physical boundary conditions deposits are built by chemical reactions of fluid mixtures of different C–H molecules and other components, i.e. lubricant and fuel. There is however still a lack of a general, abstract kinetic model that is able to describe this deposit formation and reduction, the influence of physical and chemical boundary conditions and changes of them. Hence the focus of the first part of this publication is to develop such a generalized top view kinetic model of the deposit formation and reduction process during continuous engine operation, using universalized reaction rates and describing equations, which includes the elemental fuel/lubricant composition. The generalization allows to capture many, if not all cases of deposit formation from lubricants and fuels. In the second part of the publication, the model is concretized and applied to the case of internal GDI injector deposit kinetics and the flow drift caused thereby during continuous engine operation, where the model facilitates the qualitative understanding of occurring phenomenons.

2. Development of the kinetic deposit model

2.1. Deposit formation

Deposits can in principle be found at all parts of the engine that are in contact with any sort of C–H components carrying operating fluid within the engine, mostly fuel and lubricant. Dependent on the site of the deposit and the present physical boundary conditions (BCs), either fuel or lubricant can play the major role for their formation. The fluids have to undergo chemical reactions to experience the formation of deposits. The simplest chemical reaction with one educt A and one product B states

$$A \rightarrow B \tag{1}$$
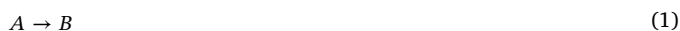
and the reaction rate is

$$v_A = c_A \cdot k \tag{2}$$

where $c_A = n_A / V$ is the concentration of A, i.e. the number n_A of molecules in the reference volume V, and k is the reaction rate coefficient. The rate of a chemical reaction is hence influenced by the number of available reacting molecules at the place of interest V and the reaction rate coefficient, which is in general dependent on the temperature, i.e. $k = k(T)$. For the formation of deposits the educts usually consist of hundreds or thousands of different lubricant and fuel components, i.e.

$$A = (A_1, A_2, ..., A_N) \tag{3}$$

where N represents the number of different compoents. Each component A_i can undergo different chemical reactions with different products, i.e. deposit components B_j. Like A, B consists of various distinct components, i.e.

$$B = (B_1, B_2, ..., B_M) \tag{4}$$

where M is the number of different deposit components. The kinetics of the different reactions can be written as

$$v_{A_i} = c_{A_i} \cdot k_{A_i} \tag{5}$$

where subindices i denote the respective quantities for A_i. In general, each A_i could react to various products B_j. Hence k_{A_i} denotes the sum of all occurring reaction rate coefficients for the specific component, i.e

$$k_{A_i} = \sum_j k_{A_i}(A_i \rightarrow B_j) \tag{6}$$

It is also possible that different educt components A_i react and form the same product B_j or that more than one educt and/or product is involved in the reaction. For simplicity reasons, these effects will be neglected, and the reaction rate of A_i is given by Eq. (5), i.e. a reaction of order one is assumed for each component. The total reaction rate is hence given by

$$v_A = \sum_{i=1}^{N} v_{A_i} = \sum_{i=1}^{N} c_{A_i} \cdot k_{A_i} \tag{7}$$

The concentration c_{A_i} of each component is dependent on the site of interest within the engine. The presence of the component is influenced by the existence of transport mechanisms that bring, respectively remove it from this site. As a consequence, c_{A_i} is a function of time and physical BCs, mainly temperature T, i.e. $c_{A_i} = c_{A_i}(t, T)$. Under constant operation conditions, physical conditions in/at combustion engines are, neglecting cycle to cycle variations, periodic recurring with period $p = 720°$ crk, respectively $p = 360°$ crk, depending on the number of revolutions per power stroke. Therefore it seems to be a convenient simplification to use values that are averaged over one period duration $\bar{t}$ to classify the operation conditions of the engine. This averaging is also applied to the concentrations c_{A_i} and the reaction rate coefficients k_{A_i}, yielding the average reaction rate of component A_i, according to Eq. (5),

$$v_{A_i}(\bar{t}, \overline{T}) = c_{A_i}(\bar{t}, \overline{T}) \cdot k_{A_i}(\overline{T}) \tag{8}$$

and the total reaction rate

$$v_A(\bar{t}, \overline{T}) = \sum_{i=1}^{N} v_{A_i}(\bar{t}, \overline{T}) = \sum_{i=1}^{N} c_{A_i}(\bar{t}, \overline{T}) \cdot k_{A_i}(\overline{T}) \tag{9}$$

where overlining indicates properties averaged over one period $\bar{t}$. With this averaging, there is no time dependence of v_A left in Eq. (9), and $v_A = $ const under constant engine operation conditions.[1] As a consequence, the deposit formation process globally appears as a chemical reaction of pseudo-order zero, even though we assumed a reaction oder of one for the elemental processes (see Eq. (5)), which is a consequence of the recurring transport mechanisms of the A_i to the site of interest V. To understand how the total reaction rate behaves under certain BCs, it is necessary to have a closer look at the two factors that define the reaction rate of component A_i according to Eq. (8), namely the concentration $c_{A_i}(\bar{t}, \overline{T})$ and the reaction rate coefficient $k_{A_i}(\overline{T})$.

2.1.1. Behavior of and influences on $c_{A_i}(\bar{t}, \overline{T})$

The two curves in Fig. 1(a) schematically illustrate possible time evolutions of $c_{A_i}(t)$ at some example control volume V of the engine over one period $\bar{t}_1$ for two different temperatures $\overline{T}_1$ and $\overline{T}_2$, with $\overline{T}_1 < \overline{T}_2$, and how the two average concentrations $c_{A_i}(\bar{t}, \overline{T}_1)$ and $c_{A_i}(\bar{t}, \overline{T}_2)$ result from that. At the beginning of the period the concentrations grow, which indicates the presence of a mechanism that brings A_i into the reference volume V, and after the c_{A_i} have reached their maxima at $c_{A_i}^{max}$, they reduce again, which indicates the presence of a removal mechanism of A_i, here by means of evaporation. As $\overline{T}_1 < \overline{T}_2$, the removal of A_i happens faster for $\overline{T}_2$ and $c_{A_i}(\bar{t}, \overline{T}_1) > c_{A_i}(\bar{t}, \overline{T}_2)$. Additionally to the temperature the duration of one period has an influence on the average concentrations, which can be seen in Fig. 1(b), where everything was left constant compared to the case shown in Fig. 1(a), except that the period duration was shortened, i.e. $\bar{t}_1 > \bar{t}_2$. As one can see, the shorter period duration results in higher average concentrations $c_{A_i}(\bar{t}, \overline{T}_1)$ and $c_{A_i}(\bar{t}, \overline{T}_2)$. (Note that it was assumed that no components A_i were present for the first transport event.) So by lowering $\overline{T}$ or $\bar{t}$ the

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[1] If one wants to model the deposit formation during a soak period, which is not addressed within this paper, no averaging over one period $\bar{t}$ can be performed as the engine is not running. However one can average over the total duration of the soak period to account for the deposit formation during that period.