

# Development of a Quasi-Dimensional Combustion Model for Stratified SI-Engines

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## ABSTRACT

The simulation of the combustion process is an essential part of the internal combustion engine development. For simulating whole engine maps quasi-dimensional models in combination with 1-D-flow simulations are widely used. This procedure is beneficial due to short computation times and accurate forecast capability of quasi-dimensional combustion models. For the simulation of homogeneous SI-engines the two-zone entrainment model is usually used, which is based on hemispherical flame propagation.

In this work a new approach for the quasi-dimensional calculation of the stratified SI-engine combustion process is proposed, which is based on the two-zone entrainment model. This proven approach was extended with regard to the inhomogeneous air/fuel composition of stratified SI-engines that make a two-zone treatment not sufficient.

Therefore, four unburnt zones are defined: a rich zone, a stoichiometrical zone, a lean zone and a remaining air zone. Furthermore in analogy to existing approaches a burnt zone is defined. These zones are connected to each other by mass flow rates which are calculated by a mixture model. This mixture model considers the current geometry of the zones. In order to model the combustion progress a complete new approach for the flame propagation was developed that meets the concerns of the stratified combustion process.

The newly developed approach was validated on measurement data of a modern, stratified SI-engine with multiple injection. 158 operating points were validated, that are covering the whole stratified range of the engine. The selected operating points also include a detailed variation of the multiple injection capabilities. A high accuracy of forecast capability could be proven by the new combustion model.

## INTRODUCTION

As a result of an injection into the compression stroke, stratified charge DI spark-ignition engines create a mixture that is ignitable only locally at the spark plug. This distinguishes them from conventional spark-ignition engines which create a mixture that is as homogeneous as possible in the entire combustion chamber. In an ideal case, the stratified charge DI spark-ignition engine can aspirate the maximum possible air quantity in partial load operation. Due to this dethrottling, the efficiency of the total process is significantly increased. Here, the entire fuel-air mixture present in the combustion chamber is partly very lean.

For stratified charge spark-ignition engines, special injection processes must be used to ensure that the required ignitable mixture is present at the spark plug. Three processes are being developed for this purpose:

- Wall-guided process: By using a special piston design, the injected fuel is redirected and guided to the spark plug.

- Air-guided process: By using a special combustion chamber flow, the fuel is guided to the spark plug.
- Jet-formed process: In this process, the injection ensures that an ignitable fuel-air mixture is formed at the spark plug.

The first stratified charge engines available on the market used wall-guided processes (Mitsubishi GDI, 1997). One major disadvantage of this process is the resulting piston wetting. This leads to decreased vaporisation and mixing, which reduces the efficiency of the combustion. In addition, the choice of injection parameters depends on the piston position. This limits the variability of the combustion process.

The air-guided processes are difficult to control due to the complex inner cylinder flows and, therefore, can be used only in a restricted charging window. Provided that the redirection of the fuel-air mixture is performed exclusively by the flow, this combustion process can be used to largely avoid a wetting of the piston.

The jet-formed process attempts to largely avoid the disadvantages of the two previously listed combustion processes by simply preparing the ignitable mixture at the spark plug through the injection spray. This process, however, has only been on the market very recently since the required reproduction quality of the injection systems could be ensured only with state-of-the-art directly-activated piezo injectors [3].

The quasi-dimensional combustion model presented here was specifically adapted to the jet-formed process since it was judged to be the most sustainable based on the theoretically highest efficiency advantage [6].

For the quasi-dimensional calculation of the energy release of a stratified SI-engine the model according to [2] was investigated. In [2], a superposition of a premixed entrainment combustion and a diffusion combustion are used for modelling. However, this model shows several disadvantages in the application of a current jet-formed combustion process, which significantly limits the predictability of the model for this application case:

- The ratio of the diffusion combustion to the premixed combustion is user-defined and generally not known.
- The calculation parameters are described in reference to additional variables (e.g. ZZP), which limits the predictability of the model.
- CFD simulations have shown that the burnout of the jet-formed DI spark-ignition engine is caused by a lean portion, which contradicts the diffusion combustion according to [2].

The flame geometry of the calculation according to [2] is based on a hemispheric model. CFD simulations have shown, however, that this assumption is not permissible for a jet-formed DI combustion process.

Due to these disadvantages, a new model was developed for the process calculation of the jet-formed DI spark ignition combustion process. The latest findings of production engines and CFD calculations were used to create a model as exact as possible. In particular, the influences of a multiple injection [3] should also be represented for this combustion process.

## MULTI-ZONE MODELING

The process of the jet-formed DI combustion process is essentially defined via its inhomogeneity. **Figure 1** shows an injection process of a jet-formed process. The inhomogeneous characteristic of the mixture composition is clearly identifiable.

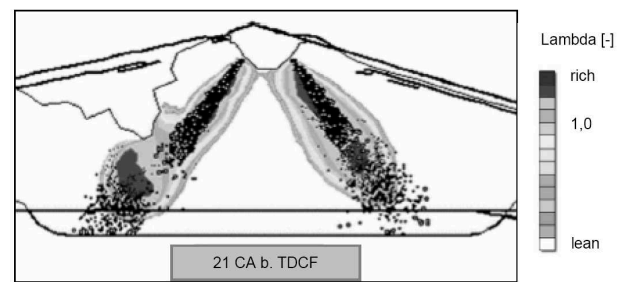


**Fig. 1:** Injection process of a jet-formed DI process [3]

CFD simulations have shown that this combustion process shows a large rich area during the beginning of the combustion whose air ratio is so low that a direct combustion appears impossible. To map the inhomogeneity of this combustion process, five zones were defined between which a mass exchange is modeled:

- An unburned "rich" zone from which no direct combustion occurs.
- An unburned "stoichiometric" zone. The combustion from this zone is responsible for the typical fast combustion increase at the start of the stratified combustion process.
- An unburned "lean" zone that is responsible for the typical slow burnout of the stratified combustion process.
- An unburned "residual air" zone that represents the surrounding residual air and is responsible for the admixture.
- A burned zone that takes up the burnt air-fuel mixture.

For this reason, an injection model, a vaporisation model, a mixture model and a flame geometry model were developed for the entire process of the jet-formed, stratified charge combustion process. The implementation of the model occurred in a simulation program for combustion engines specifically adapted for DAIMLER AG. This simulation program also features an integration into the commercial 1-D flow simulation software GT-Power.

## INJECTION AND VAPORISATION MODEL

The injection and vaporisation model represents the introduction and vaporisation of the fuel into the combustion chamber. This model also considers the effect of multiple injection.

Since fast-switching piezoelectric actuators are used for jet-formed combustion processes, it can be assumed that the injection characteristic is carried out nearly in block form.

The vaporisation of the fuel is dependent upon engine speed and the instantaneous temperature and can be calculated via the following equation [13]. In this equation  $\tau_{50}$  is a constant which defines the time of 50% evaporation.

$$\frac{dm_{vapor}}{dt} = 4.16 \cdot \frac{n_{ref}}{\tau_{50}} \cdot \left( \frac{T}{T_{ref}} \right)^t \cdot \left( \frac{n}{n_{ref}} \right)^N \cdot m_{fuel,liq} \quad (1)$$

Despite the simplicity of this approach, the vaporised fuel quantity could be calculated with high precision, which is the result of a comparison with CFD data.

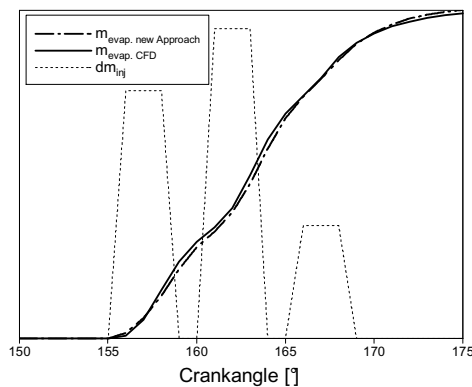


**Fig. 2:** Comparison of vaporisation of new approach ↔ CFD data

The vaporisation shown in **Figure 2** represents the total vaporisation in the combustion chamber. Depending on the boundary conditions of the injection (e.g. pause durations, injected fuel quantity, etc.), the multiple injection possible with this combustion process creates a

different distribution of the fuel in the mixture cloud. For a predictable modelling, this mixture formation quality must be represented with sufficient accuracy. Two factors,  $c_{quantity}$  and  $c_{time}$  (Equation 2 and 3), are defined for this purpose which describe the distribution of the vaporised fuel to the zones "rich" and "stoichiometric". It is assumed that no direct vaporisation into the "lean" zone occurs since such a strong leaning at the time of injection appears to be unrealistic. The factors are defined as follows:

$$c_{quantity} = \frac{m_{vapor}}{k_{quantity}} \quad (2)$$

$$c_{time} = \frac{1}{t_{SOI,i+1} - t_{EOI,i}} \cdot k_{time} \quad (3)$$

These factors help to consider that the mixing deteriorates with increasing injected fuel quantity and its proximity to the previous injection. The vaporised fuel masses are now assigned to the zones "rich" and "stoichiometric" (equation 4 and 5).

$$\frac{dm_{zone,rich}}{d\phi} = (1 + \lambda_{rich} \cdot L_{St}) \cdot (c_{quantity} + c_{time}) \cdot \frac{dm_{vapor}}{d\phi} \quad (4)$$

$$\frac{dm_{zone,stoich}}{d\phi} = \left( \frac{dm}{d\phi}_{vapor} - \frac{dm}{d\phi}_{zone,rich} \right) \cdot (1 + \lambda_{stoichiometrical} \cdot L_{St}) \quad (5)$$

This completely defines the injection and vaporisation process. **Figure 3** and **Figure 4** show a comparison of the zone assignment, each for single, double and triple injection.

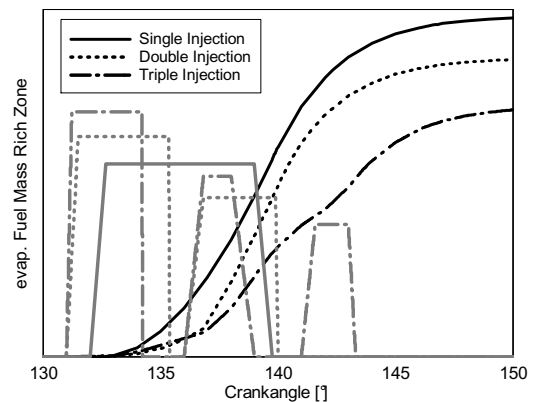


**Fig. 3:** Comparison of single and multiple injection – "Rich Zone"