

Feedforward Control Approach for Digital Combustion Rate Shaping Realizing Predefined Combustion Processes

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ABSTRACT

The aim of this research collaboration focuses on the realization of a novel Diesel combustion control strategy, known as Digital Combustion Rate Shaping (DiCoRS) for transient engine operation. Therefore, this paper presents an initial, 3D-CFD simulation based evaluation of a physical model-based feedforward controller, considered as a fundamental tool to apply real-time capable combustion rate shaping to a future engine test campaign.

DiCoRS is a promising concept to improve noise, soot and HC/CO emissions in parallel, without generating drawbacks in NO_x emission and combustion efficiency. Instead of controlling distinct combustion characteristics, DiCoRS aims at controlling the full combustion process and therefore represents the highest possible degree of freedom for combustion control. The manipulated variable is the full injection profile, generally consisting of multiple injection events. So far, however, DiCoRS was only realized by feedback-based iterative learning control, lacking sufficient control speed. Thus, an additional feedforward control unit is required to transfer the benefits of DiCoRS also to the dominating transient engine operation condition in passenger car applications.

Therefore, a new model-based feedforward control concept is developed and initially investigated in this paper. Desired combustion rates and therefore the desired in-cylinder gas state traces are formulated based on energy- and mass conservation equations. An inverse 0-D heat release model calculates the required injection profile, taking into account hardware related boundaries of the fuel injection system. Each submodule of the feedforward controller, such as the ignition delay model, is calibrated offline via steady-state engine test cell data. The overall functionality of the feedforward control concept is finally demonstrated based on a 3D-CFD combustion simulation study.

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INTRODUCTION AND MOTIVATION

Combustion efficiency, pollutant- and noise emission can be considered as main indicators for the quality characterization of the Diesel combustion process. However, these indicators show contrary trade-offs. The parallel optimization of each of these indicators and thus defusing their contrary trade-offs is the main objective of the modern Diesel combustion development.

A fuel injection path related way to approach this development is given by the principle of combustion rate shaping, using the full injection profile as the controlled variable. Combustion rate shaping can be distinguished in two methodologies: CoCoRS and DiCoRS.

CoCoRS (Continuous Combustion Rate Shaping) generates a continuous injection rate to shape the combustion, whereas switching the injection status either just "on" or "off" justifies the extended concept description of DiCoRS. While CoCoRS requires injection rate shaping capable injectors /1/, DiCoRS is inherently realizable with well-established series use DI common rail based injection systems. Experimental DiCoRS investigations on a single cylinder research engine identified, that a hydraulic dwell time of 200µs and injection duration of 150µs shall not be exceeded to realize DiCoRS with a sufficient control accuracy /5/. This is further confirmed by realizing DiCoRS with a series-use servo driven solenoid injector

with a railpressure up to 2000bar and a minimum hydraulic dwell time of 200 μ s /2/. In contrary to CoCoRS, DiCoRS can economically be realized with the current state of the art FIS technology.

DiCoRS enables the realization of predefined in-cylinder pressure traces, related to certain combustion rate traces during the working cycle. A flexible pressure trace to exploit the full optimization potential of the Diesel Combustion can be considered as the Alpha-Process /3/, as illustrated in figure 1. The SOR (Start of Ramp) indicates the start of combustion and Alpha refers to a constant pressure gradient in bar/°CA. Limit cases of the Alpha Process are the constant volume process (Alpha $\rightarrow$ inf), the constant pressure process (Alpha $\rightarrow$ 0) and the Seiliger Process when a pressure limitation is applied.

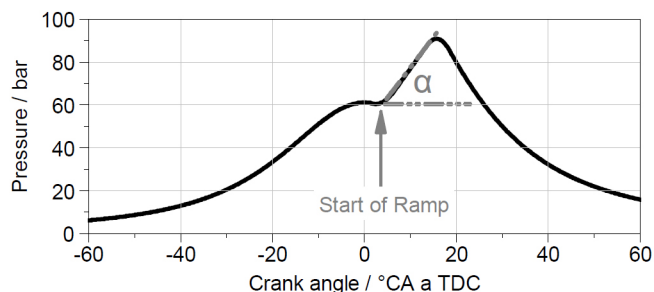


Figure 1. Schematic Alpha-Process as a flexible in-cylinder pressure trace

The parameters SOR and Alpha need to be chosen based on the engine operation point to optimize the combustion process in terms of noise-, pollutant emission-, and efficiency behavior. Direct Diesel combustion noise strongly correlates with the maximum in-cylinder pressure gradient (Alpha). The start of combustion influences the rotational imbalance of the engine and therefore the indirect combustion noise. The engine's total combustion noise emissions are expressed in CSL (Combustion Soud Level) /4/. The centroid of the cumulated combustion heat release, a strong indicator for combustion efficiency, is influenced by both, the SOR and Alpha. The adjustment strategy of SOR and Alpha can therefore be formulated as follows: SOR and Alpha need to be adjusted in a way that the in-cylinder pressure gradient corresponds to a desired CSL threshold while the resulting combustion centroid remains as close as possible to its optimum position. The resulting optimum in-cylinder pressure trace is achieved via the combustion rate shaping controller which adjusts the fuel injection profile accordingly. The controller further adapts the injector profile for any change in railpressure and therefore decouples the in-cylinder pressure gradient from the railpressure. Consequently, the railpressure and thus the air entrainment can be increased without generating drawbacks in CSL.

The well-known trade-off between soot- and combustion noise emission will be dissolved while maintaining optimal combustion efficiency as experimentally proven on a single cylinder research engine /5/, figure 2. The pressure gradient, and therefore the combustion rate, is controlled independently from the adjusted

railpressure. Choosing a single injection strategy as the reference combustion process, several Alpha processes with a constant pressure gradient of 3bar/°CA and different railpressures between 900bar and 1200bar are considered and compared. The NOx level is held constant by an appropriate control of EGR rate. The base combustion shows a very low specific particulate emission (ISPM) while resulting in a high combustion noise level (CSL) of nearly 85dB. Applying the Alpha process via 2 injections with 900bar, CSL drastically decreases due to the reduced cylinder pressure gradient of 3bar/°CA. The increased particulate emissions can be reduced down to the base combustion level by increasing the railpressure up to 1200bar. During this increase of railpressure, the combustion rate is held constant using the combustion rate shaping controller. This enables to decouple the soot-noise trade-off: The controlled Alpha process combines the low soot emission with low combustion sound level. HC/CO emissions and the indicated combustion efficiency remain within the level of the base combustion. HC emissions do not noticeable increase even for increased railpressures. This is due to the injection split and the induced avoidance of wall quenching effects.

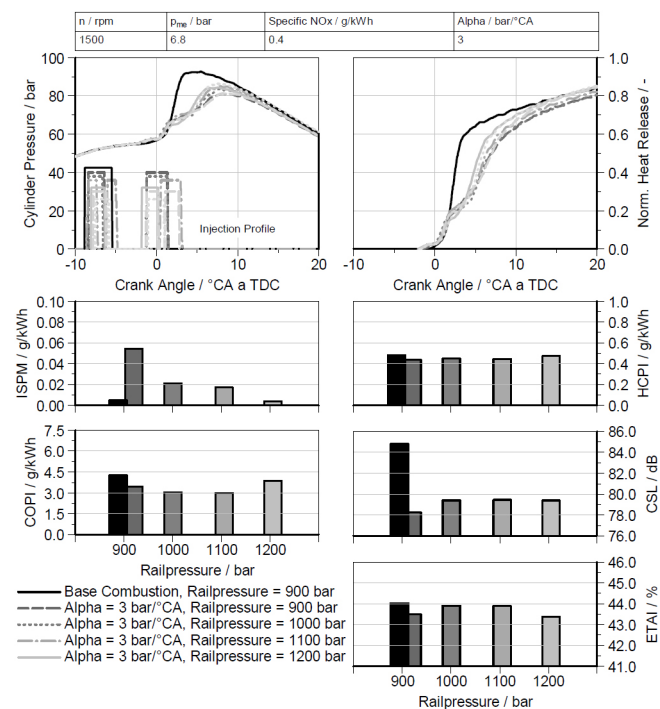


Figure 2. Experimental variation of railpressure at constant pressure gradient /5/

The Alpha-Process via DiCoRS was experimentally investigated for several NEDC representative steady state engine operation points on a single cylinder research engine /5/. The realization of the Alpha-Process was achieved using an iterative learning controller based on the cylinder pressure indication feedback signal. figure 3 shows the optimized choice for SOR and Alpha for different engine operation points resulting from a Design of Experiment (DOE) based variation of SOR and Alpha.

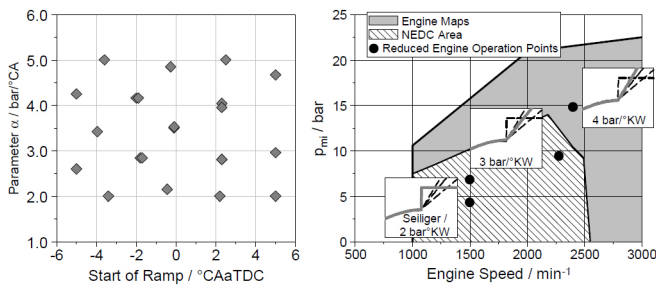


Figure 3. Experimental realization of Alpha-Process in NEDC representative steady state engine operation points using DiCoRS iterative learning feedback control /5/

The Seiliger process was found to be beneficial especially in the HC/CO critical low load region. In part load region, combustion efficiency and CSL gain further importance for which the optimal Alpha of 3bar/°CA can be found. CSL loses significance when approaching higher load regions where vehicle noise emission sources dominate. A higher Alpha value of 4bar/°CA is applied to improve combustion efficiency. The steady state engine test results were extrapolated for the NEDC engine operation point spectrum considering a representative passenger car of 1590kg equivalent mass inertia. Comparing the combustion performance of the Alpha-Process to conventional injection strategies on an equivalent NOx level, substantial advantages can be observed according to Table 1.

Table 1. Experimental combustion performance in NEDC for constant NOx level: Alpha Process versus conventional injection strategies /5/

	Base w/o Pilot	Base w Pilot	α -Process	Difference to Base w/o Pilot	Difference to Base w Pilot
PM / mg/km	5.3	9.2	4.6	-13.4 %	-50.0 %
HC / g/km	0.46	0.37	0.36	-22.5 %	-3.3 %
CO / g/km	2.11	1.89	1.54	-27.3 %	-18.7 %
FC / l/100 km	4.37	4.47	4.35	-0.5 %	-2.7 %
CSL / db	81.51	80.07	78.28	-3.2 dB	-1.8 dB

The thermodynamic benefits of optimized, railpressure independent in-cylinder pressure traces (e.g. Alpha-Process) are unmistakable and realizable with current series-use injection hardware as confirmed in /1/ and /5/. However, the remaining question towards the realization of combustion rate shaping is: How to find the injection profile which results in a desired pressure trace?

DiCoRS injection profiles generally consist of several injection events where each injection timing and energizing duration needs to be carefully adjusted synchronous to all the other injections to shape the desired combustion process for each engine operation point and condition. This can be achieved with a feedback control concept, based on an iterative learning control algorithm (ILC), as demonstrated in /3/. The ILC consists of several proportional-integral controllers distributed along the crankangle axis. This control concept was also used in /5/ to realize the Alpha-Processes as shown in figure 2 and 3. The required in-cylinder pressure sensor enables the detection of pressure deviations between the actual combustion cycle and the desired in-cylinder pressure trace for several sample points along the crankangle axis. Based on these pressure deviations, the injection profile can be adapted from one cycle to the next cycle.

However, ILC shows only slow control convergence and is therefore only suitable for steady state engine operation conditions, not for transient maneuvers.

Due to the fact that current and future certification cycles mostly operate at transient conditions, DiCoRS will only bring its benefits to practical use when drastically improving the control convergence behavior. Therefore, it is fundamental to apply an additional feedforward controller. In principle, the formulation of the feedforward controller can be data- or model based. For the data based variant, the feedback controller can be used to automatically find the appropriate injection profile for each engine operation point. The injection parameters of these injection profiles will be used to train a data-based model (i.e. neural network) or directly stored in maps which can then be used for feedforward control. This approach requires extensive calibration effort since any possible engine operation point at all relevant engine conditions need to be mapped. And once another engine configuration derivative is considered, this procedure needs to be repeated. Further, engine component wear or fuel property changes will affect the combustion behavior of the engine. The model based precontroller in turn predicts the required injection profile based on a thermodynamic engine model. This keeps the calibration effort very low and ensures the transferability also to different engine configurations. Combustion behavior changes due to e.g. component wear or fuel variations can be compensated by appropriate learning mechanisms directly adapting the affected combustion model parameter. These robustness advantages are encouraging enough to solely focus on the model based concept in the following.

OBJECTIVE

A model based feedforward control concept, capable of predicting the required fuel injection profile for a given desired combustion rate trace will be investigated in this paper. The feedforward controller consists of physical submodules, basically considering ignition delay, heat release and fuel injection behavior. These submodules are separately optimized and calibrated using offline steady state engine data from the test engine configuration as described in Table 2.

Table 2. Test engine configuration

Displacement volume / l	2.0
Number of cylinder / -	4
Compression ratio / -	15.0:1
Valves	2 Int. / 2 Exh.
Fuel injection system	Common rail, max. railpres. 1800bar
Turbocharger	Single charger with VNT
Air Path	Cooled LP- and HP EGR

These submodules are appropriately merged together in the Matlab/Simulink environment resulting in the overall feedforward controller algorithm, which is finally validated with a detailed 3DCFD combustion simulation model. This 3D-CFD combustion model simulates the engine as configured in Table 2. This procedure assures that the calibration of the physical submodules remains valid also when applying to the 3D-CFD model.

FEEDFORWARD CONTROL CONCEPT

In the short time period between the actual and the previous combustion cycle, the feedforward controller needs to predict the full fuel injection profile, including number of injections, injection timings and injection energizing durations, which shall result in a desired combustion rate trace. This means, that the complete combustion process needs to be predictively modeled as accurately as possible. To assure the required real time capability and to limit the controller complexity, physical models are formulated as mean-value models.

The overall concept is shown in figure 4. The desired Alpha-Process parameters, i.e. Alpha and SOR are obtained from engine maps. The desired in-cylinder pressure trace can be created. Once the pressure trace is available, further in-cylinder gas state traces, such as temperature and oxygen concentration can be derived, taking into account air path related targets like EGR strategy and charge air conditions. The desired heat release and the local ignition delay can be predicted for the complete working cycle as well.

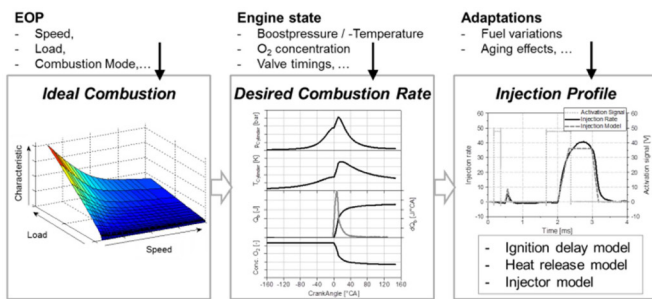


Figure 4. Overall feedforward control approach

Holding the assumption that the feedforward controller is capable of generating an injection profile which results in an actual combustion rate trace which is equal to the desired combustion rate trace, the fundamental principle of the feedforward control concept can be stated as follows: The in-cylinder gas state traces are already known before the onset of the actual working cycle. This principle enables to perform the injection profile calculation by using an inverse heat release model which directly correlates the heat release with the fuel injection profile while considering injector related boundaries. Further details of the main submodules and their validation are given in the following.

Desired In-Cylinder Gas State Traces

The in-cylinder gas states are calculated along the crankangle axis from IVC till EVO timings. Using a mean-value cylinder filling model, which considers the EGR strategy, and the charge air conditions, the in-cylinder gas state at IVC is well-known. From a desired SOR and Alpha, the pressure trace is calculated via polytropic compression from IVC till SOR, followed by constant pressure increase according to Alpha till end of ramp (EOR) and finally the polytropic expansion from EOR till EVO. EOR is iteratively obtained while considering the desired mean effective pressure by calculating the cylinder pressure ring integral for each calculation step along the constant pressure increase. The transition between the constant pressure increase and the burn out phase is smoothed depending on the railpressure and the EGR rate. The temperature is approximated

by the ideal gas law. Since pressure- and temperature traces are available, the burn rate dQ_b can be calculated with an energy balance based single zone model, equation 1, using the cylinder wall heat transfer coefficient α_i given by Woschni /6/.

$$dQ_b = \frac{\kappa}{\kappa-1} p dV + \frac{1}{\kappa-1} V dp + \alpha_i A_W (T_i - T_{mWi}) dt \quad (1)$$

The oxygen concentration is an important input variable for the ignition delay model. The initial oxygen concentration at combustion begin is well-known from the filling model. The fuel conversion rate is obtained from equation 1 under consideration of the lower heating value of the fuel. The oxygen reduction is approximated by a complete combustion using n-Heptane C_xH_y as a surrogate fuel for Diesel, equation 1.

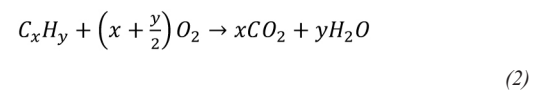


Figure 5 shows an exemplary validation of the desired traces for pressure, temperature, heat release and oxygen concentration. The experimental data is obtained from the test engine described in Table 2 and can be compared to an Alpha-Process with an Alpha of 6bar/°CA and a SOR of 2°CA aTDC. The analysis of the measured cylinder pressure results in a temperature trace and a burn rate, using a multi zone model. The test cell is equipped with oxygen concentration sensors at intake and exhaust manifold.

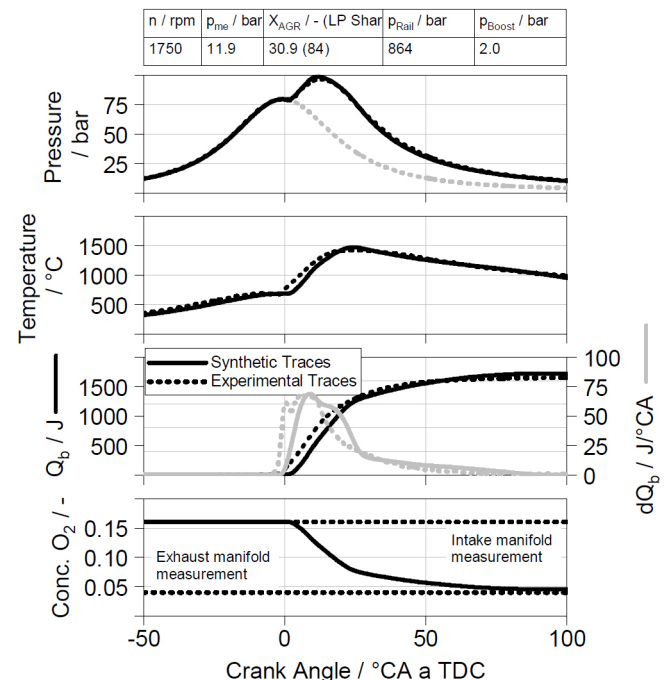


Figure 5. Comparison of synthetic in-cylinder state traces with experimental data

The desired Alpha pressure trace is synthetically rebuilt. The smooth transition between the Alpha ramp and the burn out phase matches with the experimental behavior. The modeled oxygen concentration at IVC is calculated with the cylinder filling model and matches well

with the measured oxygen concentration at the intake manifold. The modeled oxygen conversion trace, i.e. the oxygen concentration at EVO corresponds with the measured oxygen concentration in the exhaust manifold.

Heat Release Model

The previous chapter describes how the desired burn rate and the cumulated heat release are obtained. Once these traces are available, they can further be correlated with the fuel injection rate trace $\dot{m}_{Fuel}$ according to [equation 3](#)

$$\frac{dQ_B(t)}{dt} = C \cdot \left[H_u \cdot \int_{SOI}^t \dot{m}_{Fuel}(t - \tau_{ID}(t)) - Q_B(t) \right] \quad (3)$$

This correlation originates from [7] and was initially derived for a purely diffusive combustion. The basic idea is: At each sample time t within the combustion, there is a difference between the cumulated injected fuel energy which is ready for conversion (after ignition delay) and the heat energy which has already been released. This energy difference represents the maximum potential for instantaneous heat release and can therefore be correlated with the current burn rate. However, the maximum heat releasing potential cannot be fully used due to a limited mixing rate of fuel and air. Therefore, the combustion rate factor C is introduced to scale down the maximum heat releasing potential. Thus, besides the hydraulic injection rate trace, the modeled burn rate in [equation 3](#) is influenced by the ignition delay as a state variable and the combustion rate factor as a calibration parameter. The longer the ignition delay, the higher the amount of unburnt fuel energy introduced and the higher the fuel air mixture homogenization level in parallel. This results in an increased maximum heat releasing potential, i.e. a higher amount of premixed share of combustion. Thus, the modeled burn rate increases with a higher ignition delay. Once the ignition delay is bridged and the combustion has begun, the further rate of fuel oxidation is limited by the mixing rate of fuel and fresh air, which is quantified by the combustion rate factor C . Factor C , therefore describes the rate, with which the current maximum heating potential can be converted, which is also reflected by the unit 1/s. The mixing rate is mainly determined by the kinetic turbulent energy [7], which in turn is found to correlate with the burn rate. Consequently, it is possible to correlate the combustion rate factor C with the burn rate, which is known a priori in this concept as a desired trace.

The described correlation can be confirmed in [figure 6](#). Due to different scales, the three traces are normalized relative to their individual maximum value for comparison purpose in the right diagram of [figure 6](#). It can further be observed, that C increases drastically within the range of premixed combustion. In conclusion: The heat release model described in [equation 3](#) can be applied not only to the diffusive, but also to the premixed combustion when increasing the combustion rate factor C appropriately. Interpreting the findings, the premixed combustion can be modeled as a “fast” diffusive combustion. The combustion rate factor C was inverted from [equation 3](#), where the burn rate and the cumulated heat release

traces are obtained by an analysis of the measured in-cylinder pressure trace. The hydraulic fuel rate trace and the ignition delay traces are obtained by the described models. The trace of the cylinder-averaged kinetic turbulent energy was re-calculated by a 3D-CFD simulation model, which will further be described in a following chapter.

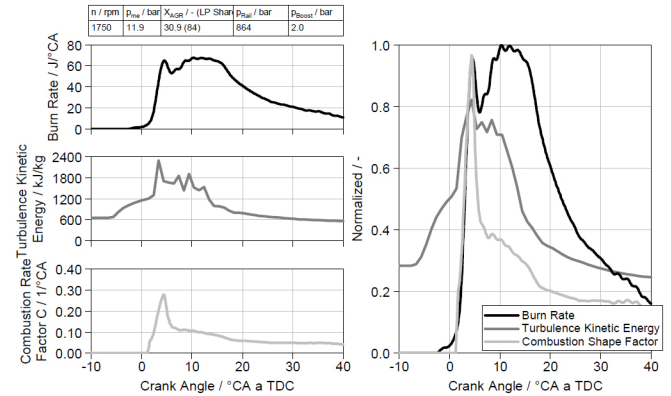


Figure 6. Relation between experimental burn rate, simulated cylinder averaged turbulent kinetic energy and modeled combustion rate factor C

Based on the previous finding, the combustion rate factor C can be calculated as a crank angle resolved trace depending on the burn rate. However, as observed in [figure 6](#), the correlation between C and the burn rate is different for the premixed and the diffusive combustion as found in [equation 4](#) and [5](#).

$$C_{pre}(t) = a_{pre} \cdot \left(\frac{dQ_B(t)}{dt} \right)^{b_{pre}} \quad (4)$$

$$C_{diff}(t) = a_{diff} \cdot \left(\frac{dQ_B(t)}{dt} \right)^{b_{diff}} \quad (5)$$

Considering the fact, that the transition between premixed and diffusive combustion is rather smooth than discrete, C_{pre} and C_{diff} can be weighted according to [equation 6](#).

$$C(t) = \gamma(t) \cdot C_{pre}(t) + (1 - \gamma(t)) \cdot C_{diff}(t) \quad (6)$$

The weighting factor γ quantifies the share between premixed and diffusive combustion at each time step. The ignition delay time was found to be a strong indicator for the split between premixed and diffusive combustion and is therefore found to be correlatable with the weighting factor. Since the weighting factor requires a value domain between 0 and 1, it needs to be scaled accordingly. For this end, a maximum ignition delay limit $\tau_{ID,max}$ needs to be defined, above which complete premixed combustion occurs, i.e. above which γ remains 1. By analogy, a minimum ignition delay limit $\tau_{ID,min}$ needs to be defined, below which complete diffusive combustion occurs, i.e. below which γ remains 0. Between these limits, γ is linearly interpolated according to [figure 7](#).