Development and application of a stereoscopic 3-color high-speed ratio-pyrometry

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ARTICLE INFO

ABSTRACT

The development of most energy conversion systems is focused on increased efficiency and decreased pollutant emissions. However, the diesel engine combustion process suffers from the systematic trade-off between soot-oxidation and NO_x-formation in the vicinity of the diffusion-flame surface. Since this process is influenced by the local flame surface temperatures, it is of great importance to investigate and understand the factors influencing the surface temperature distribution itself. For this reason, a new combination of measurement techniques called "stereoscopic 3-color high-speed ratio-pyrometry" has been developed at RWTH Aachen University. This system provides a double-redundant quantification of the temperature, topology and emissivity distributions of an optically opaque diesel-flame with a temporal and spatial resolution of 10,000 images/s and 16 Pixels/mm^2 in this set-up. Still, the system only consists of a high-speed camera, a stereoscopic double-row adapter and three optical filters. The first part of this paper includes a brief description of the theoretical fundamentals, experimental hardware, required calibration procedures and post processing algorithms to provide a general understanding about the developed measurement technique. Based on this, the second part of this paper is used to present the results of the first experimental investigations conducted on a continuously scavenged high-pressure chamber test-bench. These results indicate a general dependency between the local surface temperature and optical density, caused by several parallel processes.

1. Introduction

1.1. Diesel engine related mixture formation and combustion

Figure 1 shows a conceptional illustration of a steady-state diesel-flame in a three-dimensional cut-section to present the current understanding of the diesel engine related combustion process. This model is most dominantly derived from the investigations of Dec [1], Flynn et al. [2], Pickett and Siebers [3], Idicheria and Pickett [4] and Pickett [5].

The injected fuel evaporates and turbulently mixes with the surrounding air [2,6]. In consequence, an inhomogeneous, rich and temporally fluctuant, gaseous mixture is generated around the tip of liquid penetration. In this mixture, the initial reactions start in the case of sufficient boundary conditions [7], which results in the formation of a partially premixed reaction zone (PPRZ) at a certain distance to the injector nozzle. However, in normal conditions the amount of entrained air is insufficient for complete oxidation [8]. Therefore, partially oxidized hydrocarbon fragments exit the PPRZ [3].

The hydrocarbon fragments that propagate to the flame-surface are oxidized in consumption of the newly entrained oxygen [2]. This results in the formation of a diffusion-flame layer (i.e. the region of stoichiometric equivalence ratio) around the complete downstream region of the flame [2]. Moreover, the consumption of oxygen in the surrounding diffusion flame layer cuts off the oxygen supply into the flame and therefore causes oxygen deficiency in the inner part of the flame [3,8,9].

This oxygen deficiency in combination with temperatures of $T \geqslant 1400\,K$ and the presence of polycyclic aromatic hydrocarbons (PAHs) causes the formation of soot precursors and particles in the central part of the flame [10,8,11–14]. The PAHs are delivered by the fuel or need to be formed by various kinetic pathways starting with acetylene C_2H^2 [14,15]. Since these early acetylene and PAH formations are still in competition with oxidation reactions [8], the following soot particle formation can significantly be

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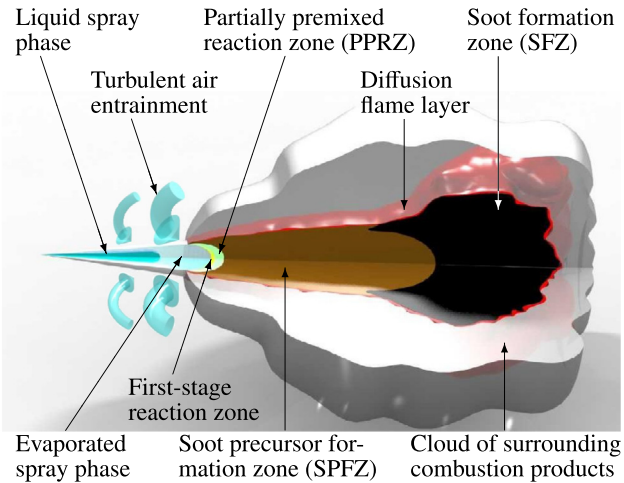[2] FEV GmbH, Aachen, Germany.

Fig. 1. Cut section of the conceptional model of the diesel engine related mixture formation and combustion in steady-state.

influenced by temporal fluctuations of air-entrainment upstream of the PPRZ. The process from PAHs to particles inside of the soot formation zone (SFZ) includes nucleation, surface growth, agglomeration and coalescence of PAHs [3,12]. Here, the entrainment of hot combustion products into the flame is required to achieve $T \geqslant 1400$ K [3] as the agglomeration and coalescence of PAHs significantly decelerate at temperatures below this limit [14,16]. Therefore, the region of the diffusion flame includes the counter-directed transportation processes of combustion product entrainment into the flame and the diffusion of particles, precursors and residual hydrocarbon fragments out of the flame.

Figure 2 shows the temperatures and relative concentrations of oxygen, fuel (the sum of particles, precursors and residual hydrocarbon fragments) and combustion products as a function of the mixture fraction $Z = m_{fuel}/(m_{fuel} + m_{oxygen})$ following the Flamelet model, which implies an infinitely fast, diffusive, single-step reaction [17,18]. Here, the stoichiometric diffusion flame surface is indicated by $Z = Z_{st}$ and the range from $Z = Z_{st}$ to $Z = 1$ represents the penetration depth of product entrainment into the flame. Since the sum of all relative concentrations always equals 1, it can be seen that the product entrainment causes a dilution of the relative fuel concentration by propagating to the diffusion flame layer. In the case of a real diesel engine related turbulent flame, the amount and depth of product dilution near the diffusion flame layer will fluctuate with time and location, which will be important for the later interpretation. Apart from this, it can be seen that relative combustion product concentrations decrease in the range from $Z = Z_{st}$ to $Z = 0$, which equals the thickness of the surrounding cloud of combustion products illustrated in Fig. 1.

Therefore, the oxidative conversion at the developed diffusion flame layer always appear in the presence of inert combustion products. However, the exothermic heat-release of oxidation at the diffusion-flame layer still causes temperatures of $T_{surf} = 2500$–3000 K [2,19,20], which are sufficient for the thermal decomposition of the triple-bound ambient nitrogen. The resulting NO_x-formation in the vicinity of the diffusion-flame layer [19–21] can be mitigated by diluting the ambient air with more inert combustion products by the application of exhaust-gas recirculation. However, the further decrease in oxygen concentration near the diffusion flame simultaneously impairs the soot oxidation, which results in the systematic soot-NO_x trade-off in the vicinity of the diffusion flame-layer.

1.2. Flame radiation

Due to the described flame temperatures, the radiation emitted by a sooting diesel engine flame consists of various chemiluminescent spectra and stronger broadband soot-luminosity [22,23]. In first approximation, the soot particles fulfill the assumption of black-body radiation. This implies that all incoming radiation is absorbed and all radiation received from this object is emitted. Therefore, the general soot-luminosity behavior can be described by Planck's law of radiation [24] given in Eq. (1) and plotted in Fig. 3. Eq. (1) shows that the radiation is a function of wavelength and radiator temperature only. Since the radiation intensity increases with radiator temperature, the strongest soot-luminosity of a diesel engine related flame is emitted by the hottest particles in the vicinity of the diffusion-flame surface, which achieve thermal equilibrium with their environment during $t = 10^{-5}$ s [25] – 10^{-7} s [26].

$$M(\lambda, T)dA\,d\lambda = \frac{2\Pi hc^2}{\lambda^5} \frac{1}{exp\left(\frac{hc}{\lambda kT}\right) - 1} dA\,d\lambda \qquad (1)$$

with:

M	spectral radiance	W/mm^2
λ	wavelength	m
T	temperature	K
h	Planck's constant	$6.6260696 \cdot 10^{-34}$ Js
c	speed of light	299,792,458 m/s
k	Boltzmann's constant	$1.38065 \cdot 10^{-23}$ J/K

Figure 3 shows the spectral black-body radiance plotted over wavelength for four exemplary temperatures and the acquisition wavelengths (i.e. $\lambda = 694$ nm, 800 nm and 905 nm) of the presented set-up indicated by blue vertical lines. It can be seen that the wavelength of black-body peak-intensity decreases with increasing temperature. This can be explained by an increasing probability of high-energetic and therefore high-frequent radiation ($E = h\,f$) [27]. Furthermore, the radiation intensity at temperatures of $T \approx 1500$ K is negligible in comparison to radiation intensity at temperatures of $T \approx 3000$ K.
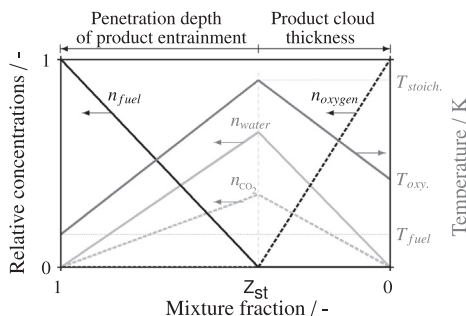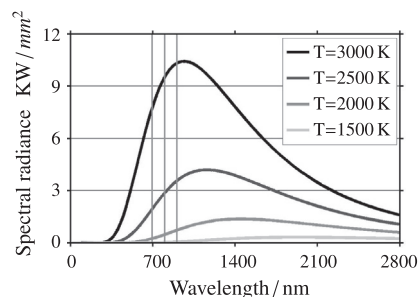

Fig. 2. Qualitative illustration of the diffusion processes during oxidation using the Flamelet model (implied assumptions are described in [17,18]).

Fig. 3. Spectral radiance of a black-body radiator over wavelength for four representative radiator temperatures.