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Full Length Article

Experimental investigation of the heat transfer characteristics of spray/wall interaction in diesel selective catalytic reduction systems

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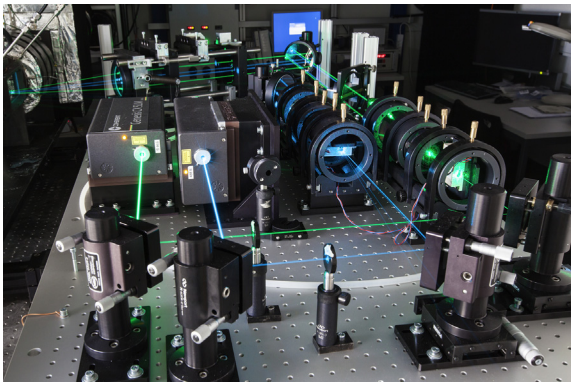
HIGHLIGHTS

- Experimental study of SCR spray/wall interaction under exhaust flow conditions.
- The wall temperature and droplets kinetics experimentally determined.
- The inverse heat conduction problem solved to evaluate spray cooling heat fluxes.
- The spray cooling on the wall results in heat fluxes of several MW/m^2.
- Spray/wall interaction regimes shift from deposition to rebound and thermal breakup.

GRAPHICAL ABSTRACT



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ABSTRACT

This study presents an experimental investigation of the heat transfer characteristics of the spray/wall interaction in diesel selective catalytic reduction (SCR) systems. The work was performed with a commercial 3-Hole pressure-driven injector dosing into a flow channel under typical diesel exhaust flow conditions. Infrared thermography captured the surface temperature of the wall around the impingement area with high temporal and spatial resolution. The resulting temperatures have been used for assessing the heat extracted from the wall. Phase Doppler Anemometry (PDA) was applied to measure the droplet sizes and velocities prior to the wall impingement, providing information on the kinetic properties of the impinging droplets. Based on these, the influence of the gas flow conditions on the heat transfer characteristics is deduced.

The spray impingement leads to a substantial and rapid temperature drop on the wall, resulting in a maximum heat flux of several MW/m^2 during the injection duration. The spray cooling effect decreases with increasing exhaust gas flow rate due to the increased entrainment of spray droplets in the flow prior to impingement. Increase in gas flow temperature affects the heat transfer by increasing the wall temperature. At lower wall temperatures, the principal spray/wall interaction regime is deposition. With increasing wall temperature, there is a shift to rebound and thermal breakup. The shorter contact times in the rebound and thermal breakup regimes result in decreased spray/wall heat transfer.

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Nomenclature

amb	ambient
back	background
CaF_2	calcium fluoride
env	environment
InSb	indium antimonide
IR	infrared
PDA	phase Doppler anemometry
SCR	selective catalytic reduction
UWS	urea water solution
c_p	specific heat [J/kg K]
I_{camera}	infrared radiation detected by IR camera [W/m^2]
$I(T)$	blackbody radiation at a given temperature T [W/m^2]
k	thermal conductivity [W/m K]
K	Mundo number [–]
$\dot{m}$	gas mass flow rate [kg/h]
Re	Reynolds number [–]
T	gas flow temperature [°C]
$\bar{U}_{gas}$	gas mean flow velocity [m/s]
We	Weber number [–]
x, y, z	nozzle coordinate system [mm]
α	thermal diffusivity [m^2/s]
ε_{CaF_2}	CaF_2 window emissivity [–]
ε_{mirror}	mirror emissivity [–]
ε_{plate}	plate emissivity [–]
ρ	density [kg/m^3]
ρ_{CaF_2}	CaF_2 window reflectivity [–]
ρ_{mirror}	mirror reflectivity [–]
ρ_{plate}	plate reflectivity [–]
τ_{CaF2}	CaF_2 window transmissivity [–]
τ_{plate}	plate transmissivity [–]

1. Introduction

To comply with the stringent regulations as stated in Euro6 legislation, the NOx emissions of light and heavy-duty vehicles have to be reduced by up to 80% in respect to Euro5 [1]. Exhaust SCR system is a promising technique to reduce NOx emissions without sacrificing engine efficiency [2]. In most mobile applications, urea water solution (UWS) is used as an ammonia precursor because of its non-toxicity and convenience of storage. UWS is sprayed into the exhaust gas flow, followed by the evaporation of water from spray droplets. Thereafter, thermal decomposition and hydrolysis take place [2,3].

The main challenges for the implementation of mobile urea-SCR systems include rapid decomposition [4,5] and homogeneous distribution of urea [6] as well as mitigation of deposit formation [7–9]. Due to compact design requirements of the exhaust pipe and the relatively long time scales of urea thermal decomposition [10], the spray impingement on the exhaust pipe or on a mixer is unavoidable [3]. UWS spray impingement on the exhaust pipe wall or on a mixer on one side can assist liquid evaporation and urea thermal decomposition; on the other side can lead to deposit formation, since spray impingement results in local cooling. As the wall temperature drops below a certain threshold, liquid film starts forming [11]. Temperature-dependent impact regimes are also decisive for the spatial distribution of the reducing agent. Evaporation from the wall film leads to further cooling and to increasing risk of deposit formation such as solid urea, biuret, cyanuric acid, ammelide, ammeline and melamine [11–13].

Incropera and DeWitt [14] summarized different modes of evaporation occurring at a solid-liquid interface: free convection, nucleate boiling, transition boiling and film boiling. The importance of the Leidenfrost temperature, where the local heat flux is minimized, is highlighted. The evaporation characteristics of urea-water solution have been recently considered due to the use of 32.5 wt% urea-water solution as a liquid ammonia precursor in diesel exhaust systems. Musa et al. [15] derived the modified boiling curve, from droplet evaporation times on a heated surface as a function of the surface temperature, for a single UWS droplet. In the study, different regimes of boiling were observed and beyond the critical heat flux point two different patterns, fast evaporation and slow evaporation, were found. Wang et al. [16] and Musa et al. [15] found the multi-stage evaporation behavior of UWS droplets through conducting experiments in an electric furnace under quiescent conditions. The first stage is only water evaporation, following the D^2 law. The second stage is characterized by micro explosion, the extent of which depends on the ambient temperature. After the complete depletion of liquid, white solid deposit remains at temperatures below 550 °C. Grout et al. [17] used synthetic Schlieren method to visualize the liquid film evolution, and Mie scattering to measure the 2D liquid distribution in stream cross-sections under exhaust flow conditions. Through analyzing these consecutive distributions, the global spray evaporation rate was deduced. Birkhold et al. [3,11] realized the importance of spray/wall interaction and included it into his systematic modelling of UWS injection. In the Kuhnke [18] model, the spray/wall interaction regime map was classified into four regimes: deposition, splash, rebound and thermal breakup based on the kinetic properties of the droplets, Mundo number K, and the temperature of the wall $T^* = T_{wall}/T_{sat}$ as displayed in Fig. 1. According to Kuhnke, the critical temperature at the non-wetting threshold was determined to be 1.1 for a variety of fluids, but Birkhold found it to be 1.4 (265–280 °C) for urea-water solution. However, to the knowledge of the author, heat transfer characteristic of UWS spray/wall impingement under exhaust flow conditions have not been studied experimentally so far.

Heat transfer of spray impingement is significant in many fields of application, like fuel spray impingement, steel quenching and electronic cooling. They [19–26] gave rise to the experimental methods used in this study.

The present study is a comprehensive experimental analysis of the heat transfer characteristics of the impinging SCR spray under typical diesel exhaust flow conditions. Infrared thermography was introduced to assess the surface temperature of the wall with high

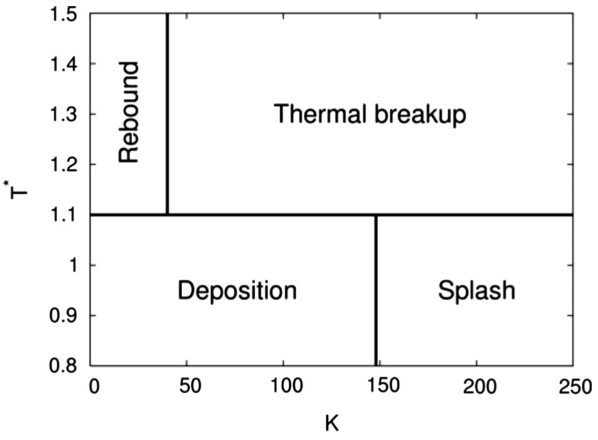

Fig. 1. Spray/wall interaction regimes according to Kuhnke [18].