International Journal of Heat and Mass Transfer 117 (2018) 447–457

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer characteristics of urea-water spray impingement on hot surfaces

Yujun Liao [a,*], Panayotis Dimopoulos Eggenschwiler [a], Roman Furrer [b], Moyu Wang [a], Konstantinos Boulouchos [c]

[a] Automotive Powertrain Technologies Laboratory, Empa, Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Dübendorf, Switzerland
[b] Reliability Science and Technology Laboratory, Empa, Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Dübendorf, Switzerland
[c] Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich, CH-8092 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 14 July 2017
Received in revised form 19 September 2017
Accepted 8 October 2017

Keywords:
Spray cooling
Urea-water solution boiling curve
3D inverse heat conduction
Critical heat flux
Leidenfrost phenomena

ABSTRACT

This study presents an investigation of the heat transfer characteristics of the urea-water spray (UWS) impingement on a stainless steel plate under typical diesel exhaust flow conditions. The rear side temperature of the spray-impinged plate has been measured by infrared thermography with high temporal and spatial resolution. The spray impinged side temperature and heat flux distributions have been computed by solving the 3D inverse heat conduction in the plate with the sequential function specification method.

Measurements show that the instantaneous plate temperature determines the heat transferred during the spray impingement. Based on the plate temperature, different regimes (film boiling, transition boiling and nucleate boiling) have been identified. At high plate temperatures, film boiling and Leidenfrost effect are prevailing and the heat transferred from the plate to the liquid is low. With decreasing plate temperatures, the critical heat flux regime is approached and the heat transferred increases substantially. At lower plate temperatures, nucleate boiling occurs limiting the heat transferred to low values. The critical heat flux and temperature found for UWS are reported and in good agreement with the trend in previous studies for water.

1. Introduction

To comply with recent stringent emission regulations (Euro 6 or higher), a significant reduction of the NOx in the exhaust of light and heavy-duty vehicles has to be achieved. Selective catalytic reduction (SCR) is a promising technique to reduce NOx emissions without sacrificing engine efficiency [1]. During the SCR process, urea water solution (UWS) is injected into the exhaust gas flow, where it decomposes into ammonia, a strong reducing agent. Due to compact design requirements, spray impingement on the exhaust pipe or on a mixer device is unavoidable [2]. The UWS spray impingement leads to local cooling [3,4]. Thereafter a wall liquid film is formed [4,5]. Evaporation from the liquid film leads to further cooling and to an enhanced risk of deposit formation [3,6,7]. Several application-oriented papers have clearly pointed out detrimental effects of solid deposits [8–10]. Temperature-dependent impingement regimes are decisive for the spray/wall heat transfer [3,11]. Further understanding of the heat transfer issues would lead to significant improvement of NOx reduction performance.

Different modes of pool boiling occurring at a solid-liquid interface have been summarized by Incropera et al. [12]: based on the wall temperature free convection, nucleate, transition and film boiling may occur. Water at atmospheric pressure undergoes free convection between 100 °C and 105 °C. The nucleate boiling follows with substantially higher heat fluxes leading to the critical heat flux point (CHF), at 130 °C. Heat flux around CHF exceeds 1 MW/m^2. At higher temperatures, the transition regime is entered and heat flux decreases. The Leidenfrost point, with minimized heat flux in film boiling, is located at 220 °C. Further increasing temperatures lead to film boiling regime and higher heat flux.

Heat transfer characteristics of the water spray impingement have been investigated in [13–19]. The dependency of the spray/wall heat transfer on the spray mass flux and the droplet diameter has been identified. Yao et al. [14] performed a dimensional analysis. The characteristic velocity (liquid mass flux over density) was introduced to define the spray Weber number (Wes) as a measure of the spray inertia. It led to an empirical correlation of the Leidenfrost temperature based on the spray Weber number. In a

---

* Corresponding author.
E-mail address: yujun.liao@empa.ch (Y. Liao).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.031

Nomenclature

CaF_2	calcium fluoride
InSb	indium antimonide
IR	infrared
SCR	selective catalytic reduction
UWS	urea water solution
SOI	start of injection
NB	nucleate boiling
TB	transition boiling
FB	film boiling
IHCP	inverse heat conduction problem
CHF	critical heat flux
SMD	Sauter mean diameter
I_{camera}	infrared radiation detected by IR camera [W/m^2]
$I(T)$	blackbody radiation at a given temperature T [W/m^2]
$\dot{m}$	gas mass flow rate [kg/h]
T	gas flow temperature [°C]
We	Weber number [–]
x, y, z	nozzle coordinate system [mm]
ε_{CaF_2}	CaF_2 window emissivity [–]
ε_{mirror}	mirror emissivity [–]
ε_{plate}	plate emissivity [–]
ρ_{CaF_2}	CaF_2 window reflectivity [–]
ρ_{mirror}	mirror reflectivity [–]
ρ_{plate}	plate reflectivity [–]
τ_{CaF_2}	CaF_2 window transmissivity [–]
τ_{plate}	plate transmissivity [–]

following study [20], Al-Ahmadi and Yao presented correlations for the Leidenfrost and critical heat flux (CHF) points over the local mass flux for industrial nozzles with mass fluxes ranging from 1.7 to 30 kg/m^2 s. It has been highlighted that the Leidenfrost and CHF points have a stronger dependency on the mass flux than on the droplet velocity and size. In general, such industrial nozzles produce relatively large droplets (350 μm) of moderate velocities (13–15 m/s) [15]. In addition to the impact mass flux, Wendelstorf et al. [15] introduced the temperature difference (between the liquid and the wall) in the analytic correlation of the heat transfer coefficient.

Moreover, several studies revealed that the critical heat flux, the Leidensrost temperature and the critical heat flux temperature are positively correlated with the mass flux [16,17,19] and negatively correlated with the droplet diameter [16,19]. Estes and Mudawar [16] provided correlations of the critical heat flux to the spray mass flux and the Sauter mean diameter (SMD) for full cone sprays. For sprays with a local mass flux of 30 kg/m^2 s and a SMD of 150 μm, for instance, the CHF reaches about 1 MW/m^2 for sprays. Jia et al. [17] conducted experiments with a multi-nozzle spray system which provided variable mass fluxes ranging from 0.156 to 1.20 kg/m^2 s and droplets around 30 μm. According to [17], the CHF is about 2 MW/m^2 at 1.2 kg/m^2 s for water spray cooling. In parallel, the CHF temperature increases almost linearly with the mass flux, being 145 °C at 1.2 kg/m^2 s. Addition of sodium dodecyl sulfate in water broadens the CHF temperature range. However, the exact reason of the broadening is not clear. Empirical correlations for the critical heat flux and the transition boiling regime have been obtained as a function of the Sauter mean diameter, the local water flux, the surface temperature, and the physical properties of water and vapor [19]. For sprays with the injection pressure of 5 bar and the local mass flux of 10 kg/m^2 s, the critical heat flux is found to be 1 MW/m^2.

To the authors' knowledge, only Musa et al. [21] have examined the urea-water single droplet impact on elevated temperature surfaces. Based on the experiments, a modified boiling curve was derived, exhibiting a higher CHF temperature of 180 °C and a relatively flat behavior around the Leidenfrost point. Two different patterns were identified in the transition and film boiling regimes, which were attributed to the processes involved in urea thermal decomposition [22]. The complex nature of spray impingement on hot surfaces and the uncertainty about urea water solution properties render the prediction of the spray wall heat transfer in real applications very difficult. Numerical simulation efforts [4,23–26] have deliberately pointed out that there is a lack of experimental data concerning UWS spray/wall heat transfer.

The present study provides a comprehensive experimental analysis of the heat transfer characteristics of the SCR spray wall impingement under typical diesel exhaust flow conditions. Infrared thermography has been applied to measure the rear surface temperature of the impinged wall with high temporal and spatial resolution. Different boiling modes, as well as the CHF and Leidenfrost temperatures have been identified from the temporal gradients of the surface temperatures. Finally, the measured rear surface temperature distributions have been used to compute the spray cooling heat flux by solving the 3D inverse heat conduction problem (IHCP) with the sequential function specification method.

2. Experimental setup and methods

Measurements were conducted in the flow channel, which was designed for the experimental investigation of thermo-fluid properties of UWS sprays in general and the impingement processes in particular. The schematic diagram of the flow channel has been shown in [3]. All measurements within this work were performed with dry heated air as exhaust flow. The urea-water spray was introduced by a commercial SCR injector, mounted with an angle of 50° with respect to the gas flow direction, in a channel part with a quadratic 80 mm by 80 mm cross section equipped with various optical accesses. The injector has 3 nozzles with 190 μm diameter evenly located on a 1.9 mm diameter circle. Operated at 9 bar, the static flow rate is 7.2 kg/h. For all results presented in this study, the injection frequency was set to 2 Hz. The standard injection duration in this study was set at 100 ms resulting in 0.2 g UWS per injection. For studying the impingement process a plate was introduced in the channel 14 mm above and parallel to the channel wall. Thus the gas flow wetted the upper (impinged plate surface) as well as the lower plate surface providing stable thermal boundary conditions. The injection commenced once the thermal equilibrium between the plate and the surrounding gas flow was achieved. The plate, consisting of stainless steel type 304, had 0.7 mm thickness.

Temperature profiles on the impinged plate were captured by the infrared camera, Infratec ImageIR 8300 hp, with a 50 mm lens. The radiation detector is an InSb quantum detector that is sensitive in the 2–5.7 μm wavelength range. It is cooled by a Stirling motor to 77 K. During the measurements, the IR camera recorded 200 frames per second with a resolution of 640 × 512 pixels at 0.149 mm/pixel. Since water absorption varies with the water film thickness [27], it was decided to measure the temperature profile of the rear surface of the plate. A calcium fluoride (CaF_2) glass window with a high transmissivity in the mid-infrared range allows a